Generative co-design & non-planar additive manufacture of aesthetic prostheses

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Abstract

Traditionally, the prosthesis has been treated as medicalised device and primarily designed for function. The aesthetics of prostheses appeared to be a secondary concern, and even when they were considered, the appearance of prostheses often tried to mimic human limbs to hide disability. However, a new trend of aesthetic prosthesis has emerged recently which solicits attention, expresses the personal style and self-identity of the individual with limb loss or absence, and emphasises their individuality and uniqueness rather than incompleteness, which has been demonstrated to significantly impact users' psychological well-being.

However, such aesthetic prostheses must be unique to each individual, which requires a degree of personalisation in both design and manufacture that exceeds the capabilities of conventional design and manufacturing techniques. In response, I establish techniques for the generative co-design and non-planar additive manufacture of personalised aesthetic prostheses. This involves following an interdisciplinary approach that weaves together techniques from human-computer interaction (HCI), prosthesis and disability research, dance and motion capture, and additive manufacture.

My proposed generative co-design strategy combines the advantages of generative design, which enables the efficient exploration of many designs, with the collaborative design which enables users' involvement in the design pro-

cess so as to embody a deep expression of individual identity within the designed prostheses. The strategy enables the direct personalisation of aesthetic prostheses through a personally expressive skill, in this case, dancing, without the involvement of professional designers.

The strategy is embodied in three algorithms that collectively address the whole design flow from conceptual design to final design for manufacture. Mogrow is a generative co-design algorithm driven by motion capture technology so that dancing can generate personalised aesthetic seeds - archetypal designs that might be applied to various products. Leg sculpting is a generative design algorithm that applies an aesthetic seed to a specific product, a prosthesis cover that is personalised to fit users' unique body features. A final algorithm optimises the design of the prosthesis produced by leg sculpting to be manufactured without printing supports, significantly improving the efficiency of additive manufacture without compromising aesthetic details.

While the application of additive manufacturing technology can significantly improve the efficiency of customisation, the aesthetic prosthesis requires higher freedom of morphology to open up a broader space for aesthetic consideration, which potentially conflicts with the requirements of mechanical strength and weight. The final contribution of this thesis is therefore to establish a non-planar additive manufacturing platform based on a six degrees of freedom (6DOF) robotic arm, that accommodates trade-offs between visual aesthetic, form, weight, and mechanical properties of aesthetic prostheses.

This research uses disabled dancers as research collaborators. Three workshops are conducted to interact with the algorithms and discuss the results.

Author contributions to thesis

The research theme of "Prostheses" was suggested by the Horizon Centre for Doctoral Training (CDT) and the partner, Additive Manufacturing CDT, who jointly funded this PhD research. The idea of applying generative co-design design, additive manufacture and motion capture to aesthetic prostheses was proposed and developed by the author during the first year of doctoral training, with feedback from a number of academics associated with the Horizon CDT, in particular from Prof. Steve Benford, and Prof. Ian Ashcroft who later became the authors' PhD supervisors.

All the research in the thesis was designed by the author, with guidance and oversight from his two supervisors. The author was responsible for producing protocols, acquiring ethical approvals for participants in the thesis and associated tasks of data collection, analysis and interpretation. Major help was received from Prof. Sarah Whatley and Dr. Kate Marsh in working with disabled dancers. Dr. Marie Dilworth from the Horizon CDT assisted in the workshops with dancers.

The author established both the generative co-design system consisting of three algorithms and the non-planar additive manufacturing platform including designing and building hardware, as well as developing a corresponding controlling system and slicing software. Dr. Paul Tennent and Dr. Joseph Marshal at the Mixed Reality Lab supplied significant help on motion capture and transformation of motion data.

Publications

Articulating Soma Experiences using Trajectories. Tennent, Paul, et al. “Articulating Soma Experiences using Trajectories.” Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. 2021. This paper recieved Honorable Mention of the CHI conference (for top 5% submissions).

Unpacking non-dualistic design: The soma design case. Höök, Kristina, et al. “Unpacking non-dualistic design: The soma design case.” ACM Transactions on ComputerHuman Interaction (TOCHI) 28.6 (2021): 1-36.

Personalising prosthetics: digital interventions in disability and dance. This abstract was accepted by DRHA 2022 conference

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Chapter 1

Introduction

1.1 The need for aesthetic prostheses

Prosthetic limbs have historically been intended for replacing loss (Mullins, 2009), and as a result, are usually functional or naturalistic in design (Pullin, 2009). The basic, or "functional," prosthesis meets the rudimentary operational needs of the user (Mital & Pierce, 1971). A naturalistic prosthetic limb is focused on discretion, thereby disguising limb loss (Mullins, 2009). However, a new type of artificial limb – "aesthetic prostheses" – is now appearing in the marketplace. These prostheses differ from traditional designs, in that they solicit attention and express the personal style and self-identity of the individual with limb loss or absence. Based on the Lamb & Kallal (1992) FEA Consumer Needs Model, these prostheses fulfil the expressive needs of prosthetic limb users, which have historically been overlooked. Vainshtein (2011), Pullin (2009) and Hall & Orzada (2013) have also argued that prostheses shouldn't be limited to addressing only functional or cosmetic issues and claimed that "aesthetic prostheses" significantly impact users' psychological well-being by emphasising their individuality and uniqueness rather than incompleteness. However, an aesthetic prosthesis is usually unique for each individual, which means it requires customisation in both design and manufacture. The established approach to getting a customised and aesthetic design is based on traditional, even handmade, design and manufacture processes. This is already not scalable to large numbers of users within the budgets or many people in the healthcare system. It is even less scalable to a future in which aesthetic prosthetics might be uniquely made for different purposes and occasions, perhaps eventually acquiring the status of fashion items. The challenge explored by this thesis is to establish a radical new approach to design and manufacture that can deliver personalised aesthetic prostheses at scale.

1.2 Generative co-design & non-planar additive manufacture of aesthetic prostheses

This thesis explores how the extension and integration of two emerging technologies -generative co-design and non-planar additive manufacture could address this challenge.

Generative co-design is the integration of generative design and co-design approaches.

- The generative design approach investigates how to use the power of computers to perform creative tasks more efficiently or even to make computer design solutions. This is known as computational creativity (Gabriel et al., 2016), which includes any application capable of generating product shapes other than those directly created by the designer. The generative design was seen as an efficient tool to produce the customised design (McKnight, 2017).

- The co-design (participatory design) allows users, stakeholders, and designers to work collaboratively in the design process (E. B. N. Sanders et al., 2010). It enables designers to elicit tacit and latent knowledge they might not otherwise discover through conventional research methods (Sanders, 1999). Blom (2018), explored the role of the co-design approach in establishing artisanship in prosthetic aesthetics. The research demonstrated that the co-design approach enabled users' involvement in the process of designing their prostheses. Through this involvement, the personal experience was implanted into the aesthetic prosthesis, which embodied a deeper, richer expression of the individual identity of the amputees in a beautiful and intricate way (Blom, 2018).

This thesis integrates generative design and the co-design approaches to establish the generative co-design approach, in order to explore a design approach for aesthetic prostheses which enables massive aesthetic customisations and expression of self-identity by the user's involvement in the prosthesis design process.

The aesthetics require a high degree of geometric freedom, which easily conflicts with the requirements of physical factors of a prosthesis, e.g. mechanical properties and weight. While, customisation for each individual challenges the efficiency of traditional manual manufacture and massive manufacture. Thus, this thesis explored non-planar additive manufacturing technology with six degrees of freedom (6DOF) robotic arm to be the manufacturing approach in order to accommodate tradeoffs between visual aesthetic, form, weight, material and mechanical properties of aesthetic prostheses.

Therefore, this thesis aims to explore generative co-design & non-planar additive manufacture of aesthetic prostheses.

1.3 Research questions

Research question 1: Is generative design a feasible approach to efficiently producing aesthetic designs that are acceptable by dancers and applicable to prosthetic designs?

Research question 2: How can dancers effectively interact with generative design to produce personalised designs?

Research question 3: How can the resulting designs then be applied to diverse forms of prostheses?

Research question 4: How can the resulting prosthetic designs be made viable for additive manufacture without compromising their aesthetics?

Research question 5: How can additive manufacture accommodate tradeoffs between visual aesthetic, form, weight, material and mechanical properties of aesthetic prosthetics?

Research question 6: How does the integrated flow of design and manufacturing prosthetic prostheses incorporate aesthetics?

1.4 Method

As part of the UKRI Horizon Centre for Doctoral Training that focuses on interdisciplinary research, my PhD project follows an interdisciplinary approach that spans computer science, engineering and dance.The overall research approach is “research through design” in which generalizable knowledge emerges from a practice-led process of designing, making, and reflecting on various kinds of products (Gaver, 2012; Zimmerman, Forlizzi, & Evenson, 2007). We engaged dancers as co-designers, involving them in a process of ‘inquiry and imagination’ (Spiel et al., 2018). While co-design emphasizes users’ input, it does not entirely put the user in the position of designer (Mazzone, 2012; Sanders, 1999), but rather requires that the designer analyze and translate acquired knowledge into design-relevant information (Sanders, 1999). Our process involved moving back and forth between design-led technical innovations and dancer-led responses to these. This required us to balance our own technical ideas with facilitating, listening to, and observing our co-designers.

We recruited two professional disabled dancers and two dance researchers. The dancers, referred to as T and W, were both female with many years of training and professional experience in expressing themselves through improvised bodily movements. Both had high amputations on one leg. They were compensated using industry daily rates recommended by their professional body. The two dance researchers, S and K, were also experienced dance practitioners. They recruited the dancers and contributed insights into dance and disability from their research. K is also a disabled artist researcher with lived experience of disability. The relatively small number of external participants was due to the scarcity of and demand for professional disabled dancers, combined with the effects of the global COVID pandemic which halted our plans for hosting a larger event to gather feedback from the wider dance community. However, engaging even just a few professionals in our design process proved highly illuminating, revealing unanticipated insights as we report below.

The two dancers were fully informed about the research. They were asked to perform a series of improvision, while wearing the ROKOKO Smart Suit, and interact with the design algorithm by seeing the screen in front. Their movements and produced designs were recorded and analysed. The research was conducted in Centre for Dance Research in Coventry University a safe and supportive environment, with all necessary measures taken to ensure the physical and emotional well-being of the dancers. The data collected was be kept confidential and anonymous, and was only be used for the purpose of the research.

1.5 Structure

The thesis will present these threads in three discrete chapters that each used different methods, then bring them together into a framework in the discussion chapter. These three chapters are:

- Generative co-design – the method here is creating and demonstrating nature-inspired generative design algorithms as well as enabling disabled dancers' involvement in the designing process to explore how they can interact with the various algorithms to produce personalised aesthetic prosthetic designs.
- Non-planar additive manufacture – the method here is engineering research to identify and solve key additive manufacturing challenges.

- And user evaluation – the method to evaluate whether the design and manufacturing methods demonstrate acceptable aesthetics by dancers.

1.6 Contribution

This thesis explores a radical new approach to design and manufacture that can deliver personalised aesthetic prostheses at scale by answering the six research questions stated above.

- The established generative co-design algorithm – Mogrow creates designs with an organic aesthetic style obtaining a high degree of disabled dancers' acceptance.
- The application of motion capture and dancing principles (Raheb et al., 2018) brings an applicable manner of interaction between dancer and generative design algorithm.
- The developed generative design algorithm – leg sculpting enables the customisation of aesthetic prosthetic designs to fit the user's specific body features.
- The developed generative design algorithm – optimisation of additive manufacture enables improvement of efficiency of additive manufacture by eliminating the requirement of support during the process of additive manufacture, without compromising the design's aesthetics.
- The established non-planar additive manufacture platform is potential to accommodate tradeoffs between visual aesthetic, form, weight, material and mechanical properties of aesthetic prosthetics.

- Considering aesthetics throughout the co-design and additive manufacturing process

1.7 Impact of COVID-19

COVID-19 has significantly impacted the present study.

- The pandemic has also held back the user study. The research collaborators are disabled dancers who are rare and the pandemic made it even more challenging to run workshops.
- Limited access to the required facilities e.g. high-precision 6DOF robotic arm hindered the experiment of manufacturing. The compromising solution was to conduct experiments, with a lower-precision facility.

Chapter 2

Literature Review

This research follows an interdisciplinary approach including aesthetics of Human Computer Interaction(HCI), aesthetics of prostheses, design approach: co-design and generative design, dance and interaction, and additive manufacturing of prostheses. This chapter will state relevant research separately for these four fields. Figure: 2.1 illustrates the structure of this chapter.

2.1 Aesthetics

While the study of aesthetics often focuses on appearance, visual style, and beauty, other factors come into play when making aesthetic judgments. Consideration of aesthetics within HCI has included the aesthetics of interaction as extending beyond the appearance of objects to include the sense of experience and expression that arises from interacting with them (Petersen, Hallnäs, & Jacob, 2008). Baljko and Tenhaaf present the aesthetics of emergence as a theoretical perspective on the aesthetics of interaction, focusing on how co-constructed interactions occur when there is shared

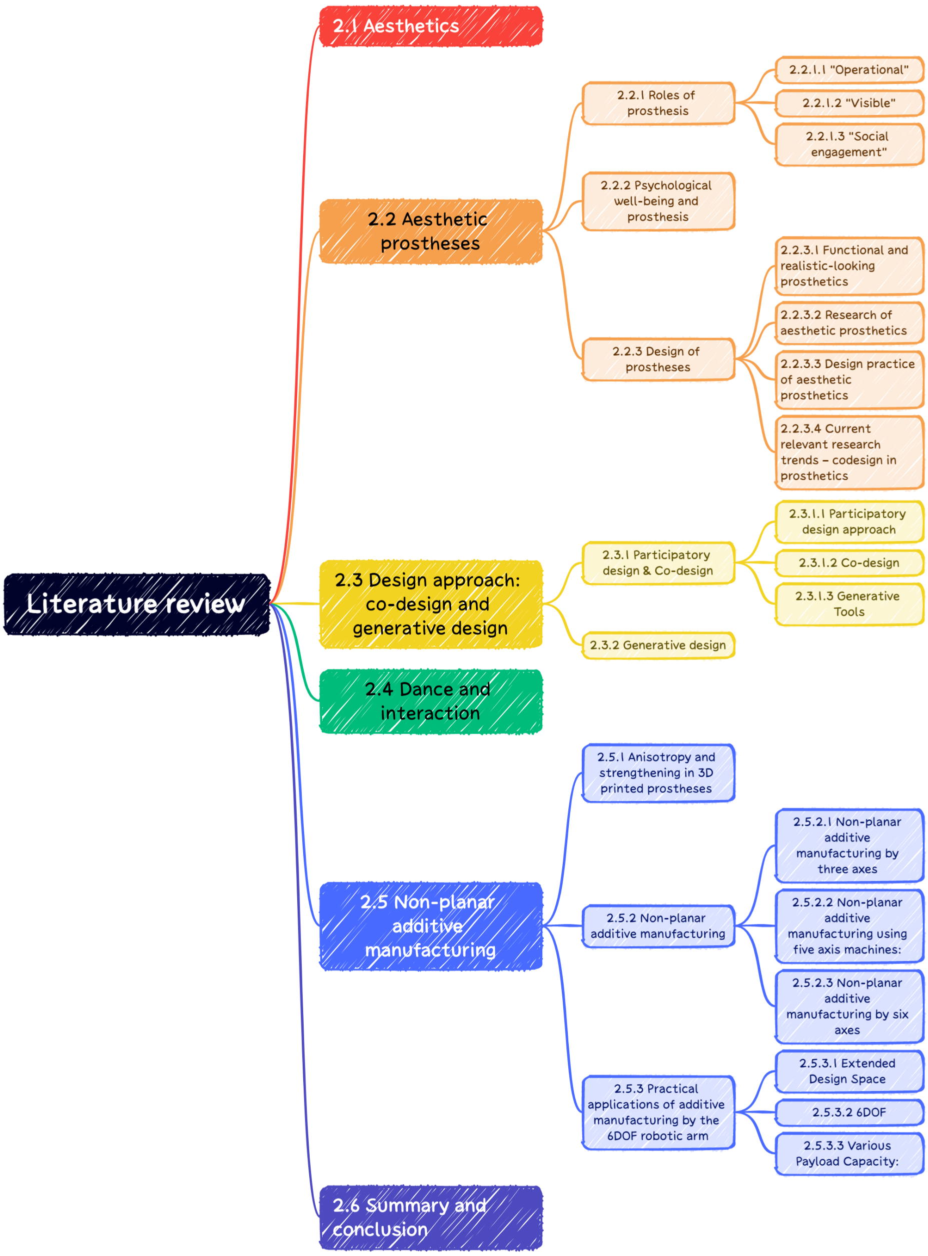


Figure 2.1: Structure of chapter literature review.

agency between user and system (Baljko & Tenhaaf, 2008). Dalsgaard and Hansen propose considering the perspectives of operators, performers, and spectators as part of the aesthetics of staging interactions (Dalsgaard & Hansen, 2008). Redström introduces 'tangled interaction' to express the relationship between appearance and functionality in the aesthetics of interaction (Redström, 2008). Hallnäs and Redström introduce the concept of the 'expressional' as an aesthetic foundation for how computational things can be the bearers of certain expressions, just as appliances are the bearers of functionality (Hallnäs & Redström, 2002). Wright et al. focus on feelings and emotions as aesthetically important facets of interaction, highlighting the importance of sense-making (Wright, Wallace, & McCarthy, 2008).

Our interest in prosthetics and dance brings into focus the aesthetics of bodily experience. While historical accounts have often treated aesthetic experience as being something of the mind that stands apart from the everyday world of the body, contemporary scholars have argued for the inherently embodied nature of aesthetic experience, often drawing on the pragmatic aesthetics of Dewey (1929). Xenakis and Arnellos argue for aesthetic experience as being fundamentally bodily and emotional, involving sense-making through our bodily interactions with our environments (Xenakis & Arnellos, 2015). Brinck argues that aesthetic experience is enacted and skillful, involving sense-making of movement (Brinck, 2017). Shusterman's practical philosophy of somaesthetics promotes a holistic mind-body approach to training one's aesthetic appreciation of bodily experience (Shusterman, 2012) and has inspired the approach of soma design for embodied interactions (Hook, 2018).

With specific reference to dancing, our approach mirrors Hsueh et al.'s exploration of the dynamic relations between the moving body and interactive technology during the creative process of movement ideation (Hsueh et al., 2019). Building on the idea "kinaesthetic creativity" that describes the body's ability to enact alternate future possibilities via movement (Svanaes, 2013), they classified dancers' interactions with a dynamic system as being directed, co-creative, following, negotiating, control-based or expressive.

Finally, returning to prostheses, Tamari reflects on how the visibility of disabled athletes and their prostheses at the London 2012 Paralympic Games brought to the fore the relationship between elite Paralympians and advanced prosthetic technology, arguing that the modern discourse of prostheses has shifted from the made-up and camouflaged body to the empowered and exhibited body, leading to the idea of prosthetic aesthetics as negotiating a tension between the two "polarized sensitivities" of attractiveness/coolness and abjection/the uncanny (Tamari, 2017). In defining the concept of disability aesthetics, Siebers argues that disability provides a critical framework for questioning aesthetics, is worthy of representation in its own right, and that "good art incorporates disability" (Siebers, 2010). We build on these notions of prosthetic aesthetics and disability aesthetics, and also HCI's wider interest in the aesthetics of interaction, by introducing an approach whereby disabled dancers are empowered to decorate and reveal their prostheses in a way that reflects their identities.

2.2 Aesthetic prostheses

This sub-chapter will start with summarising relevant research based on Hall & Orzada (2015) 's three criteria that prostheses must meet: "Operational", "Visible", and "Social engagement. Then it will state the relationship between aesthetics of prostheses and psychological well-being. After that, styles of prostheses: functional prostheses, realistic-looking prostheses and aesthetic prostheses will be introduced. At last, there will be a summary of the current research situation and trend of aesthetic prostheses.

2.2.1 Roles of the prosthesis

In a study on aesthetic prostheses, more than half of lower limb prosthesis users in the UK expressed a neutral or unsatisfied attitude on cosmetic characteristics (Cairns et al., 2014). The conventional bare pole model, foam model, or silicone cosmetic model only covers a limited visual diversity range, and many customers have unmet needs (Sansoni et al., 2016). Pullin & Higginbotham (2010) looks at the typical purpose of medical design, which is to correct for handicaps as discreetly as possible, while also questioning whether flesh-coloured prostheses send out implicit messages that impairment is something to hide. Many prosthesis clinics emphasise physical function, which is being challenged by research that emphasises the necessity of building a user-centred care delivery paradigm (Schaffalitzky et al., 2011)

According to (Hall & Orzada, 2015), prosthetic limbs must meet three criteria. The first is an 'operational' need, which refers to the body's basic functional capacities. Second, there is a 'visible' need related to the appearance of embodied wholeness. Finally, a social requirement pertains to the user's capacity to engage in activities and social gatherings.

Operational

A prosthesis is first and foremost a tool that a person utilises to control their body efficiently. Furthermore, the increased capability allows for more significant physical movement and flexibility. (Murray, 2005, 2009; Sousa et al., 2009). Prosthesis users see a restoration of function as a notable feature of the device's use, offering independence, dignity, and better self-worth (Donovan-Hall et al., 2002; Sousa et al., 2009). Participants in research by Sousa et al. (2009), for example, stated that the most significant expectation of an artificial limb is operational demands. These respondents required their prostheses to adapt to vigorous and demanding use because they wanted to participate in sports. Staker et al. (2009) also mention "socket fit" as "the essential concern" when it comes to prosthetics in the field. Prosthetics provided freedom and independence to other users, vital for retaining their adult identity and perspective (Murray, 2005).

Visible

Wearing a prosthesis also has a visual or aesthetic benefit. A prosthesis is a part of one's personal look because it is worn on the body. It gets ingrained in how users interact with others (Murray, 2009). Prostheses give the appearance of a healthy physique, improving aesthetic appeal so that the individual believes they conform to the socially acceptable body image (Sousa et al., 2009).

Some research suggests that a prosthetic limb should seem as natural as feasible to enable enhanced appearance (Donovan-Hall et al., 2002; Sousa et al., 2009). For example, Murray (2009) and Sousa et al. (2009) found that a realistic-looking passive limb pleased female participants more than the functional prosthetic limb. According to the study, female participants were more worried about prostheses' visual and realistic-looking features than their male counterparts. Following limb loss, Sousa et al. (2009) observed that women are more concerned with seeming "normal," whereas males are more concerned with functioning "normally."

However, some other research indicated that the appearance of prosthetics does not have to simulate realistic limbs. The goal is to design prostheses in a way that does not aim to duplicate the aesthetic of a human limb can assist the user in promoting their own distinctive identity (Hart, 2021; Labarre, 2010; Summit, 2016; Vlachaki et al., 2020). By wearing something that emphasises the embodied cause of stigma, the prosthesis user is reclaiming and reframing the disability identity by fostering pride and positivity of the non-normative body, as Hall & Orzada (2013) discovered. For instance, Hilhorst (2005) highlights designing personalised prosthetic hands for children for giving them a sense of identity.

To sum up, with prosthetic limbs, the desire to look physically whole is a powerful motivator (Saradjian et al., 2008). The prosthesis is perceived as a part of the user's body and, hence, part of themselves. So much so that people who have lost limbs feel ashamed of their physical peculiarities if they do not have a prosthesis.

Social engagement

The third condition that prosthesis use satisfies is social perception. A prosthetic limb facilitates social contact for someone who has lost or is missing a limb (Murray, 2005; Sousa et al., 2009). In research by Murray (2005), participants claimed their prostheses offered social normalisation by allowing them to fit in with others. Many studies (Donovan-Hall et al., 2002; Murray, 2005, 2009; Saradjian et al., 2008) have found that patients are more depressed after amputation. Some of these situations occurred due to feelings of perceived isolation (Donovan-Hall et al., 2002). A prosthesis was proven to reduce this emotional response while also providing favourable social chances (Donovan-Hall et al., 2002; Murray, 2005, 2009; Saradjian et al., 2008).

To summarise, prostheses' aesthetics value both "visible" and "social engagement".

2.2.2 Psychological well-being and prostheses

The importance of the prosthesis in helping the psychological well-being of persons with limb insufficiency is gaining popularity (Carroll & Fyfe, 2004). Prosthesis improves psychological well-being in both aspects of function and aesthetics.

The prosthesis's functioning is thought to influence one's well-being substantially (Sansoni, 2014). It has been demonstrated that wearing a prosthesis can help people gain movement and carry out everyday tasks (Pohjolainen et al., 1990). It has also been suggested that improving mobility and gaining new abilities might help people overcome the negative sensations that a lack can create. Dunn (1996) recommends concentrating on three areas to improve psychological well-being: 1) finding positive meaning in having limb insufficiency, 2) adopting an optimistic attitude, and 3) experiencing control over handicaps. When considering one's well-being in the context of adaptation to disability, numerous elements such as daily activities, social support, and level of insufficiency have been examined (Bosmans et al., 2007).

Aside from its functional role, prosthetic aesthetics have been shown to impact people's psychological well-being in various studies. (Bhuvaneswar et al., 2007; Murray, 2005; Nguyen, 2013; Rybarczyk & Behel, 2008). Millstein et al. (1986) suggest that for a prosthesis to be accepted by users, it must be “comfortable, functional, and attractive.” Similarly, Bhuvaneswar et al. (2007) emphasise the importance of cosmetic appearance in the user’s psychological well-being and the functionality of the assistive device. Aesthetics are essential for prosthetics in ways that go beyond the desire to wear attractive accessories. A person’s acceptance of a prosthetic device is influenced by its look, and stunning aesthetics have the potential to increase psychological well-being (Cairns et al., 2014; Pohjolainen et al., 1990). Visual aesthetics have also been shown to positively impact user compliance in other areas of supportive device design, such as hearing aids (Profita et al., 2016) and scoliosis braces (Law et al., 2016).

2.2.3 Design of prostheses

The multifaceted nature of well-being is reflected in the design literature from different perspectives that focus on subjective well-being. Nevertheless, many design researchers agree that design has a vast potential to bring fulfilment to one’s life (Desmet & Pohlmeyer, 2013; Kanis et al., 2009). This section will start by stating two traditional styles of prostheses: functional prostheses – bare pole models and realistic-looking prostheses. After that, the theoretical research and design practice of aesthetic prostheses will be demonstrated. At last, this section will introduce the current relevant research trends – codesign in the prosthesis.

Functional and realistic-looking prostheses

Most artificial limbs are either functional or cosmetic due to their historical purpose of replacing lost limbs (Mullins, 2009; Pullin, 2009). In medical design, there is a “duality between aesthetics and functionality,” according to Pullin (2009). Depending on its functionality and aesthetics, an artificial limb either looks good, in which case aesthetics are stressed, or performs well, in which case the function is emphasised. As Mital & Pierce (1971), some doctors focus a great deal on the functional necessities of prostheses to the extent that cosmetic considerations are often overlooked. Further, these doctors describe patients' unrealistic expectations about what an artificial limb should look like. The doctors state that amputations won't be able to fully replace a human limb, citing Mital & Pierce (1971). Therefore, this design of functional prosthesis is most common. A metal bar is attached to a rubber foot, or a bifurcated hook is attached to a metal bar (Mital & Pierce, 1971; Mullins, 2009).

Additionally, amputees have the option of purchasing a realistic-looking prosthesis, which mimics a flesh-toned human appendage and hides the absence of a limb (Donovan-Hall et al., 2002; Mullins, 2009; Murray, 2009). This medical device is intended for discretion, similar to hearing aids, which come in ever-reducing sizes with a flesh-toned clear appearance (Pullin, 2009). In the research of Hamilton (1997), women can get prosthetic feet with realistic-looking toes when wearing sandals, while men can have replica legs with a hairy appearance.

Research of aesthetic prostheses

Pullin (2009) argued that prostheses should not be limited to addressing only functional or cosmetic issues. According to him, medical engineering should include fashion. Pullin (2009) cited glasses as an aid that has moved from a prescribed, medical aid that aims to be as invisible as possible to a fashion statement. He proposed the concept of resonant design: 'a design intended to address the needs of some people with a particular disability and other people without that disability but perhaps finding themselves in particular circumstances'. Pullin's argument is that resonant design, steered by art and design graduates, would offer a wider variety of designs for assistive devices, and offer users more options and more opportunity to express themselves through their choices of design (Pullin, 2009). Drawing on methodologies from fashion studies, body studies, the history of emotions and visual studies, Vainshtein (2011) explored the topic of fashion and disability from an interdisciplinary perspective. Vainshtein (2011) claimed that fashion as cultural production successfully generates new visual languages, breaking the barriers of invisibility traditionally associated with disabled bodies and contributing to human well-being. Lamb & Kallal (1992) proposed the FEA Consumer Needs Model, which stated that a consumer product should fulfil the end user's functional, aesthetic, and expressive needs. Functional needs pertain to fit and comfort, while aesthetic needs relate to the intrinsic beauty found in the item. However, expressive needs relate to the symbolic and psychological aspects, which refers to how well a product communicates our sense of self: how we view ourselves, essentially our identity, and how we want to present ourselves to others (Lamb & Kallal,1992). This FEA Consumer Needs Model supported the future research on expressive prostheses by Hall & Orzada (2013), who indicated the requirement of fulfilling expressive needs of prosthetic limb users had historically been overlooked by conventional prostheses. Hall & Orzada (2013) then analysed literature from disability and fashion studies, in order to establish a context for what would be the designed expressive prostheses (EP) and claimed that expressive prosthetic limbs that focused on highlighting the user's identity, could reduce stigmatisation of users by increasing their self-confidence. Most recently, Vlachaki et al. (2020) aimed to explore the effects of the prosthetic appearance on users' lives by semi structured interviews and stated that expressive prostheses customised to highlight users' identity, could increase their self-confidence. Figure: 2.2 (a,b) show expressive prosthetic covers, whilst Figure: 2.2 (c) shows an expressive prosthesis. However, relevant research, especially on the approach of creating it, is still little.

Figure 2.2: Expressive Prostheses: (a) Racer: modelled by Braydon Luscombe (adjusted by Alleles Design Studio); (b) Prosthetic cover designed by Scott Summit (adjusted by SummitID); (c) The Synchronised arm designed by Sophie de Oliveira Barata and Dani Clode. Photographed by Omkaar Kotedia and used by Kelly Knox (adjusted by The alternative limb project, a). (Vlachaki et al., 2020)

Design practice of aesthetic prostheses

Some pioneer designers are attempting to fill this void in designing practice. Bespoke Innovations, a commercial prosthesis manufacturer, was founded by industrial designer Scott Summit (Summit, 2016). Custom covers are created by Bespoke Innovations to cover the standard metal bar prosthetic legs (Figure: 2.3). The covers consist of a variety of materials, including chrome and embossed leather. Bespoke Innovations can create additions to limb prosthetics that complement the person's appearance and functionality. They take the functionality of prosthetics and add the human body's sculpture, beauty, and elegance. An individual's uniqueness and personality are reflected in the sculpture created as a work of art (Summit, 2016). As an ind ustrial designer, Aviya Serfaty developed an artificial leg titled "Outfeet" (Labarre, 2010). Her prototype is intended for female users, as the lower limb prostheses are traditionally designed for men's legs. The concept behind her design was that of a prosthesis as a fashion accessory. Carbon fibre frames are attached to various "shoe" attachments on the leg (Figure: 2.4). It is Serfaty's goal to help women with amputations move beyond the label of physically disabled and be able to fully express themselves (Labarre, 2010). Sophie de Oliveira Barata, a prosthetics specialist who specialises in special effects, founded the Alternative Limb Project (or Art Limb Pro) in 2011. She has reportedly been working on many exaggerated prosthetic limbs since then. By creating alternative limb covers, she aims to bring joy to the eye, break down social barriers and facilitate a positive dialogue about difference and the human body (Hart, 2021) (Figure: 2.5).

Figure 2.3: Prosthesis cover. Courtesy of Bespoke Innovations (Summit, 2013).

Unlike traditional prostheses: functional and realistic prostheses, these pioneer designers' aesthetic prostheses emphasise the user's individuality and uniqueness through unique and customised aesthetic patterns. In other

Figure 2.4: Prostheses. Courtesy of Aviya Serfaty (Labarre, 2010).

Figure 2.5: Alternative limbs by Sophie de Oliveira Barata (Barata, n.d.)

words, bespoke aesthetics plays a significant role in aesthetic prostheses.

Current relevant research trends: co-design in aesthetic prostheses

More than aesthetic customisation, combining customised aesthetic design with personal experience can ulteriorly improve the self-identity of aesthetic prostheses. Blom (2018) explored the role of the co-design approach in establishing artisanship in prosthetic aesthetics. They investigated the design of a prosthetic given, a traditional item worn on the shin that also fulfilled a decorative function (Fortenberry, 1991). The process they developed enabled makers and amputees to focus on co-designing elements of the grave in a workshop setting. Figure: 2.6 to Figure: 2.8 show the final designs. The greaves created in the project were designed such that the amputees could wear them and allowed the personal identity of the amputees to be reflected through the design. However, the insights from amputees suggest that the benefits of being involved in the design process extend beyond designing the greave as a reflection of personal identity. These experiences suggest that the body image that was sought through the design process was not aimed at covering up their prosthesis with a 'nicer looking' thing. The resulting greaves embodied a deeper, richer expression of the individual identity of the amputees in a beautiful and intricate way: 'What do I want to have?' and it's about them personally rather than it being 'I can get this beautiful thing'. It's like, 'This is a part of me, and I want to make it mine (J. Blom, 2018).

To summarise, the aesthetics of prostheses plays a significant role in well-being, while two traditional types of prostheses – functional prostheses and realistic-looking prostheses failed to match all users' requirements. The

Figure 2.6: Angular shape of the rear of the greave, executed in crystal clear resin and white metal and final greave design (J. Blom, 2018)

Figure 2.7: Final greave design, willow (J. Blom, 2018)

Figure 2.8: Final greave design, wood (J. Blom, 2018)

emergence of aesthetic (expressive or fashionable) prostheses, especially the ones integrated with users' involvement efficiently fills this gap. Aesthetic prostheses emphasise personal identity through two factors: customised aesthetic design and personal experience. However, the limited literature indicated that relevant research is still in its infancy. Especially there needs to be more research into how to support the aesthetic personalisation of prosthetics from both of perspectives: design and manufacturing, as a way of increasing well-being. Therefore, this research aims to explore an integrated flow to customise aesthetic prostheses through both design and manufacturing perspectives.

2.3 Design approach: co-design and generative design

Most relevant research follows a traditional design approach to customise aesthetic prostheses, which means every single customised design of prostheses takes a great deal of designer effort. That indicates aesthetic prostheses designed by the traditional design approach are not able to benefit users broadly. Thus, this sub-chapter will investigate relevant research on two design approaches: co-design and generative design approaches, which are the potential to benefit aesthetic prostheses to a mass of users.

2.3.1 Participatory design & Co-design

The above-mentioned research that applying the co-design approach to the design of aesthetic greave by Blom (2018) demonstrated that the co-design approach embodied a deeper, richer expression of the individual identity of the amputees by enabling them to be deeply involved in the design process and get their unique personal experience. This section will state the concept of participatory and co-design, the generative tool of co-design that enables users without professional design skills to deeply participate in design processes, and analyse the potential to benefit the design of aesthetic prostheses.

In tradition, users are involved in the design process for usability testing. However, the study of Gould & Lewis (1985) emphasises the importance of the user's contribution in the early stages of a design process. Thus, users may be more involved in the design process with a more central role, positively affecting the outcome (Scaife et al., 1997). Both Participatory design and Co-design approaches emphasise the user‘s involvement in the integrated design process.

Participatory design approach

The participatory design approach emerged in the 1970s when computer professionals and managers in Norway decided to involve workers in decisions about computer systems at work (Sandusky, 1997). Participatory design has since been used in product design, architecture, urban planning, organisational development, and information technology (Sanoff, 2007). The participatory design allows users, stakeholders, and designers to work collaboratively in the design process (E. B. N. Sanders et al., 2010). Following Schuler & Namioka (2017), the participatory design aims to include people who are affected by a decision in influencing it. Many studies have demonstrated the effectiveness of participatory design in collaborating with users (Halskov & Hansen, 2015; E. B. N. Sanders et al., 2010; Sanoff, 2007).

Co-design

In recent years, the terms 'co-design' and 'co-creation' have gained popularity in discussing how designers can collaborate with users. Sanders (1999) first introduces co-creation in design practice by presenting an example of a co-creation toolkit. In her article, Sanders (1999) compares traditional design methods focused on what people say, do, and think with co-design practices that focus on what people know, feel, and dream. A co-design process allows designers to elicit tacit and latent knowledge they might not otherwise discover through conventional research methods (Sanders, 1999). (Figure: 2.9)

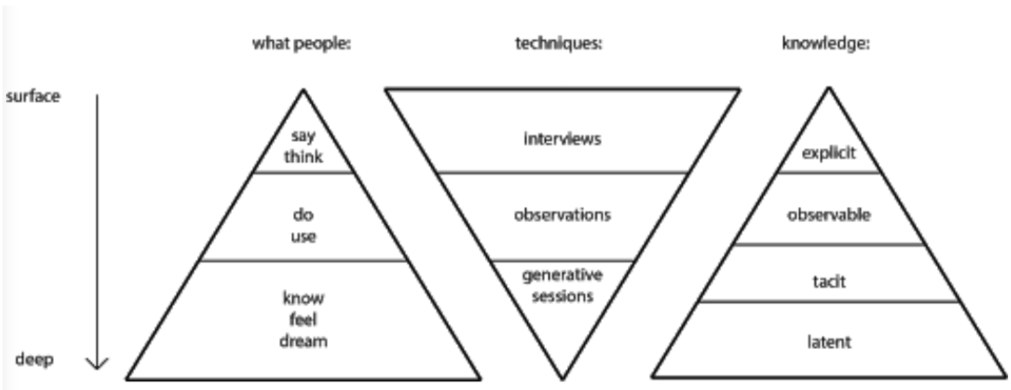


Figure 2.9: Different levels of knowledge about experience are accessed by different technologies (Visser et al., 2005).

Co-design, which facilitates a process of collecting information from users, requires that designers change their roles in the design process to facilitate, listen, and observe (Shackleton, 2010). In this sense, collaboration with users depends on the designer's ability to design tools and techniques for adapting different contexts (Kujala, 2003). Co-design, however, emphasises utilising users' input and does not entirely put the user in the position of designer (Mazzone, 2012). Instead of replacing the designer with the user, co-design requires that the designer analyse and translate acquired knowledge into design-relevant information, enriching the overall inputs for design (E. B.-N. Sanders, 2000).

Generative Tools

The user can become a member of the design team as an 'expert of his/her experiences' (Visser et al., 2005), but for them to take on this role, appropriate tools must be provided for them to express themselves. In Sanders (1999), generative tools/toolkits are a form of a participatory design language that can be used by non-designers (i.e. future users) in the front end of a design project for them to express their ideas about how they want to live, work, and play in the future. Generative tools have been used for some time now in the early phases of the design development process for the creation of products, services, systems and facilities.(e.g. E. B. N. Sanders, 2006; E. B.-N. Sanders, 2000; E. B.-N. Sanders & Stappers, 2008; Visser et al., 2005). This approach has been used with people of all ages and backgrounds.

Hussain & Sanders (2012) claimed that a user's input is not the only source of information but elicited through a shared understanding resultant from the communication between the designer, the user, and the artefact created by generative tools. According to Sanders (2000), the tools can be collages, maps, drawings, or prototypes. Figure: 2.10 to Figure: 2.12 illustrate some of the examples.

These cases demonstrate that a generative toolkit particularly serves a specific target. So it varies from the aims of utilisations. It also differs from the users. For instance, E. B.-N. Sanders (2000a) noticed many preschoolers are not verbally proficient, so they invented a generative tool that did not require verbal output skills. The children could respond by selecting, points, drawing, colouring and or constructing, which significantly improved the

Figure 2.10: Tools and techniques support the user in taking the role of an experienced expert. This photograph shows a presentation technique with a cartoon square TV frame that can help shy people to express their opinions more readily. (van Rijn & Stappers, 2007).

Figure 2.11: This photograph shows nurses co-creating a concept for ideal workflow on a patient floor. Note that the toolkit components are round, helping them to think in terms of activities, not rooms. (E. B. N. Sanders, 2006)

efficiency of feedback collection comparing asking questions verbally. Thus, the generative tools/toolkits that bridge the non-professional users and design need to be customised depending on the particular purpose and specific users. The aim of research on design aesthetic prostheses is to customise aesthetic prostheses and broadly benefit users. And the target research group of this study is dancers. Therefore, investigating the application of co-design to the design of aesthetic prostheses needs to explore proper generative tool/toolkits by its aim – efficient aesthetic customisation and its users – dancers. The following section will demonstrate the Generative design approach that is the potential to produce aesthetic customisation efficiently.

Figure 2.12: This photograph shows nurses co-designing the ideal future patient room using a three-dimensional toolkit for generative prototyping (E. B. N. Sanders, 2006)

2.3.2 Generative design

Using algorithms, the generative design allows for exploring variants of a design beyond what is currently feasible using traditional design methods. The generative design utilises parameters and goals to quickly explore thousands of design variants to find the best solution, imitating nature's evolutionary process. (McKnight, 2017)

Unlike Traditional Computer-Aided Design (CAD), where CAD tools are used in comparison to paper and pencil sketching (computers as digital representation tools) (Alcaide-Marzal et al., 2020), Generative Design, on the other hand, investigates how to use the power of computers to perform creative tasks more efficiently, or even to make computers design solutions. This is known as computational creativity (Gabriel et al., 2016), which includes any application capable of generating product shapes other than those directly created by the designer. In this case, the computer generates variations based on the designer's information, which helps increase the number of possible solutions. It has been suggested by Stones & Cassidy (2010) that designing digitally is more about computers enabling designers to explore solutions that go beyond what they can draw or imagine, rather than about designers using computers more efficiently to represent shapes. Mitchell (2005) referred to this as "digitally mediated design". The computer is not a replacement for the designer, but it is also not a mere representation tool. The right use of a computer may complement the designer's abilities, enabling the designer to explore a much broader spectrum of solution possibilities. For instance, Preston et al. (2017) explore a designer-centred approach in which skilled designers handcrafted seed designs that are automatically recombined to create many markers as subtle variants of a common theme, under the help of an algorithm.

In architecture, there are many applications because the nature of architectural objects allows for easy generative shape exploration and optimisation. (Chase, 2005; Gu & Behbahani, 2018; Rodrigues et al., 2015; Shea et al., 2005; Singh & Gu, 2012; Bae et al., 2017). In contrast, there are fewer applications in product design. Consequently, generative product design still lacks formal methodologies for its implementation (Krish, 2011). New contributions, however, are appearing in various fields, including graphic layouts (Cleveland, 2010), consumer electronics (Lin & Lee, 2013), jewellery (Kielarova et al., 2013) and interface design (Troiano & Birtolo, 2014). Renner & Ekárt (2003) presented a review of the application of genetic algorithms to computer-aided design and demonstrated that it had been widely used for computational design exploration. Many studies have investigated the use of evolutionary algorithms in product design since some early works, such as (Bentley, 1999); (Gero, 1996); (Hybs & Gero, 1992). For example, lamp holders (Liu et al., 2004); shape optimisation for mobile phones (Sun et al., 2007); and wine glasses profiles (Su & Zhang, 2010). Shieh et al. (2018) used Kansei and evolutionary algorithms in order to design vase designs. Genetic algorithms and shape grammar are combined in (O'Neill et al., 2010) and (Lee et al., 2012).

McKnight (2017) summarised generatively designed products have the following key characteristics:

- Maintained or improved performance: reducing weight, a generative design process optimises structures to meet the specific structural requirements of a design. By doing so, they are able to not only meet strength and stiffness performance requirements but also use less material.
- Reduce development time: The use of infinite computing makes it possible to examine 1,000s of design variants at the same time that a traditional approach might take to create one.
- Increased creativity: By creating 1000s of ideas, designers and engineers can quickly assess the suitability of forms they may not have otherwise considered.
- Increased efficiency: By including simulation and testing as part of generative design, designers and engineers can avoid making iterative changes as in more traditional design processes.
- Customised product development: With generative design and additive manufacturing, complex geometries specifically tailored to suit an individual's needs are more accessible than ever.

These studies indicated that with the aid of computers, the generative design approach could produce various designs and ulteriorly benefits customisation. It is a pain spot of the conventional approach of designing aesthetic prostheses and the purpose of the generative tool of co-design approach when applying it to design aesthetic prostheses.

However, generative design also raises difficult challenges. One of these concerns is the relationship between algorithms and human designers. Stones and Cassidy focus on computers enabling human designers to explore solutions that go beyond what they might normally imagine (Stones & Cassidy, 2010). Mitchell referred to this as 'digitally mediated design'; the computer is not a replacement for the designer, but neither is it equivalent to a traditional passive tool (Mitchell, 2005). A second challenge concerns how to involve the consumer. Sanders considers generative tools/toolkits as a form of participatory design language that can be used by non-designers early in a design project (Sanders, 1999). However, appropriate tools must be provided if the consumer is to become a member of the design team as an 'expert of his/her experiences' (Visser et al., 2005). Responding to this latter challenge, our focus is on creating a suite of tools that enable consumers to become co-designers of their own products. This involves finding ways in which they can meaningfully interact with generative algorithms and then embedding this within a wider co-design process.

2.4 Dance and interaction

As demonstrated above, investigating the application of co-design to the design of aesthetic prostheses needs to explore proper generative toolkits by its two key factors: aim – efficient customisation of aesthetics and users – dancers. The literature on generative design demonstrates that the generative design approach can support efficient customisation with the aid of computers. So it could be a potential foundation to produce generative toolkits for the application of co-design to aesthetic prosthetic design. Then it would be crucial to analyse the feature of this particular group of user – dancers and how to integrate these features with a generative design approach to compose generative toolkits. There are existing academic examples of applying generative design to create personalized prosthetics, which offer the potential for improved comfort, functionality, and aesthetics. For instance, Zuniga et al. (2016) utilized generative design to create custom-fit 3D-printed prosthetic hands for children, resulting in lightweight, low-cost, and functional devices. Another study by Telfer et al. (2012) explored the use of additive manufacturing to design personalized foot and ankle orthoses, demonstrating the potential for improved patient outcomes. These examples highlight the significance of generative design in developing personalized prosthetics that address individual needs while optimizing form and function.

Zhou et al. (2021) presented that dance - novel using bodily signals as “Body as the instrument”. A body is viewed as an extension of our experiences, perceptions, and expressions within the world in which we reside, serving as an integral part of our cognition, with a malleable shape and size. (Hsueh et al., 2019). This body image is profoundly influenced by phenomenology, as advocated by Heidegger and Merleau-Ponty (Heidegger et al., 1962; Merleau-Ponty, 1996). According to HCI researchers, these works have laid the theoretical foundations for understanding the body in HCI: 1) within the context of tools and practices; 2) as part of our cognitive experience; (3) as a space of active perception with directed intent; and 4) as dynamically altered in shape and size as perception changes when spatial and functional relationships are altered. (Dourish, 2001; Svanæs, 2013). In the discipline of dance, this multifaceted image of the body is fully exploited, making it an instrument for artistic expression, which exploits the aesthetic, expressive, and creative qualities of the body. (L. A. Blom & Chaplin, 1988; Loke & Robertson, 2011).

The body could be extended by computing. The use of robots and algorithmic agents as an accompaniment to human dancers and sometimes as the main performer is becoming increasingly common (Zhou et al., 2021). They are often visualisations, costumes, or mechanical bodies which respond to the performance's human dancer as either pre-programmed or autonomous agents (Karpashevich et al., 2018) when acting as accompaniments. In addition, through the moving body, dancers live the experience of the performance on the stage and are shaped and influenced by that experience simultaneously (Svanæs, 2013). While dancing, the dancer won't only pay attention to the audience or the stage but also to his or her own body movements.

The extension of the dancing body by computing has also been explored by some pioneers, in order to promote creative uses of the body and propose visualisations as means to give feedback to participants on different representations of their movement (Flong.Com • Work by Golan Levin & Collaborators, n.d.; Schiphorst, 2011). For instance, Hsueh et al. (2019) explored the emergent and dynamic relations between the moving body and interactive technology during creative processes such as movement ideation. They focused on the embodied creative process related to the notion of "kinaesthetic creativity", coined by Svanæs (2013), to describe the body's ability to enact alternate future possibilities via movement. The Kinect-based motion tracking system and algorithmic visualisations by particle systems were their primary tools for researching the interaction between dancing motion and dynamic visual systems (Hsueh et al., 2019). Real-time motion data of dancing was captured by the Kinect-based motion tracking system. After that, these data were applied as interactive parameters to the dynamic particle system. As a result, the real-time interaction between dance and visualisation was realised (Figure: 2.13).

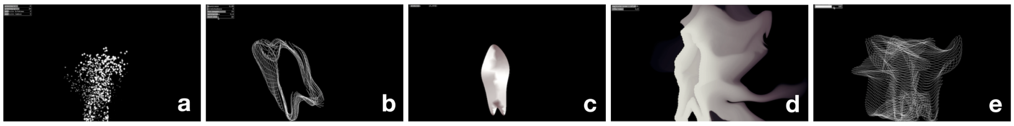


Figure 2.13: Visualization vignettes: (a) Particles (b) Springs (c) Blobby form (d) Fluid body (e) Trails (Hsueh et al., 2019)

Expect for visualisation, dynamic systems like this particle system are also generally utilised in the generative design approach (Dierichs & Menges, 2015; Kim, 2013; Nejur, 2019). Thus, similar to the interaction between dancing motion and algorithmic visual system in Hsueh et al. (2019)'s research, dancing motions are also potential to work as interactive parameters to influence generative design algorithms. Then the dancers' unique expression - dancing motion is the potential to work collaboratively with the generative design approach as generative tools/toolkits for co-design that is applied to designs of aesthetic prostheses.

In summary, to fill the research gap that the current design of prostheses: functional and realistic-looking prostheses failed to match all users' requirements, the co-design with generative toolkits by integrating a generative design approach and dancing would be the primary approach to explore aesthetic personalisation of prosthetic design.

2.5 Non-planar additive manufacturing

As demonstrated above, the design of aesthetic prosthetics requires aesthetics and customisation. The aesthetics require a high degree of geometric freedom. The relationship between geometric freedom and aesthetics has been an area of interest for researchers and practitioners in various design disciplines, including architecture, industrial design, and digital art. Some researches provide valuable insights into the relationship between geometric freedom and aesthetics. They emphasise the importance of geometric freedom in enabling designers and artists to explore diverse design alternatives, ultimately leading to more creative and visually appealing outcomes (Chau et al., 2004; Stiny & Gips, 1971; Leyton, 2003).

However, high geometric freedom easily conflicts with the requirements of physical factors of a prosthesis, e.g. mechanical properties and weight. While, customisation for each individual challenges the efficiency of traditional manual manufacture and massive manufacture. Thus, the aesthetic prosthesis has two requirements in the manufacturing approach: high geometric freedom degree to match aesthetic requirements without or with a limited compromise with requirements of mechanical properties and weight, and efficiency of customising manufacturing.

A traditional method of customised manufacturing prostheses entails plaster casting, a highly customised process centred around the patient (Y. Wang et al., 2020), since personalised prostheses have a better fit to a patient's body, which is crucial to patient satisfaction (Berke et al., 2010; R. Gailey et al., 2008). Manual techniques for customising prosthetics can involve a combination of skilled craftsmanship and the application of various materials. The current methods for customising prosthetics manually, focusing on socket design, alignment, cosmetic finishing, and other aspects of the process.

Socket design is a critical aspect of prosthetic customisation, as it directly affects the user's comfort, function, and overall satisfaction (Gholizadeh et al., 2014). Manual techniques for customising sockets involve taking accurate measurements of the residual limb, followed by casting and molding processes to create a customised socket that closely fits the user's anatomy (Boutwell et al., 2012). Materials such as plaster, fiberglass, or silicone may be used in this process (Fernández et al., 2016), and the socket is often further refined through manual adjustments to ensure optimal fit and comfort (Alley et al., 2011).

Proper alignment of the prosthetic components is essential for the user's comfort and functionality (Hafner et al., 2002). Manual alignment techniques involve adjusting the position and orientation of the prosthetic components relative to each other and the user's body (Esquenazi, 2004). Suspension systems, which secure the prosthetic to the residual limb, can also be customised manually using straps, belts, sleeves, or vacuum systems to provide a secure and comfortable fit (Gholizadeh et al., 2016).

Cosmetic finishing is an important aspect of prosthetic customisation, as it affects the user's perception of their prosthesis and its integration into their overall appearance (Biddiss et al., 2007). Manual techniques for customising the appearance of a prosthesis can include the application of foam covers, silicone skins, or fabric to create a lifelike appearance (Pitkin, 2009). Skilled artisans may sculpt, paint, and add details to the prosthetic, matching the user's skin tone, texture, and other characteristics for a more natural look (Sansoni et al., 2015).

Beyond the basic requirements of fit and function, prosthetic users often seek personalized solutions that cater to their individual preferences and lifestyles (Biddiss et al., 2007). Manual customisation may involve the addition of specific features or adaptations to meet the user's unique needs, such as sports attachments, specialized grips, or other modifications (Lura et al., 2015). Furthermore, users may opt for personalized design elements, such as unique patterns, colours, or artwork, to express their identity and individuality (Ferguson-Pell et al., 2013).

However, the traditional manufacturing method has inefficiency in customisation, since every prosthesis takes much time and human labour. As opposed to traditional subtractive manufacturing technologies, additive manufacturing (AM) builds objects layer by layer from 3D data, usually using digitally controlled and operated material laying tools (Tofail et al., 2018). With AM, waste materials are greatly reduced, fabrication time is shortened, and most skill-based manual operations are eliminated (Han, 2017). Considering its efficiency of customised manufacturing, additive manufacturing also seems a potential manufacturing approach to aesthetic prostheses.

However, conventional research on additive manufactured prostheses usually overlooked the requirements on mechanical properties, especially the weakness brought by Anisotropy of 3D printed prostheses by Fused Filament Fabrication (FFF) (Maroti et al. 2019). In addition, the aesthetics of prostheses requires higher freedom on the geometry of prostheses, which brings further challenge. Modifying the geometry of design is a general approach to strengthen 3D printed objects (Stava et al., 2012) (Zhou et al., 2013). However, the geometric requirements of aesthetics and functional consideration can then conflict with each other. Therefore, in order to manufacture personalised aesthetic prostheses with proper mechanical properties, there is a requirement for strengthening the mechanical properties of 3D printed prostheses without negatively changing their appearance.

This subchapter will be presented in the following sections: (1) Strengthen mechanical properties of aesthetic prostheses and Anisotropy; (2) relevant research of non-planar additive manufacturing. (3) Practical applications of additive manufacturing by the 6DOF robotic arm.

2.5.1 Anisotropy and strengthening in 3D printed prostheses

Material Extrusion (ME), also called Fused Filament Fabrication (FFF), is the most widely adopted 3D printing process and can fabricate more types of materials than most other 3D printing technologies. (Fang et al., 2020) It has also been widely used in additive manufacturing prostheses (Gretsch et al., 2016; Ramot et al., 2016; Resnik et al., 2012; Smurr et al., 2008; Zuniga et al., 2015). However, a drawback to FFF is anisotropy in mechanical properties, with greatest strength in the filament direction and weakest strength between layers in the build direction. Maroti et al. (2019) explored anisotropic mechanical properties in additive manufacturing of upper limb prosthetics. He stated that special care should be taken in designing the printing processes, because the mechanical properties of the manufactured objects are significantly influenced by the orientation of printing.

The anisotropy in layer-by-layer processes, such as FFF, are well known and result from the slicing process that uses equally spaced parallel layers. In this process, materials are usually accumulated layer upon layer in planes along a fixed direction. The weak adhesion between neighbouring planar layers of filaments leads to an easy-to-delaminate problem. The Anisotropy of mechanical property – strong along with the axial directions of filaments but weak in other directions – can be observed in all models fabricated by FFF (Ahn et al., 2002). Previous work has reported the anisotropy of mechanical strength in models fabricated by FFF (Ahn et al., 2002) (Tam & Mueller, 2017). Fractographic analysis using scanning electron microscope (SEM) images (Riddick et al., 2016) has shown that the weak adhesion between neighbouring layers and also voids between layers from incompletely filling of the area between filaments (Xie et al., 2020) are the major reasons for tensile failure.

The mechanical property of 3D printed prostheses has been largely overlooked in previous research (Maroti et al. 2019). In order to strengthen 3D printed objects without changing the material, three approaches are often used (Mueller, 2012). 1) modifying the geometry of design (Stava et al., 2012) (Zhou et al., 2013). 2) optimising the printing processing, such as printing orientation (Umetani & Schmidt, 2013), infill patterns and rate (Lu et al., 2014) (W. Wang et al., 2013) (Zhang et al., 2015), and 3) conducting thermal post or chemical treatment. Most of the conventionally existing methods in the literature of additive manufacturing are based on the first two approaches (Fang et al., 2020). However, in manufacturing aesthetic prostheses, these two approaches have significant limitations. Modification of design geometry can conflict with the requirements of aesthetics. Moreover, increasing infill patterns and rates may bring extra weight, which is another sensitive factor for prostheses. It is agreed by most prosthetists that the weight of prosthetic devices should be as light as possible, once the requirements of the safest, efficient and most functional componentry possible are matched (R. S. Gailey et al., 1994; Lewallen et al., 1986; Macfarlane et al., 1991; Martin & Morgan, 1992; Winter & Sienko, 1988). A lightweight prosthesis is desirable as it minimises the muscular effort for locomotion. As a result of the above considerations, a manufacturing approach needed that strengthens the mechanical properties of aesthetic prostheses without significant modification of geometry nor increase of infill rate. A newly emerging manufacturing approach, non-planar additive manufacturing, has the potential to achieve this target by eliminating or reducing the negative impact of Anisotropy (Pelzer & Hopmann, 2021) (Allum et al., 2021) (Fang et al., 2020) (Kubalak et al., 2019)

2.5.2 Non-planar additive manufacturing

Besides improving mechanical properties, researchers are also exploring non-planar additive manufacturing to expand the design space, improve printing quality and increase manufacturing efficiency. These researches are mainly based on three approaches:

- non-planar filament deposition with a traditional three-axis 3D printer,
- five-axis CNC-type machine
- 6-DOF robotic arm.

This section will summarise non-planar additive manufacturing by these three approaches.

Non-planar additive manufacturing by three axes

A number of publications have reported non-planar additive manufacturing by designing sliding strategies with conventional 3 – axis hardware. Traditionally, 3D objects are sliced by two-dimensional planes to produce print paths. Correspondingly, slicing strategies for non-planar additive manufacturing by three axes use non-planar surfaces to slice 3D objects. The earliest demonstration of an additive manufacturing approach to curved print layers, named “Curved Layer Fused Deposition Modeling” (CLFDM), was conducted by Chakraborty et al. (2008). H. Allen & Trask ‘s (2015) study explored Curved Layer FFF (CLFFF) tool paths with a commercially available parallel, or delta, style FFF system to achieve the deposition process in which the printing head follows the topology of the component. Llewellyn-Jones et al. (2016) the manufactured a shell model by depositing a double-curved layer on top of a sandwich structure printed with conventional planar layers. The result was a smooth surface, without the staircase effect seen in planar FFF. Ming Zhao et al. (2018) demonstrated an innovative manufacturing strategy, inclined layer printing (ILP), that enable printing without supporg structures. Unlike conventional planar slicing approach, it sliced the printed objects at an incline to avoid geometries requiring support structures. Ezair et al. (2018) explored 3-axis motion tool-paths in more detail. They described the limitations of layer accumulation, nozzle reach, and multiple methods to produce such paths. Etienne et al. (2019) investigated an algorithm that produced non-planar layers, either following the natural slope of the input surface or, on the contrary, making them intersect the surfaces at a steeper angle to improve the printing quality. Ahlers et al. (2019) explored a novel slicing approach that combined non-planar and planar layers, improving surface quality and achieving smoother, stronger object surfaces. Their slicing algorithm automatically detected the parts of the object that needed to be printed with non-planar layers and produced collision-free tool-paths by using a geometric model of the printhead and extruder. Pelzer & Hopmann (2021) proposed an algorithm for non-planar sliding with changeable layer height, which enabled accurate represention of freeform surfaces and introduced the potential to improve the printed parts' mechanical properties by tailoring the layers to the load case. Allum et al. (2021) investigated an approachin which material was deposited when the nozzle moved in the X or Y direction, whilst simultaneously moving up and down in the Z direction in which the repeating non-planar layers were produced throughout the specimen's geometry. This ZigZag tool-path significantly improved the printed objects' mechanical properties in Z-direction, by 62% in strength, 123% in strain-at-fracture and 245% in toughness.

This research on three-axis non-planar additive manufacturing demonstrates the potential improvements that can be made in printing quality by eliminating the staircase effect (Llewellyn-Jones et al., 2016) (Etienne et al., 2019), in printing efficiency by reducing or removing the requirement of supporting structure (H. ming Zhao et al., 2018), and in mechanical properties by tailoring the layers to the load case (Pelzer & Hopmann, 2021) (Allum et al., 2021). Improvement in printing quality, manufacturing efficiency and mechanical properties are also the primary research targets of non-planar additive manufacturing using increased dof machines axes, such asCNC-like five-axis machine and 6-DOF robotic arms. The added advantage of these extra dof machines is greater flexibility in allowing rotation of the print so that the angle of the nozzle to a non-planar work surface can be controlled.

Non-planar additive manufacturing using five axis machines

Pan et al. (2014) developed a five-axis motion system similar to CNC machining to enable printing onto an existing model. Based on the freedom brought by five axes, Wu et al. (2016) computed collision-free tool paths for printing wire mesh models using 5DOF. Fang et al. (2020) presented an algorithm for non-planar volumetric slicing and showed that printing non-planar layers oriented along stress lines could increase the strength of prints by more than 6x. Although five-axis 3D printing brought much flexibility to non-planar additive manufacturing, there are still significant challenges in this research. For five-axis additive manufacturing, there is no standard hardware or control systems. Also, the complexity of designing non-planar printing paths remains a challenge. Most of the five-axis additive non-planar research is based on the hardware, control system, and in house slicing software.. Some researchers have tried to overcome the challenge of missing standard hardware by utilising commercial 6-DOF robotic arms.

Non-planar additive manufacturing by six axes

Research of non-planar additive manufacturing by 6DOF robot arm has focused on support-free additive manufacturing. Two primary approaches are "rotating bed" and "rotating head". By "rotating bed", the extruding nozzle is vertically fixed, and the printing bed is attached to a robot flange which is flexible to rotate in multiple axes. Steep overhangs (over 45°) can be printed without support materials by keeping the angle between the extruder and the previously printed layer under 45° with a rotating printing bed. Keating and Oxman (2013) successfully achieved a proof-of-concept multi-axis printing process by integrating a 6-DOF robot arm into the FFF process. Wu et al. (2017) presented a 6DOF robot system ,RobotFDM aiming to print models without support structures. They also developed an algorithm that decomposed the model into support-free parts and generated a collision-free tool path. Dai et al. (2018) explored the tool path planning approach further for multi-axis, support-free additive manufacturing using two successive decompositions: volume-to-surfaces and surfaces to curves.

The other primary support–free approach is "rotating head", which means printing to a fixed print bed with a rotating printing head following non-planar trajectories. Zhao et al. (2018) presented two non-planar slicing approaches to reduce the requirements for support structures and the number of layers: a decomposition-based curved surface slicing approach and a transformation-based cylinder surface slicing strategy. Manufacturing samples by a robotic fused deposition modelling system validated the feasibility of the proposed methods. Xu et al. (2019) developed a curved layer decomposition method based on the original boundary representation of the input model, in order to obtain support-free additive manufacturing.

Besides support-free additive manufacturing, there is also research on 3D wireframes to improve the printing efficiency by utilising a 6-DOF robotic arm. For example, Huang et al. (2016) proposed a manufacturing sequence for general frame shapes via a divide-and-conquer strategy that first decomposes the input frame shape into stable sub-layers then generates a feasible manufacturing sequence for each layer. This algorithm was tested on a robot fabrication system based on a KUKA 6DoF robot arm.

Preventing the negative effect of Anisotropy is another research focus for non-planar AM. Kubalak et al. (2019) evaluated the influence of altering the layering and deposition directions on a 6-DOF robot multi-axis printed part. The tensile specimens were printed at various inclination angles and the tensile strengths of the multi-axis specimens compared to similarly oriented specimens manufactured by a traditional 3-DoF method. The experiment showed that the yield tensile strength of vertically oriented tensile bars was improved by 153 per cent using multi-axis manufacturing compared to geometrically similar samples built via 3-DoF deposition. Fry et al. (2020) developed a multi-axis additive robot manufacturing system (ARMS) based on the collaboration of two 6-DOF robots. Using the substantial kinematic freedom brought by the 12 DOF, they conducted experiments that demonstrated fundamental capabilities and quantitatively evaluated the benefits they offer. Specifically, they indicated that the feed pressure of the plastic has a much more significant effect on printing quality than gravity and investigated dynamic build orientation to reduce the roughness of printed objects.

In summary, the relevant research demonstrates that non-planar additive manufacturing, especially multi-axis non-planar additive manufacturing, can improve printing efficiency by support-free additive manufacturing and 3D wireframe printing approach, improve print quality by eliminating the staircase effect and improve mechanical properties by reducing or eliminating the effect of anisotropy. Since the mechanical properties can be improved by the design of layer geometry and eliminating Anisotropy, there is no significant increase in volume and weight. Thus, this is a potential approach to obtain the balance of weight and mechanical properties required by lower limb prostheses. However, there are still significant challenges to conducting multi-axis non-planar additive manufacturing, such as a lack of standard hardware and a corresponding control system.

2.5.3 Practical applications of additive manufacturing by the 6DOF robotic arm

The section will further investigate the challenges of conducting multi-axis additive manufacturing mentioned I the previous section, namely: a lack of (1) standard hardware, (2) corresponding control system, and (3) slicing software. It will also discusspractical additive manufacturing applications for a the 6-DOF robotic arm AM system and summarise its main features.

Extended Design Space

Several applications of robotic arm 3D printing take advantage of its feature–long reach. For instance, an interior 3D printing company, Nagami, focus on architectural scale 3D printing by recycled plastic. One of their projects – “Plasticity”, is a 3.6-metre high sculpture, 3D-printed with Parley Ocean Plastic (Plasticity — Nagami, n.d.). (Casas Niccolo, 2021) This 3.6-metre high sculpture is printed in a single operation by the robot ABB IRB 6700 - 150, which has a reach of 3.2m. (Handling, n.d.) There are also applications of 3D printing building by concrete. For instance, the project “Striatus” is a footbridge composed of 3D – printed concrete blocks by the Block Research Group at ETH Zurich. It is constructed using an ABB robotic arm. (ETH Zurich Creates First 3D Printed Concrete Bridge without Reinforcement - 3D Printing Industry, 2021) An extra linear axis can significantly increase the working range of a robot arm 3D printer. For instance, Branch Technology explored Cellular Fabrication (C-Fab) for 3D printing polymer lattice structures, used KUKA robotic arm and KUKA Linear unit to increase the printing range. (Molitch-Hou, 2020) (Figure: 2.14)

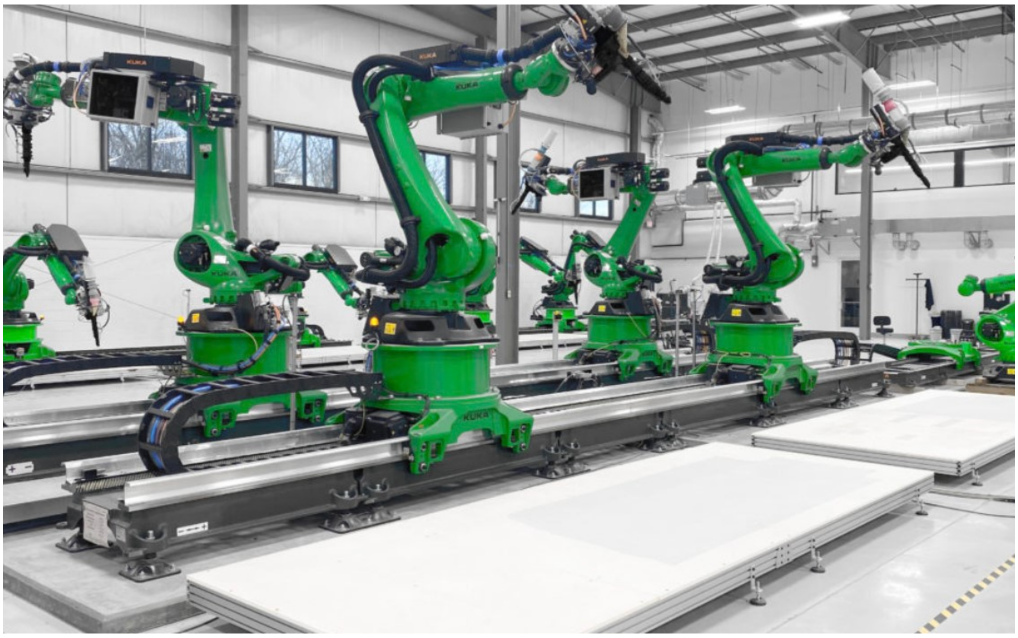


Figure 2.14: Robotic 3D printer by Branch Technology (Branch Technology Raises $11M to Grow “Largest Fleet” of Construction 3D Printers - 3DPrint.Com — The Voice of 3D Printing / Additive Manufacturing, n.d.)

Six degrees of freedom (6DOF)

Another feature of the robotic arm that benefits 3D printing is its 6DOF, which allows the robot arm 3D printer to reach any location within its operating range and rotate the printing head to any orientation. For instance, the project "Thullus"; a collaboration of Zaha Hadid Architects and AI build. (Schumacher, 2017) This was printed by aligning the printing head with the normal direction of the curved surface of a mould. (Thallus on Vimeo, 2017) The flexibility of rotation can be further increased by adding extra rotation axes and there are commercial products in the market from multiple brands for this requirement, such as a series of KP1 products that act as an extra single-axis positioner (Figure 12), a series of KP2 products that can acta as extra dual-axis positioners, and a series of KP3 products as extra triple-axis positioners. (KUKA Positioners — KUKA AG, n.d.) The Scalable Composite Robotic Additive Manufacturing (SCRAM) system developed by ELECTROIMPACT with a KUKA six-axis robot arm and a KUKA single-axis positioner enabled the layering of continuous fibre-reinforced thermoplastic in the shape of complex contours, such as aerodynamic surfaces and ducts for fluid flow. Furthermore, as it is a 6-axis process, fibre orientation within each layer can be tailored to the specific application to provide optimal strength and stiffness distribution throughout the part, much like a conventional AFP system. (Electroimpact, n.d.)

Various Payload Capacity

For the above mentioned applications of 6DOF robotic arm 3D printing technology, in broad fields such as furniture, architecture and continuous fibre composite structures, the extruders will have different weights. Thus another feature of the 6 DOF robot arm in the market – various Payloads can match this requirement. A robot's payload capacity refers to the amount of mass its wrist can support. Industrial robots are available in a wide range of payloads, from as light as 0.5 kg to as heavy as over 1000 kg. (Robotic Payload - Robots Done Right, n.d.)

Compare with conventional three-axis 3D printers, a 3D printer built with a commercial 6DOF robotic arm has some drawbacks. High cost: minimum cost of commercial 6DOF is usually over 15,000. Added the cost of the extruder, the whole cost is easy to over 20,000. Hard to control: the conventional 3D printer slice 3D models by 2D plane, which suits the most slicing situation. While the 6DOF additive manufacturing by commercial robotic arm requires extra attention in designing slicing surface since it easily triggers collisions. Larger operation space: Enabled by the high degree of freedom of 6DOF, operating a 6DOF robotic arm requires larger space than the same size machine with three axes. However, the features of long reach, 6DOF, and various payload of commercial 6-axis robotic arms in the market brings significant benefits to additive manufacturing. Its long-term industrial use across many applications also guarantees the stability and accuracy that hardware built for research cannot guarantee. Thus the 6DOF robotic arm seems a high potential hardware to develop additive manufacturing beyond current size and shape limitations. From the additive manufacturing perspective, this research will explore a platform broadly suitable to commercial 6DOF robotic arms for multi-axis non-planar additive manufacturing research. It will consist of a multi-head extruder, sliding software, and control software.

2.6 Summary and conclusion

To summarise, the literature demonstrates that aesthetic prostheses especially the ones integrated with users' involvement play a significant role in users' well-being. However, the limited literature indicated that relevant research is still in its infancy. Specifically, there are significant research gaps on how to efficiently customised design aesthetic prosthetics and the manufacturing approach enables high geometric freedom for aesthetic customisation and simultaneously matches the requirements of mechanical properties and weight.

Thus, this research will use dancers as research collaborators to explore a generative co-design and additive manufacturing process for producing aesthetic prostheses. From the perspective of design, it explores customising the personalised aesthetic design of prostheses through a generative co-design approach with the interaction of dance motion. From a manufacturing perspective, this study investigates manufacturing methods that are suitable for both the structural and aesthetic demands of the designs. Following a study of potential manufacturing methods, a commercial 6DOF robot arm was selected as the most appropriate platform for the non-planar additive manufacturing of aesthetic prostheses, enabling the required mechanical performance without concession to aesthetics and weight.

Chapter 3

Personalise aesthetic designs for prostheses by generative co-design approach

The design phase aims to fill the identified research gap concerning inefficient approaches for customising personalised aesthetic designs for prostheses. For that, I developed the strategy - personalise aesthetic designs for prostheses by generative co-design approach. This strategy explored a process through which people can co-design personalised prostheses by interacting with algorithms that (i) generate unique personal visual designs called aesthetic seeds from moments of meaningful and expressive interaction (dance in this research); (ii) apply these to a chosen form of prostheses; and (iii) optimise the final design for efficient additive manufacturing. The approach to achieving this proposed in this work integrates co-design and generative design approaches with the dancer's interaction to achieve the customised designs of aesthetic prostheses. This approach combines unique aesthetics with the users' personal experience. One concept – the aesthetic seed was defined and three algorithms were developed for this phase.

Aesthetic seed is a 3D archetype produced by the interaction between dance motion and generative design algorithms 01 – Mogrow and then being extended to specific design – prosthesis by the Algorithm 02 – leg sculpting, at last being optimised by the algorithm 03 – optimisation of additive manufacturing for manufacture.

Algorithm 01 - Mogrow: This algorithm produces aesthetic seeds by interacting with dancers to record their unique interactive experience through a personalised archetype. It is basically an algorithm for co-design utilising a generative design toolkit and dancer interaction. Co-design is its aim, while the generative design is its underlying technology.

Algorithm 02 – leg sculpting: This algorithm enables the conceptual design of aesthetic prosthetic covers. Aesthetic seeds are applied to prosthetic covers in order to customise them.

Algorithm 03 – optimisation of additive manufacturing: This algorithm addresses additive manufacturing efficiency. It renders the aesthetic design manufacturable by eliminating overhanging parts, which would otherwise require an underlying supporting structure, which would then have to be removed.

The following subchapters will introduce details of aesthetic seeds and these three algorithms.

3.1 Aesthetic seed

A key concept – aesthetic seed needs to be defined before introducing details of the three design algorithms.

"An aesthetic seed is a 3D design (archetype) produced by an interaction between the algorithm of generative design (Mogrow in this research) and creative human behaviours (dance in this research). It records a particular interaction experience by unique geometry. Rather than any specific design, the aesthetic seed is an archetype applicable to various designs."

An aesthetic seed is a unique 3D geometry with an identifiable pattern produced by the interaction between human creative behaviours like dance, singing, or drawing and the form-creation algorithms. Most of the Generative design algorithms inspired from nature can be applied to generation of aesthetic seeds. For instance, Fractal algorithms use recursive patterns to create complex, self-similar designs that are found in nature. These algorithms often involve the use of geometric shapes, which are iteratively combined and transformed to create intricate patterns (Prusinkiewicz & Lindenmayer, 1990). Flocking algorithms simulate the behavior of groups of animals, such as birds or fish, by considering the interactions between individual agents (Reynolds, 1987). Cellular automata are discrete, grid-based models that simulate the behavior of systems with simple, local interactions between cells (Gardner, 1970). Swarm intelligence algorithms are inspired by the collective behavior of social insects, such as ants or bees, and focus on decentralized, self-organized systems. Examples include Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO), which are commonly used for solving optimization problems (Bonabeau et al., 1999). Reaction-diffusion systems are mathematical models that simulate the behaviour of substances as they diffuse and react with one another.

These models can generate complex patterns that resemble those found in nature, such as animal markings, coral formations, and more. The Gray-Scott model is a popular example of a reaction-diffusion system (Pearson, 1993). Artificial neural networks are computing systems inspired by the biological neural networks found in animal brains. They can be trained to learn and generate complex patterns, such as natural language or image recognition tasks (Goodfellow et al., 2014). The Physarum model is a computational model inspired by the slime mould Physarum polycephalum, which exhibits complex behaviours despite its simple biological structure. The model can be used to generate networks that closely resemble natural transportation networks, such as roads, veins, or rivers (Tero et al., 2010). They have been all widely applied to designs (Barnsley, 1988; Carrick, 2017; Wolfram, 2002; Bentley, 1999; Witkin & Kass, 1991; Karras et al., 2018; Adamatzky, 2019).

The algorithms listed above hold significant potential for application in conjunction with creative behaviors to generate aesthetically appealing designs. Taking into account factors such as manufacturing strategy, effective representation of human interaction over time, and ease of operation, I have chosen to develop a generative algorithm called Mogrow, which is based on the fundamental behavior and algorithm of a particle-spring system.

Firstly, Mogrow considers the principles of additive manufacturing, which constructs designs from the bottom up, layer by layer. The generative design algorithm follows a similar approach, generating designs by stacking 2D layers. This method allows for greater compatibility with manufacturing requirements, such as limiting overhang angles during the design generation process, making the resulting designs more easily producible through additive manufacturing techniques.

Secondly, the algorithm is designed to facilitate real-time interaction with human creative behaviors. Aesthetic design needs to encapsulate the human interaction experience over a certain duration. To achieve this, Mogrow was designed to stack freeze frames of continuous interaction states between creative behaviors and the algorithm.

Lastly, although many of the aforementioned algorithms can optimise for additive manufacturing and duration recording, the selected particle-spring system is one of the simplest approaches that works with closed chains, which form the foundation for optimisation in additive manufacturing and duration recording. Developing Mogrow based on the particle-spring system aims to minimise hindrances for this initial exploration. In the future, other algorithms may also be investigated for their potential application in generating aesthetic designs.

Mogrow has two primary features. One is "record" meaning each aesthetic seed records a specific interacting experience of a specific dancer. The other one is "unique". The form-creation is based on a particle–spring closed chain, which is dynamic and constantly changing, and supplies sufficient variety to be unique for every single interaction. Moreover, each dancing experience is unique, so the geometry recording the dancing process is also unique and customised based on this specific dancing experience.

For interaction strategy, our design collaborators are dancers and dancer researchers, who appreciated being able to interact through a highly tuned and hard-earned skill that enabled them to express themselves. In response, we developed an interaction technique that was attuned to this skill, in our case by drawing on deeper knowledge of dance principles.

However, the broader implication here is to seek out equivalent personally expressive skills in other situations. This might be a recognised artistic skill such as music, dance, painting, or sculpting, or perhaps some other somaesthetic skill that involves an aesthetic bodily interaction (various sporting skills spring to mind). In turn, this requires developing interaction techniques that embody a deep knowledge of the chosen skill (as we were able to do by drawing on dancing principles from dance research).

Figure: 3.1 summarises the relationship between the user, aesthetic seed, conceptual design and final design for manufacturing. A particular aesthetic seed is produced by a dancer's specific interactive experience with the algorithm 01: Mo-grow. This aesthetic seed varies with different interactive experiences, so a dancer can produce multiple aesthetic seeds through multiple interactions. The dancer may then choose any of the aesthetic seeds to be extended to various specific product designs. This "extension" step is conducted by generative design algorithms, which can also be varied to achieve a specific design aim. In the present study, the extension of aesthetic seed to prosthesis cover design is conducted by algorithm 02: leg sculpting. Then each extended design is revised using algorithm 03: optimisation of additive manufacturing to eliminate the overhanging parts and produce the final design ready for additive manufacturing. In short, a dancer can produce multiple aesthetic seeds, each of which can produce multiple final designs.

3.2 Algorithm 01 - Mogrow

Mogrow is an algorithm which combines the co-design approach with dancer interaction and the generative design approach. Its aim is to support co-design and so embody a deeper, richer expression of the individual identity of the disabled dancers by enabling them to be deeply involved in the de-

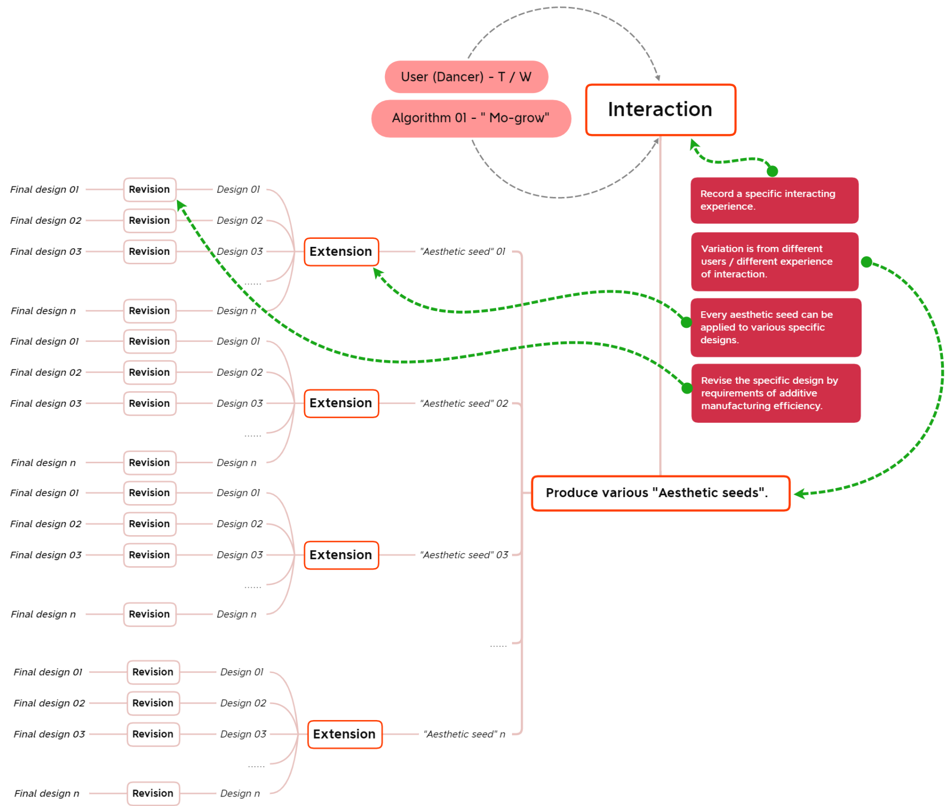


Figure 3.1: Relationship among users, aesthetic seed, conceptual design and final design.

sign process and get their unique personal experiences (Blom, 2018). While the generative design approach could produce various designs without r with limited involvement of professional designers and ulteriorly benefits efficiency of customisation. Interaction between a dancer and Mogrow produces customised patterns (aesthetic seeds) based on a particular dance experience. Since no two interactive experiences are the same, every aesthetic seed produced by them is unique. Thus, the production of aesthetic seed accomplishes the tangible form of a unique dancing experience, which normally has an ephemeral nature, as a customised pattern.

3.2.1 Computational beauty and inspiration

Principles inspiring computational beauty

The algorithm Mogrow aims to produce aesthetic customisations. What then might be the principles guiding the aesthetic qualities of its design?

Due to the subjectivity of aesthetics, Hoenig (2005) claimed that one of the most significant challenges of any metric, method or algorithm dealing with aesthetics lies in the evaluation of claimed validity. Without clear standards of aesthetic evaluation, relevant research usually comes across challenges to achieve convincing results. Many researchers have explored the approaches to formalising aesthetic measures. Birkhoff (1933) wrote the first quantitative theory of aesthetics in his book Aesthetic Measure. His work showed an attempt to formalise aesthetic measure as M = Order / Complexity, a formula intended to describe an aesthetic relationship commonly known as the “unity in variety” (Hoenig, 2005). To Birkhoff, complexity was the amount of effort the human brain has to put into processing an object. An effort is necessary for the experience of aesthetic reward. While the role of order was to reward the effort of focusing attention on something complex perceptually. He also assumed that order elements exist, such as symmetry, rhythm, repetition, contrast, etc (Birkhoff, 1933).

Birkhoff's ideas broke new ground for aesthetics research and were inherited by various researchers (Greenfield, 2005). Many researchers wove them into aesthetic theories, using the term information aesthetics, trying to develop Birkhoff's work into a new approach towards "complexity" (for a summary of this movement, see Frank and Franke (1997). There is also plenty of research related to the concept of "order". For instance, Machado & Cardoso (1998) tried to apply fractal image compressibility as an element of order aesthetic measure, assuming that self-similarities can be more easily perceived. Similarly, Spehar et al. (2003) showed a direct comparison of fractal dimension and human aesthetic preference in Universal aesthetic fractals. Although, as Greenfield (2005) claimed, these researchers have not developed a solid theory or methodology for aesthetics, they highlighted some aspects of visual aesthetics, such as order and complexity, components that might provide a measurable basis for aesthetics (Hoenig, 2005).

Flake (2000) developed in depth the simple idea that recurrent rules abstracted from nature can produce rich and complicated behaviours. Distinguishing "agents" (e.g., molecules, cells, animals, and species) from their interactions (e.g., chemical reactions, immune system responses, sexual reproduction, and evolution), Flake argues that it is the computational properties of interactions that account for much of what we think of as "beautiful" and "interesting." (Flake, 2000)

Birkhoff's aesthetic formula - M = Order / Complexity and Gary William Flake's computational beauty of nature, specifically the natural beauty of Antelope Canyon, provide inspiration for the development of Mogrow.

Though this does not mean this study subscribes to their agenda. Since the aesthetic is still primarily subjective, feedback from users would be collected through user studies to evaluate the aesthetics of Mogrow. Most importantly, aesthetics run through the whole research, such as aesthetics of interaction experience between dancers and algorithm, visual aesthetics, aesthetics of phycology (feeling of agency and accomplishment), aesthetics of manufacturing materials and so on. The visual aesthetic is only one part of the overall aesthetic experience of the prosthetic design.

Inspiration – the natural beauty of Antilope Canyon

a b

Figure 3.2: Photos of Antilope Canyon. (a) Photo of Antilope Canyon by Zafra (2019). (b) Photo of Antilope Canyon (Upper Antelope Canyon, Arizona, USA, n.d.)

Drawing on Flake (2000)'s argument, recurrent rules abstracted from nature might provide the computational basis for generating visual aesthetics that we might think of as being "beautiful" and "interesting". The present study, therefore, searched for inspiration from nature. Specifically, Mogrow was inspired by the unique erosional landform of Antelope Canyon, which is well known for its ever-changing streamlined section of the stratum. It was formed by the erosion of Navajo Sandstone (Kelsey, 2018) due to flash flooding. Rainwater, especially during monsoon season, runs into the extensive basin above the slot canyon sections, picking up speed and sand as it rushes into the narrow passageways (Best Antelope Canyon Tour Companies — About Navajo Tours, n.d.). Over time the passageways eroded away, deepening the corridors and smoothing hard edges to form characteristic "flowing" shapes. (All About Tours of Antelope Canyon By Navajo Tours In Arizona, n.d.) (Figure: 3.2a and Figure: 3.2b) These "flowing" shapes consist of ever-changing smooth curves. Due to the various factors, such as flow magnitude, erosion time, erosion resistance and so on, in the different parts of the canyon, every curve composing this landform is unique. It is hard to find two identical curves in the valley.

In addition, each layer of the stratum was created over a long period. It records the specific information of this time, such as geology and climate. Thus walking through the Antelope Canyon and watching the section of the stratum consisting of layers created through a long-span historical period is just like reading its earth's history. While visitors enjoy the breathtaking and ever-changing streamlined landscape, a thick sense of history comes to them. Therefore, the combination of its ever-changing streamlined "flowing" shape combined with the idea of "historical recording" inspired the Mogrow algorithm.

3.2.2 The logic of form-creation

The form-creation of Mogrow is therefore inspired by the natural beauty of Antilope Canyon and guided by Birkhoff's aesthetic formula - M = Order / Complexity. Two behaviours compose Mogrow's form-creation: wrinkling and stacking. This section will demonstrate the logic of the form-creation of Mogrow through these two behaviours.

“Wrinkling”

Wrinkling behaviour is inspired by the natural beauty of Antilope Canyon – the ever-changing streamlined flowing shape. Mogrow’s wrinkling behaviour is developed based on the well-known particle-spring system in which lumped masses, called particles, are connected by linear elastic springs (Kilian & Ochsendorf, 2018). Each spring is assigned a constant axial stiffness, an initial length, and a damping coefficient. Springs generate a force when displaced from their rest length. Besides the internal force from springs, particles can also be influenced by external forces, such as a vertical downward force, simulating gravity, a horizontal force, simulating wind or attractive and repulsive forces from external objects. In this physical simulation, the spring linking particles gives them stability in a force balance. Thus, when forces are applied to break the balance, the particle-spring system adjusts itself to reach a new balance. If the external forces are continually changing, the system will become dynamic, constantly changing to adapt itself to match the continuous changing balance. Thus, the behaviour of this dynamic particle-spring system is daedal, as a change in any single factor may trigger complex behaviour in the whole system. Every frame of this complex dynamic system could be a unique aesthetic design. Thus, the designs produced by this particle-spring system are multitudinous, leading to variety and complexity.

This research is based on a closed chain of particle-spring system, which means there is a spring connecting the first and the last particles to seal the closed chain. Wrinkling is primarily produced by two behaviours: ejection and shrinking, The nozzle mentioned below refers to the particle conducting ejection or shrinking. Ejection produces particles from the nozzle. Conversely, shrinking is an inverse process - reducing particles from nozzles.

In other words, ejection produces more wrinkle patterns, while shrinking makes smoother patterns.

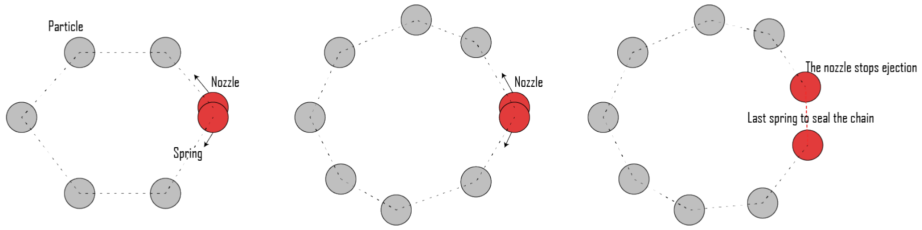


Figure 3.3: Ejection on a closed chain.

This paragraph describes wrinkling on a closed chain with single nozzle. Figure: 3.3 illustrates the procedure of ejection on a closed chain with a single nozzle. The noteworthy point is that two particles on nozzles (red circles in the left and middle images of the figure: 3.3) actually overlap, but for clearer expression, particles on nozzles do not fully overlap in the image. Moreover, there is no spring between these two particles of the nozzle. Initially, velocity is applied to the two overlapped particles. Then, both particles will leave their original position. At the same time, there will be two more particles created at the nozzle. Then these two new particles are separately linked to the particles that just leaving their positions with new springs. Similarly, the two new particles also overlap. This procedure of ejecting new particles and building new springs keeps operating until the ejection behaviour terminates. Finally, for ending this ejection circulation, a spring is connected between the latest created two overlapping particles to seal the entire closed chain. (the right image of Figure: 3.3) During this process, at each moment the new two particles are created, there is velocity to push the old two particles away from their original positions. This velocity on the two old particles pushes away their neighbour particles by springs between them. Then the pushed neighbour particles also push their neighbours. This conduction goes through the whole system. Thus, every creation of new particles breaks the balance of the whole system.

If the behaviour of ejection keeps happening, the entire system becomes dynamic.

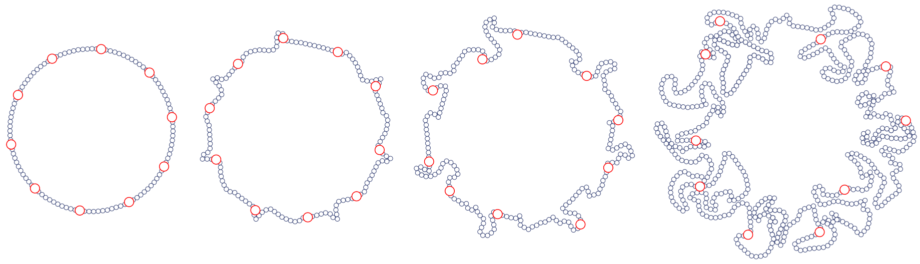


Figure 3.4: Wrinkling behaviour on a closed chain with multiple nozzles.

Multiple nozzles on a closed chain can bring much more complex changes. Figure: 3.4 illustrates the process of ejection happening on a closed chain with multiple nozzles. Red points are nozzles, only which could generate new particles. As the ejection happens, more and more particles are generated. And then the closed chain shows increasing wrinkles. Similar to the open chain, shrinking as an opposite process of the ejection, produces a smoother closed chain by reducing particles and springs. In summary, ejection and shrinking by multiple nozzles on a closed chain is the primary approach to conducting wrinkling behaviour by Mogrow.

The wrinkling behaviour happens on a 2D particle-spring closed chain, with constant augmentation or reduction of particles and springs. Augmentation or reduction of any single particle and spring break the balance of the whole particle-spring system, since all of the particles are linked by springs. Then, the constant augmentation and reduction of particles by ejection and shrink keeps breaking the balance and forces the particle-spring system to become dynamic. As a result, the wrinkled geometry of the closed chain keeps transforming and the wrinkling behaviour becomes complex and hard to predict, reflecting the complexity of Birkhoff's aesthetic formula.

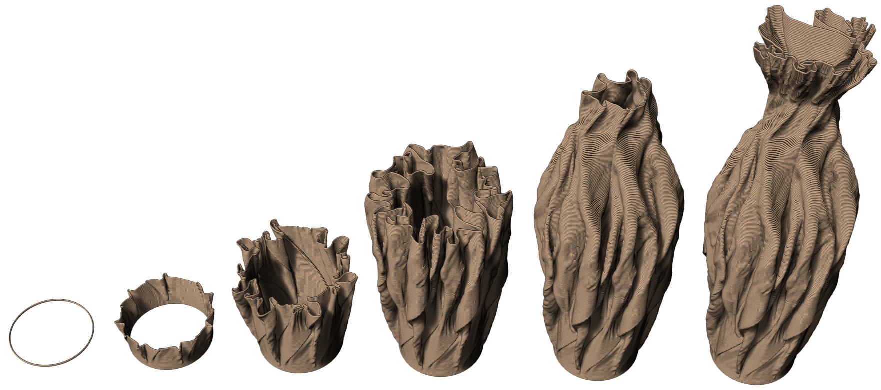


Figure 3.5: Stacking behaviour.

Stacking behaviour

The above transformations happen on a 2D closed chain, which then needs to be made into a 3D geometry to be further developed for designs of prosthetics. Making this dynamic particle-spring closed chain into a 3D geometry is conducted by the algorithmic process of stacking, which is inspired by the stratum recording history of Antelope Canyon. Specifically, the continuous transforming process of wrinkling described above is periodically recorded by freeze-framing at regular time intervals. These freeze-frames are then stacked from bottom to top to form a 3D geometry. Since all freeze-frames record a continuous transforming process, stacked curves composing the 3D geometry show a gradual transformation from bottom to top (Figure: 3.5). This phenomenon reflects the "order" of Birkhoff's aesthetic formula. In addition, similar to recording earth history by stratum, the 3D geometry produced by stacking records the history of a 2D particle-spring closed chain dynamic transformation. When the transformation of the 2D particle-spring closed chain is produced by interaction with dancers, this dancing–interacting experience is tangibly recorded by the 3D geometry produced by stacking.

In summary, the wrinkling behaviour enables the complex transforming of a 2D particle-spring closed chain, which can produce massive variety and reflects the "complexity" of Birkhoff's aesthetic formula. Moreover, the behaviour of stacking turns the dynamic 2D closed chain into a static 3D geometry by stacking freeze-framing of the transforming process of this 2D closed chain following an equal interval time. It records a dynamic transforming history of a 2D closed chain by a static 3D geometry, which also reflects the "order" of Birkhoff's aesthetic formula.

3.2.3 Production of aesthetic seed by the interaction between Mogrow and dancers

The last section – the logic of form-creation states the approach that Mogrow produces massive organic geometries that record the transforming history of a dynamic particle – spring closed chain by two behaviours – wrinkling and stacking. This section aims to demonstrate how to integrate dancers' involvement with the process of form-creation to produce the aesthetic seed - a personalised 3D geometry recording a particular dancing-interaction experience. We recruited two professional disabled dancers. The dancers, referred to as T and W, were both female with many years of training and professional experience in expressing themselves through improvised bodily movements. Both had high amputations on one leg. They were compensated using industry daily rates recommended by their professional body. This section will start with stating how different parameters affect form creation. Then two interaction modes – functional and dancing principles will be introduced. Finally, it will illustrate the aesthetic seeds produced by the interaction between dancers and Mogrow through a user study.

Parameters control the form creation of Mogrow

Since stacking simply records the transformation procedure, there are few parameters on it to affect the outcomes of form-creation. The parameters that affect form creation are mostly relative to the wrinkling behaviour. These parameters are classified into two types: pre-set parameters and real-time interaction parameters.

The geometry of the imported closed chain is a pre-set parameter that significantly affects form creation. It means the original geometry of the 2D particle-spring chain, which is the start of all transformations. For the present research, the design aim is to produce aesthetic customisation of prosthetic covers. So for functional consideration and simplification of the developing environment, a circle is selected to be imported closed chain for the following research.

Another pre-set parameter that will be explored for the following research is the number of nozzles. In the last section – the logic of form-creation states that nozzle means the particle conducting ejection, where wrinkle patterns are produced. Thus, the increase in the number of nozzles usually triggers more wrinkle patterns. Figure: 3.6 illustrates the comparison of form-creation with different values of the number of the nozzle while fixing all other parameters. It shows that the number of nozzles significantly affects the density of wrinkle patterns on the outcome of the form-creation. The examples presented later equally divide the imported circle into 10 segments to produce 10 nozzles.

More than the pre-set parameters, the real-time interaction parameters are the primary link with dancing motions to enable dancers to conduct real-time interaction with the form-creation process. One real-time interacting

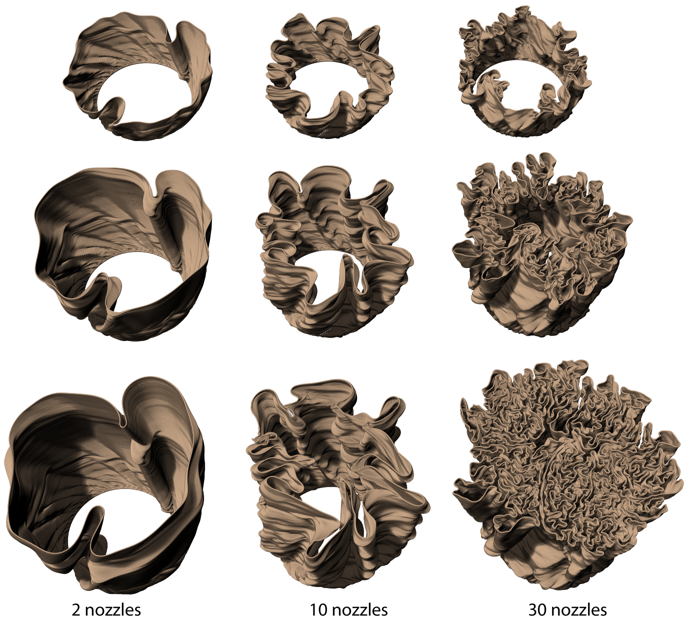


Figure 3.6: Comparison of different the number of nozzles.

parameter is friction which spontaneously slows down or stops the dynamic of the spring–particle system. Figure: 3.7 illustrates the different values of friction producing quite various geometries. When the value of friction is lower, the activity of particles is stronger. Then the geometry shows larger wrinkles with low density. When higher, it shows smaller wrinkles and is compact. Moreover, the friction as a real-time interacting parameter, can be changed in the whole process of transformation. Thus, the single outcome of form-creation can simultaneously contain large and small wrinkles, when the friction value is not constant. For the following research, the friction will be linked with dancers dancing motion and keep changing based on the state of dancing. For example, when dancers dance faster, the output will show a larger wrinkle. Conversely, it shows smaller wrinkles and compact geometry on the part reflecting slower dancing.

The other real-time interacting parameter is ejection and shrinking. Ejection increases wrinkles by constantly ejecting particles while shrinking produces smoother patterns by reducing particles. The varied application of

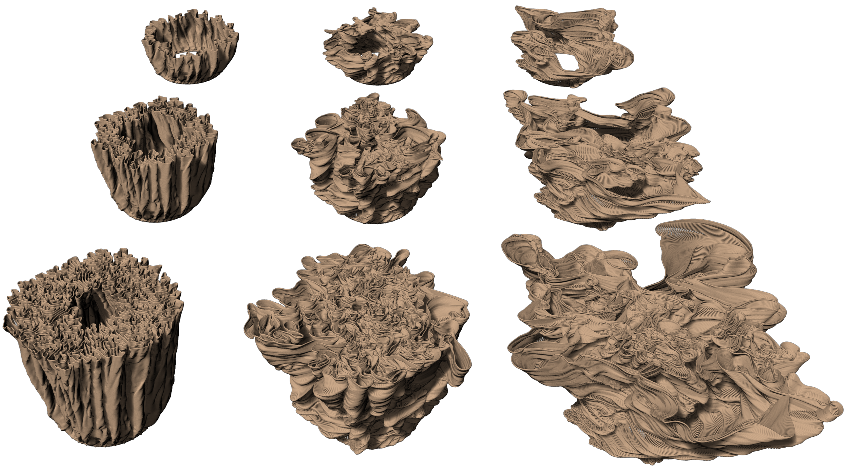


Figure 3.7: Comparison of different friction.

ejection and shrinking at different moments of the whole transforming process produces diverse outcomes of form-creation. Figure: 3.8 illustrates a vase design affected by the parameter ejection and shrinking. From the bottom up, all of the stacked curves show the transforming history of the 2D particle-spring closed chain to form the vase design. It starts with an imported circle. In the beginning, ejection produces more and more wrinkles. When it goes near the neck, particles are gradually reduced by shrinking and show a smoother and narrow neck. After the neck, the ejection starts again to produce more wrinkles and a wider top. This ejection and shrinking will also be linked with dancing motions to produce sufficient form-creation.

In summary, in the examples that follow, a circle is imported as the imported closed chain to start the transformation. It is divided into 10 segments to produce 10 nozzles for wrinkle production and elimination. Two real-time interaction parameters: friction and ejection and shrinking will be applied to link with dancing motions to enable real-time interaction between dancing motion and the form-creation of Mogrow (Figure: 3.9).

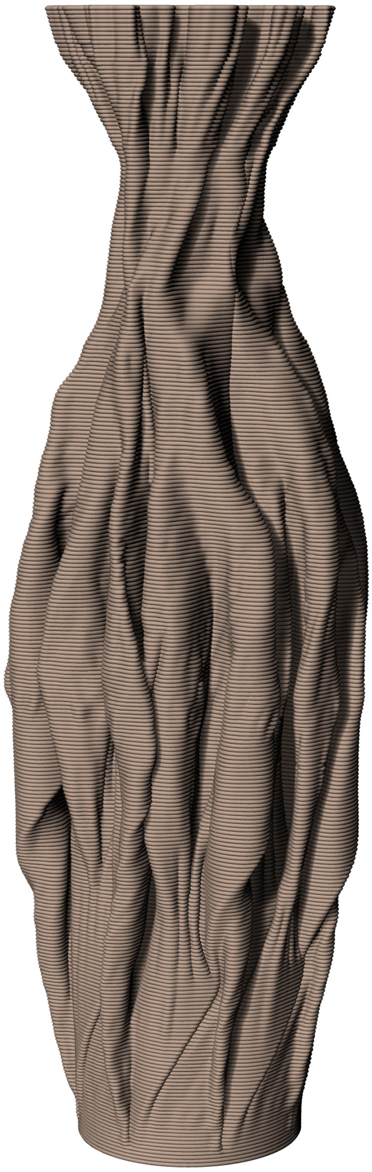


Figure 3.8: Vase design by Mogrow controlled by the parameter ejection and shrinking.

Parameters control the form creation of Mogrow					
	Mogrow parameter name	Mogrow parameter definition	Value set in the user study	Functional Mode	Dancing mode
Pre-set parameter 1	Geometry of the imported closed chain	The form transformation of Mogrow starts from a single closed chain. Its geometry will determine the following shape transformation.	A circle	No changes	No changes
Pre-set parameter 2	The number of nozzles	Nozzle is the point produces more particles or eliminates existing particles. This value determine the number of nozzles.	10	No changes	No changes
Real-time interaction parameter 1	Friction	Like the real world, friction will spontaneously slows down or stops the dynamic of the spring–particle system.	Change reflecting dancing motion data	Fraction is inversely proportional to the maximum velocity of all tracking points except the trackers on left and right hands, on the the body of dancers,	Fraction is inversely proportional to the maximum velocity of four trackers on dancer's left and right shoulders as well as the left and right edges of the hipbone.
Real-time interaction parameter 2	Ejection and shrinking	Ejection increases wrinkles by constantly producing new particles, while shrinking produces smoother patterns by reducing particles.	Change reflecting dancing motion data	The acceleration value of the tracker on dancer's left hand controls ejection, and the acceleration value of the tracker on dancer's right hand controls shrinking.	The angle value between two axes separately formed by linking left and right shoulders and the left and right edges of the hipbone is applied to be control ejection and shrinking.

Figure 3.9: Parameters control the form creation of Mogrow.

Motion mode of interaction

We now turn to the question of how dancers might meaningfully interact with the various real-time interaction parameters. The capture of the dancing body by computing technologies has been explored by a number of pioneers (Hsueh et al., 2019; Karpashevich et al., 2018; Schiphorst, 2011; Zhou et al., 2021). In particular, the interaction between dancing motion and dynamic visual systems, e.g. particle system by Hsueh et al.(2019), inspires a potential possibility to interact with generative design algorithms through dance.

In this work, dance data is the basis to enable interaction between a design algorithm, such as Mo-grow, and dancers. The method applied to collect basic kinematic data from different body parts is motion capture. Specifically, a ROKOKO Smart suit (Smartsuit-Pro Tech Specs, n.d.) is used for the practical work in this thesis. The smart suit has 17 tracking points, each of which can record or calculate the corresponding position's basic kinematic data, such as relative position, velocity, acceleration, rotation, the velocity of rotation and acceleration of rotation (Figure: 3.10). All of these kinematic data and their various combinations might potentially be connected to the parameters of the Mo-grow algorithm. Thus the basic kinematic data of 17 tracking points provides a wealth of motion data to interact with Mo-grow.

Hence, in this study, basic kinematic data from motion capture supplies the influence parameters to a dynamic generative design algorithm. However, the first user study with dancers using the basic kinematic data as a bridge between dancers and Mo-grow, resulted in negative feedback on the interactive experience, which will be explored in greater depth in the user study chapter. The reason was that the basic kinematic data differs from

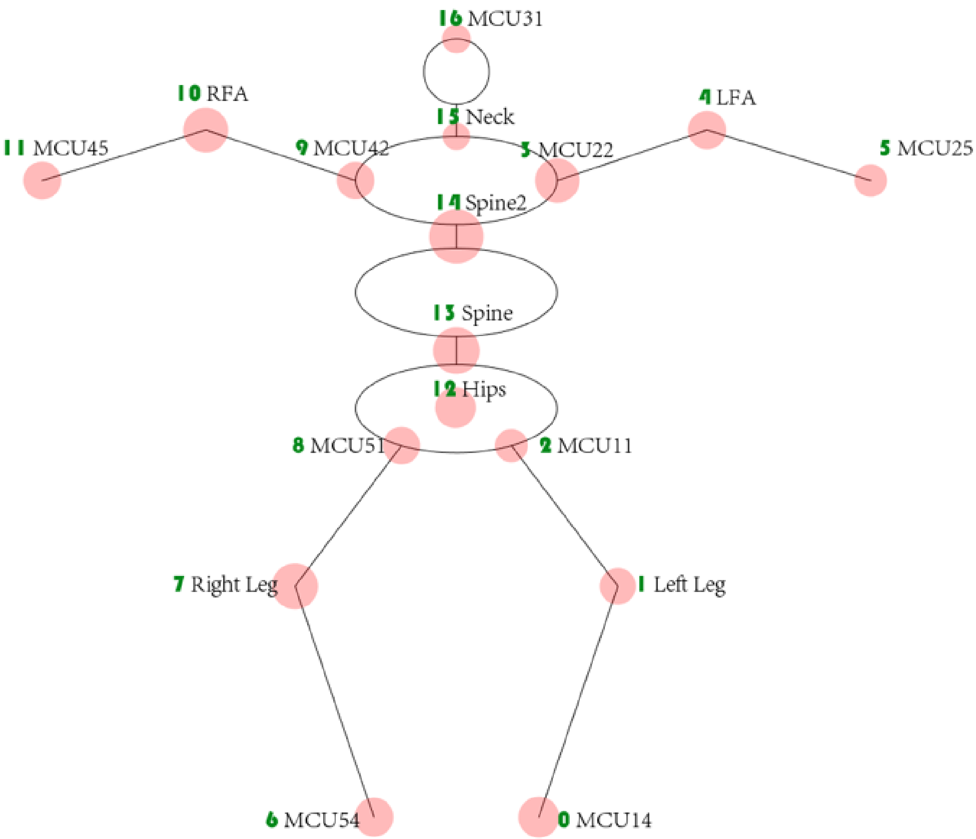


Figure 3.10: Tracking points for their corresponding kinematic data.

the dancing motions that are both familiar to and aesthetically expressive for dancers. Thus, the research direction turned to consider the expressive language of dance. Considering such different cases as contemporary dance, ballet, Greek folk and flamenco, it is almost impossible to find one solution to fit all. Fortunately, Raheb, Whatley and Camurri (2018) proposed a conceptual framework broadly suitable to various dance genres. Their framework defines ten key dancing principles that we utilise in this research (el Raheb et al., 2018):

- Symmetry: the ability to perform with both right and left side of the body, arm or leg the exact same movement, simultaneously or sequentially, both in position and in motion.
- Directionality: the awareness of body orientation in space. Usually, this is derived from the position of the hips and torso, but interesting

postures might derive from various directions of each body part in relation to a specific space, e.g., the audience, camera or studio.

• Balance: the ability to stand and move in balance, but also out of balance, depending on whether the line of gravity falls within the line of your supporting limb(s), or not. This relies on the awareness of the different vector forces in your body.

• Alignment – posture stability: the awareness of the geometry of the body (e.g., the sagittal, horizontal, vertical axes) and planes, and how the relation of different body parts and joints create "lines" in the body shape.

• Weight bearing vs gesturing: this principle concerns the capacity to distinguish between movements implying bearing weights (e.g., weight transference, stepping) and gestures which simply involve an analogous intention/expression.

• Gross vs fine motoric/isolation/articulation: the ability to distinguish small movements executed by specific body parts (e.g., hand, hip, shoulder) without moving the rest of the body, from those moving larger parts of the body as a whole.

• Coordination: one of the most important skills in every kind of dancing, it represents the ability to synchronise (or not) different parts of the body, that can move in the same or separate tempos.

• Motion through space: the capacity of progressing through space, towards particular directions, paths etc., versus dancing on the spot. Also, the use of body as a moving point in space, or as a continuously changing moving volume.

• Rhythm and phrasing: the ability to move in particular (predefined or improvised) rhythms. This principle also implies how the dancer's movement is related (or not) to the music and its rhythmical aspects (tempo, time signature, rhythmic patterns etc.).

• Stillness: while movement seems to be the essence of dance, a dancer needs to improve her/his ability to remain still, either if it is part of choreography or interpretation of rhythmical pauses or an exercise for balance and isolation of body parts.

When these dancing concepts from the dancing conceptual framework are parameterised, they might supply dancers with familiar and flexible ways to interact with the dynamic generative design algorithms. Specifically, this study applied one of the dancing concepts, alignment, to enable dancers to interact with Mo-grow. Several reasons were considered to choose the alignment. First, various axes by linking random two points on the body and various relationships of these axes e.g. angles, changing speed and acceleration of angle between any two of all axes, bring sufficient parameters of motion input to reflect Mogrow's various changes. Moreover, the flexibility of defining axes by random body parts can easily fit the unique body features of disabled dancers. At last, any one of the ten dancing concepts can produce countless parameters of motion input, the present study had limited time to explore all of them.

The following paragraphs will summarise two different interaction modes: functional mode and dancing principle mode, which have been developed and explored with dancers.

The functional mode enables controlling form-creation of Mogrow by kinematic data of 17 tracking points, through the following logic:

• The velocity of all tracking points except points 5, and 11, and the acceleration of points 5 and 11 tracks left and right hands are applied to link with two real-time interaction parameters: friction and ejection and shrinking of Mogrow to control its form-creation.

• The velocity of all tracking points except points 5, and 11 is constantly being collected and compared with each other to obtain the maximum value of the velocity of these 15 tracking points.

• Then this maximum velocity is scaled and applied as the real-time interaction value 1/ friction, which can be described as the following formula: friction= 1/(maxvel $\times$a). The value fraction is the value of the real-time interaction parameter friction. The value maxvel reflects the maximum velocity of the 15 tracking points. And the value a represents a constant value to scale the maxvel to a proper range for controlling form-creation. In addition, the value friction controls the size of wrinkles and the degree of compactness of the geometry. As a result, when the dancer moves fast, which means a bigger value of maxvel triggering a smaller value of friction, the 3D geometry shows bigger wrinkles.

• Moreover, the acceleration of points 5 and 11 tracks left and right hands are applied to be the other real-time interaction parameter ejection and shrinking. Specifically, the acceleration value of point 5 tracking left hand controls ejection, and the acceleration value of point 11 tracking right-hand controls shrinking.

• When the acceleration value of point 5 is more than a pre-set constant value: ejection button, all of the 10 nozzles on the particle-spring closed chain start to eject and produce wrinkles.

• The velocity of ejection is directly proportional to the acceleration value of point 5, which means a bigger acceleration value triggers faster ejection. When the acceleration value of point 5 reduces to be smaller than the ejection button, the ejection stops.

- Following a similar logic, the acceleration value of the tracking point 11 on the right hand controls the on/off and the velocity of the shrinking behaviour.

As a result, the specific functional mode of the present study could be summarised as that the moving speed of the whole body of the dancer controls the interaction value of friction: when the dancer moves faster, the geometry shows bigger wrinkles, inversely, slower movement results in smaller wrinkles and compact geometry; dancer shakes left hand to increase wrinkles and shake right hand to reduce wrinkles in real-time.

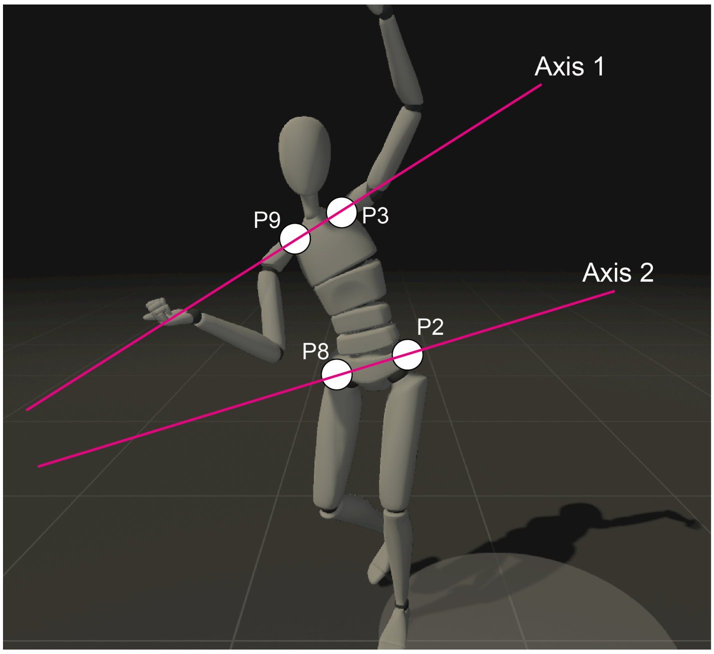


Figure 3.11: Axes for dancing principle mode.

The dancing principle mode allows dancers to control the form-creation of Mogrow by motions following dancing concepts. The present study applies one of the dancing concepts – alignment to guide the design of interaction mode. Alignment means the awareness of the geometry of the body (e.g., the sagittal, horizontal, vertical axes) and planes, and how the relation of different body parts and joints create lines in the body shape. Its logic is stated as follows:

- The dancing principle mode is developed based on four basic tracking points: points 3 and 9 track left and right shoulders and points 2 and 8 track left and right edges of the hipbone (Figure: 3.11).
- Similar to the functional mode the maximum velocity of these four points is reflected and transformed to the value friction by the same formula: friction= 1/(maxvel ×a). The value fraction is the value of the real-time interaction friction. The value maxvel reflects the maximum velocity of the four tracking points. And the value a represents a constant value to scale the maxvel to a proper range for controlling form-creation.
- Moreover, the controlling of ejection and shrinking is conducted following the dancing concept – alignment. Specifically, the angle value between two axes separately formed by linking left and right shoulders and the left and right edges of the hipbone is applied to be the other real-time interaction parameter: ejection and shrinking.
- The angle between these two axes is constantly being collected and compared to calculate the velocity of angle change.
- When the velocity of angle is bigger than the pre-set constant value ejection button and simultaneously the left shoulder is higher than the right shoulder, the ejection starts. And the velocity of ejection is in direct proportion to the velocity of angle change.
- Correspondingly, when the velocity of angle change is bigger than the other pre-set constant value shrinking button, and simultaneously, the right shoulder is higher than the left one, the shrinking starts. And the velocity of shrinking is also in direct proportion to the velocity of angle change.

To simplify, the dancing principle mode enables dancers to control wrinkle size and degree of compactness of the geometry by shaking the speed of their shoulders and hips; and increasing or reducing the density of wrinkles by tilting their shoulders and hips.

Aesthetic seeds produced by the interaction between dancers and Mogrow

The previous sections introduced the logic of form-creation through two behaviours wrinkling and stacking of a particle-spring the closed chain; and two interaction modes: functional mode and dancing principle mode so as to enable dancers' interaction with form-creation. This subsection will illustrate the 3D designs – aesthetic seeds produced by the form-creation of Mogrow under interaction with dancers.

Figure: 3.12 illustrates some aesthetic seeds produced by the user study of the present research. In addition, rather than any specific design, the aesthetic seed is an archetype which is the potential to be applied to various designs. The following subchapter will demonstrate how to extend these aesthetic seeds to various designs.

3.3 Algorithm 02 – leg sculpting

Once an aesthetic seed has been generated, it can then be applied to various different products in order to personalise their decoration. This involves further algorithms that map aesthetic seeds to particular physical forms. This section introduces an algorithm to map aesthetic seeds produced by Mogrow to the physical form of a prosthetic leg cover. However, we first demonstrate the principle through a simpler mapping – creating vases from

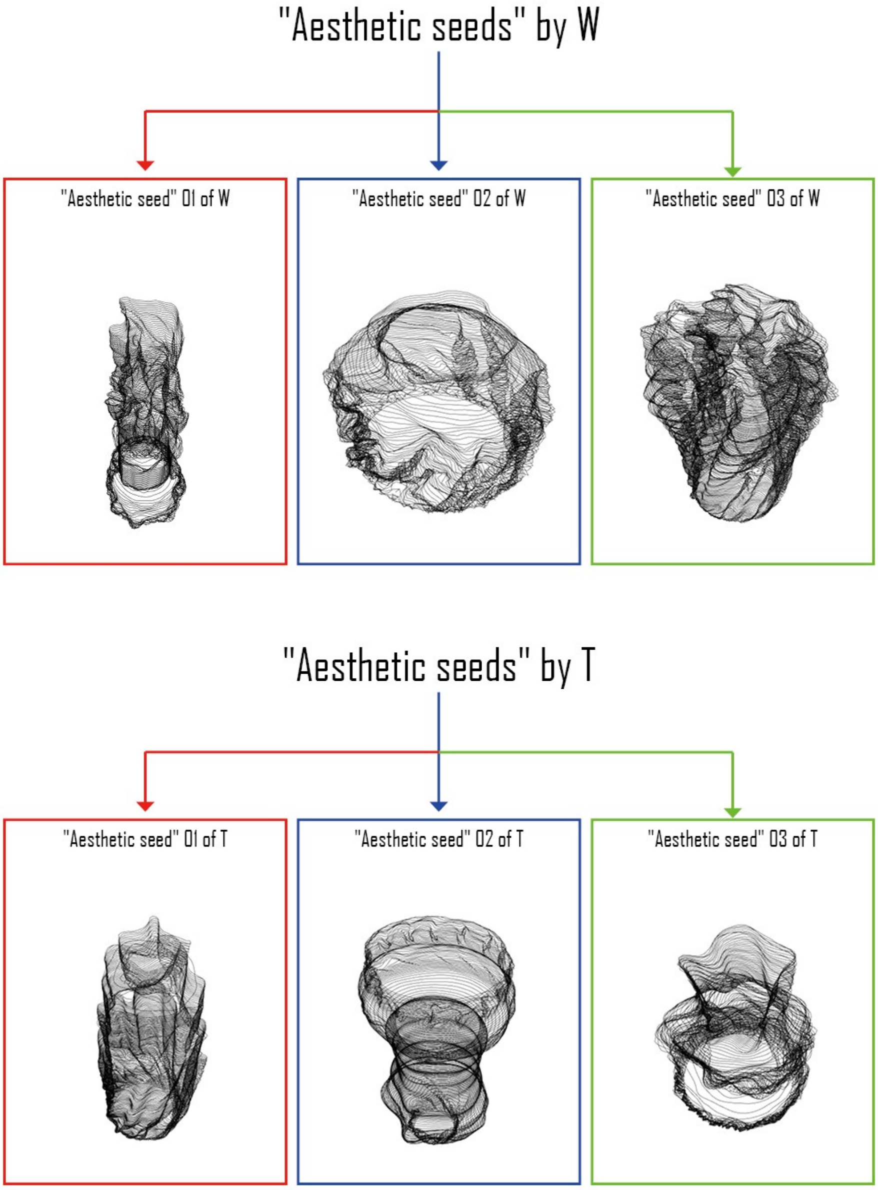


Figure 3.12: Aesthetic seeds.

aesthetic seeds.

3.3.1 Vase design

In this research, two types of conceptual designs are explored, namely vase and aesthetic prosthetic cover. The aim of vase design is to quickly show how the aesthetic seed can be extended to a specific product design and supply comparison to the design of aesthetic prosthetic covers produced by the same aesthetic seeds with the vase designs. The generation method of the vase is straightforward. An algorithm lofts all of the contours composing aesthetic seed from bottom to top to form a 3D geometry of vase (Figure: 3.13).

3.3.2 Design of prosthetic covers

A typical transtibial prosthesis, as seen in Figure: 3.14, consists of the following parts: Socket: The socket acts as the basic interface between the patient and the prosthesis. It is a moulded shape that consists of a rigid outer and soft inner shell that is sculpted to fit the residual limb. Pylon and modular components: The pylon and its modular components replicate the function of bones in human limbs. These components are primarily made from titanium, stainless steel or aluminium, depending on the function and patient weight. Foot: Depending on the patient weight and activity level, a basic SACH foot can be prescribed for a patient with a low activity level to a high-performance carbon fibre foot mimicking natural foot motion for high activity level patients. Although the basic typical transtibial prosthesis satisfies the basic functional requirements, its mechanical appearance often fails to meet the aesthetic needs of users. Thus, prosthetic covers emerge

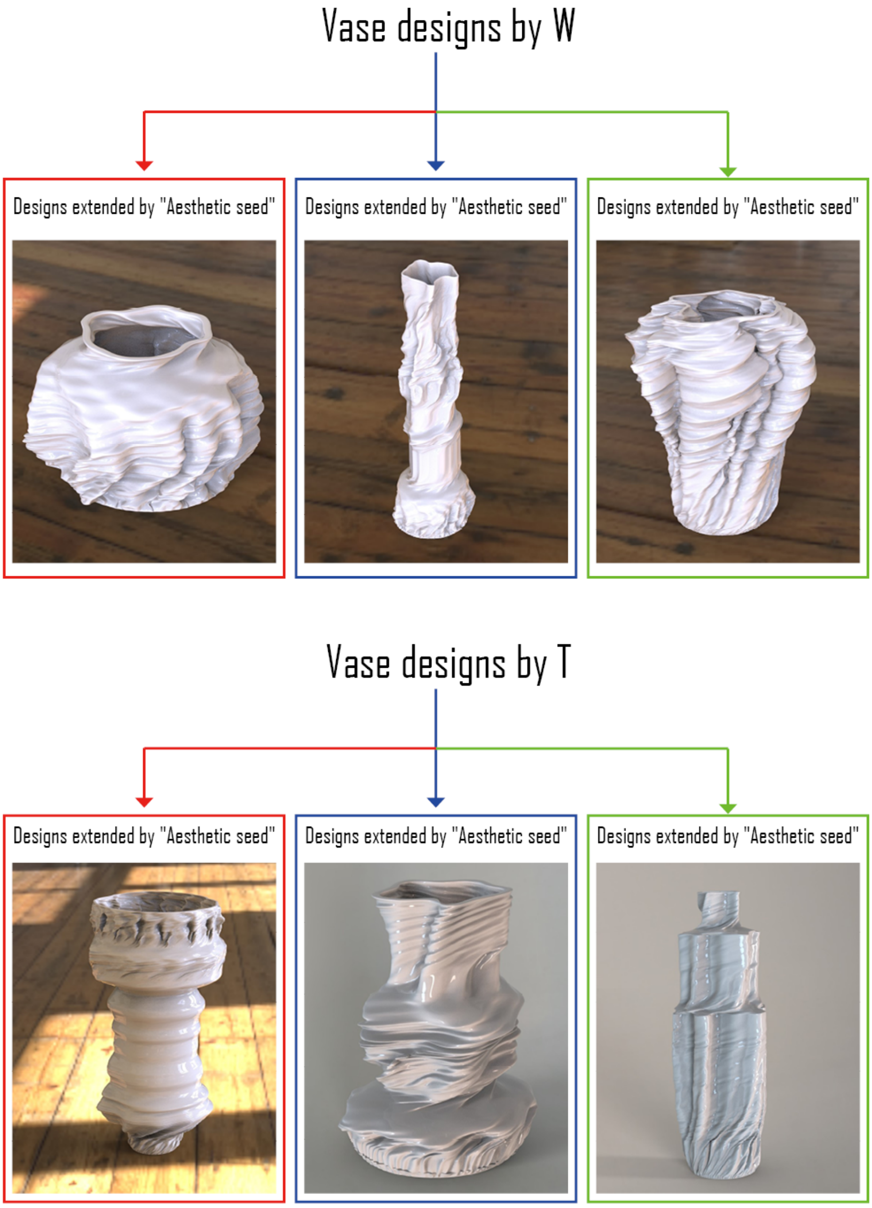


Figure 3.13: Vase designs.

to cover prosthetics' mechanical exterior. Moreover, since the prosthetic cover is primarily for aesthetics and there is no requirement of considering mechanical properties, the prosthetic cover is also usually chosen by designers and researchers who focus on exploring the aesthetics of prosthetics (Blom, 2018; Hart, 2021; Labarre, 2010; Summit, 2016; Vlachaki et al., 2020). Thus, the present study also chose the prosthetic cover as a specific design to conduct further research.

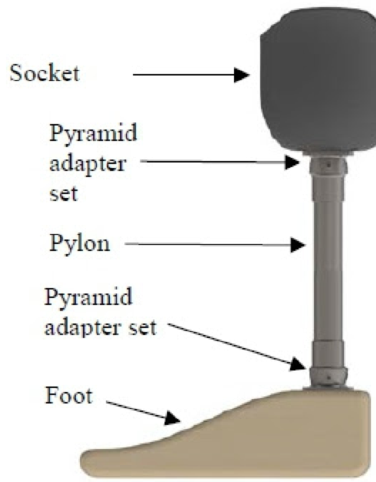


Figure 3.14: A typical transtibial prosthesis.

The aim of algorithm 02 – leg sculpting

The algorithm that generates the conceptual design of the aesthetic prosthetic cover is Algorithm 02 - leg sculpting. It aims to satisfy the morphological and functional requirements of prosthetic cover without losing the unique aesthetic appearance of the aesthetic seed. There are two requirements to achieve this aim. One is to personalise the overall geometry based on the personal body features for satisfying the morphological and functional requirements of the prosthetic cover. The other requirement is avoiding losing the unique aesthetic patterns of the aesthetic seed during the process of personalising the overall geometry by personal body features.

Since body features vary among different individuals, there is a need to establish a method to create the natural shape of an individual's limb recreated digitally. Developments in 3D technologies offer affordable methods not only to create objects through additive manufacturing (3D-printing) but also to scan 3D objects. These objects can be imported into software programs that allow manipulation and creative use in the design process (Blom, 2018). 3D scanning technologies have made significant contributions to the field of prosthetics, enhancing the accuracy and efficiency of the design and manufacturing process (Telfer, Pallari, Munguia, Dalgarno, McGeough, Woodburn, 2012). By capturing high-resolution anatomical data, 3D scanning allows for the creation of custom-fit prosthetic devices tailored to individual patients, ensuring greater comfort and functionality. The digital models generated can be readily integrated with computer-aided design (CAD) software and 3D printing techniques, further streamlining the overall process. For a person missing part of one of their limbs, the sound limb might be scanned and mirrored so that the designed cover exactly replicates the natural shape of their missing limb.

On the other hand, the prosthetic cover designs remain the detailed patterns of the aesthetic seed. Since vase designs are produced by directly lofting the contours composing the aesthetic seeds, these vase designs retain much of the original pattern of aesthetic seeds. In order to clearly illustrate the similarity between the aesthetic seed and the conceptual design of prosthetic covers, the vase design is selected as a representation of the aesthetic seed, since the aesthetic seed consists of multiple closed curves, through which, it is hard to observe the design details. Figure: 3.15 illustrates this comparison showing that although the form of the conceptual designs of the prosthetic cover is significantly different from the original aesthetic seed in terms of overall geometry, the detailed aesthetic patterns still inherit the aesthetic characteristics of the original aesthetic seed.

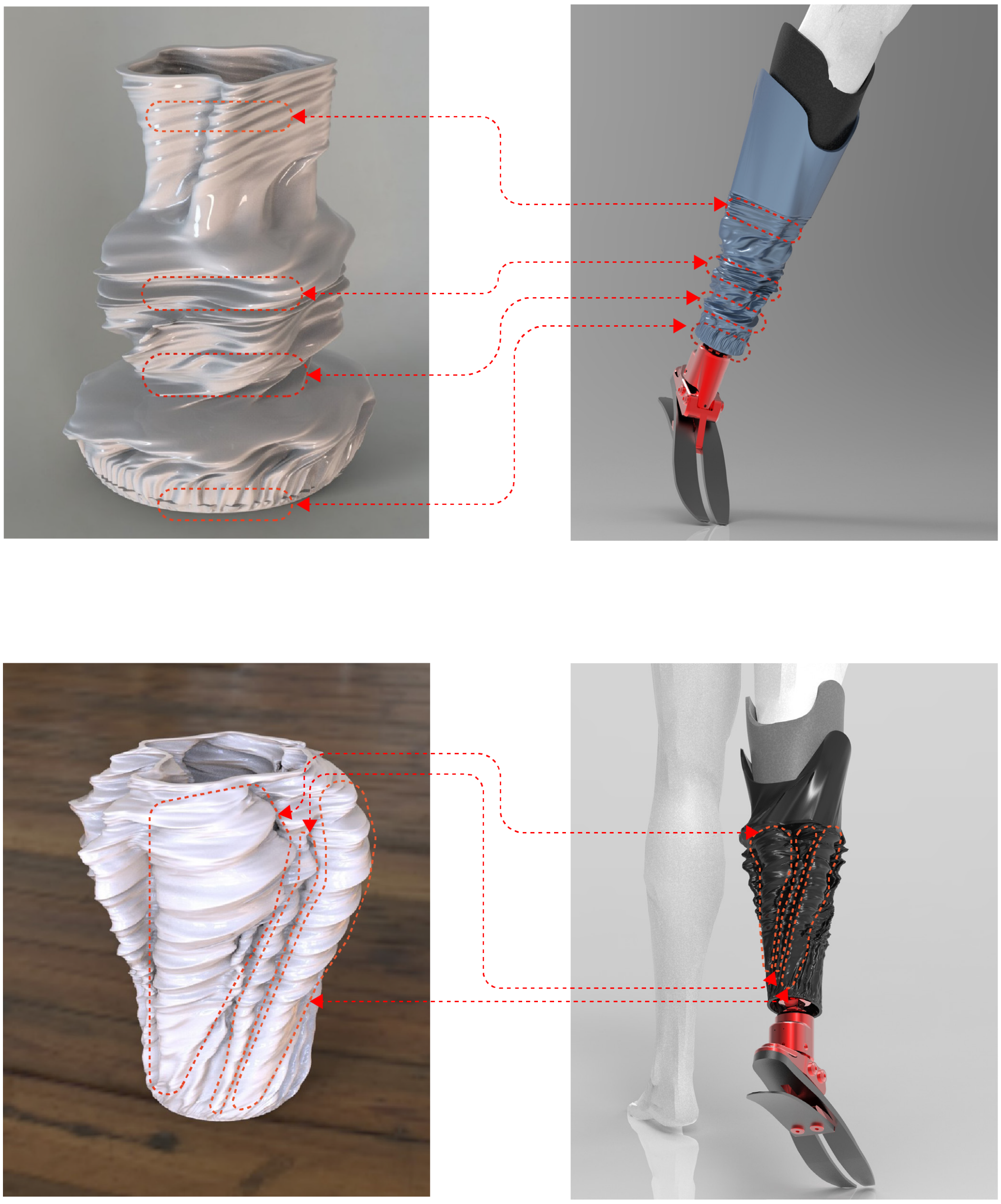
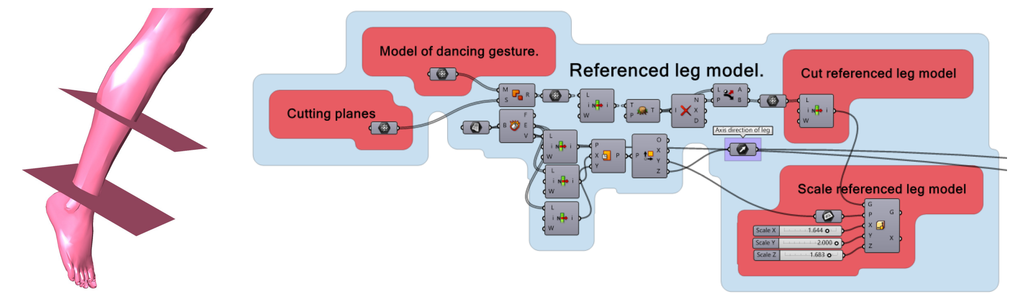


Figure 3.15: Structure of chapter literature review.

The logic of the algorithm 02 – leg sculpting

This subsection will state the logic of algorithm 02 – leg sculpting. The first step is to obtain a referenced 3D model which is suitable to personal body features. One ideal approach is to scan the user's sound limb (if the user has) with the 3D scanner. Limited by access to amputated dancers, the 3D scanning of the sound limb was not conducted. Alternatively, a referenced 3D model of a limb from a female is applied as the representation of the scanned sound limb for developing algorithm 02 (Figure: 3.16a). Then the segment locations need to be confirmed by simply moving the two cutting planes (Figure: 3.16a). In the end, a referenced model suitable to a specific user is produced to guide the design of the aesthetic prosthetic cover. In addition, details of the scanned reference leg can be modified directly by sliders. For instance, a human's leg shape can be different in various gestures or movements, the process enables directly switching the scanned referenced limb by right-clicking on the model of the dancing gesture component. Then the segment of the referenced limb can be directly determined by moving the position of the cutting plane. After that, the size of the segment of the referenced limb can be scaled in the axial or length and width direction, by the three sliders (Figure: 3.16b).



a b

Figure 3.16: 3D model and process to modify the segment of the referenced limb.

After obtaining the segment of referenced limb, the next step is to scale the aesthetic seed according to it, so that the overall shape conforms to the referenced limb. It starts with lofting the contours composing an aesthetic seed to produce a surface. This surface is then scaled in the axial direction to be the same length as the segment of the referenced leg. After that, the surface produced by lofting contours of the aesthetic seed and the 3D model of the referenced limb segment is simultaneously contoured by a 1.5

mm interval into multiple contours. The value of 1.5mm comes from consideration of the balance of resolution and computing efficiency. Smaller the value means higher resolution, which enables more details, but simultaneously increases the computing load. The next step is to separately move the new contours of the aesthetic seed until their centre points are separately in the same position with their corresponding contours of the reference leg segmentation (Figure: 3.17).

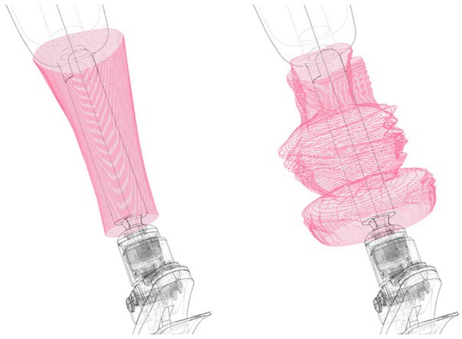


Figure 3.17: Contours with 1.5mm interval of the referenced limb segment and aesthetic seed.

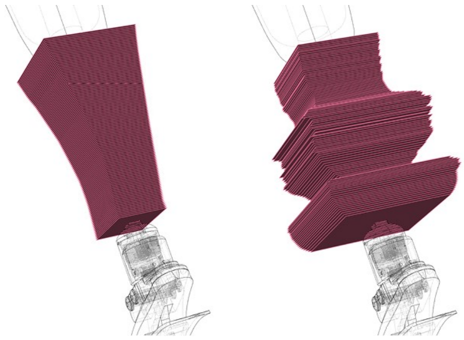


Figure 3.18: Bounding box of contours on the referenced limb segment and aesthetic seed.

After obtaining the contours of the referenced limb segment and aesthetic seed, both of them are processed by the algorithm – bounding box, which means the smallest box covering the aimed object (Figure: 3.18). Then each bounding box of the aesthetic seed contours is separately compared with its corresponding bounding box of the referenced limb segment contours to get the size comparison in the length and width direction. After that, the contours of the aesthetic seed are scaled to be similar in size to the corresponding contours of the referenced limb segment (left image of Figure 3.22).

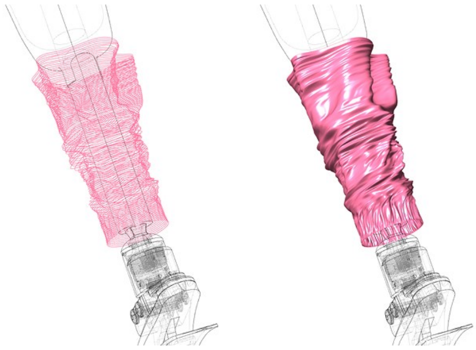


Figure 3.19: Loft the scaled contours of aesthetic seed to produce 3D geometry.

The next step is to loft the scaled contours of the aesthetic seed to produce 3D geometry (right image of Figure 3.22). In order to achieve a natural transition of the geometry, a socket cover is generated by lofting the top contour and the edge of the socket, shown in the middle image of Figure: 3.20. Then, integrating the 3D geometry by lofting scaled contours of the aesthetic seed with the socket cover produces the mirrored conceptual design of the aesthetic prosthetic cover. Since the whole process is based on the referenced leg segment which is supposed to be the sound limb of the missing one, the last step to finalise the conceptual design of the aesthetic prosthetic cover is to mirror the design.

Figure: 3.21 summarises the whole procedure that produces the conceptual design of the aesthetic prosthetic cover from aesthetic seeds by the algorithm 02 – leg sculpting. To simplify, it starts with 3D scanning the sound limb to get the segment of the referenced limb. Then the contours of the aesthetic seed are scaled by this scanned segment of the referenced limb. After that, contours are lofted into 3D geometry and combined with the socket cover. At last, the design is mirrored to get the final design. Figure: 3.22 illustrates designs of aesthetic prosthetic cover.

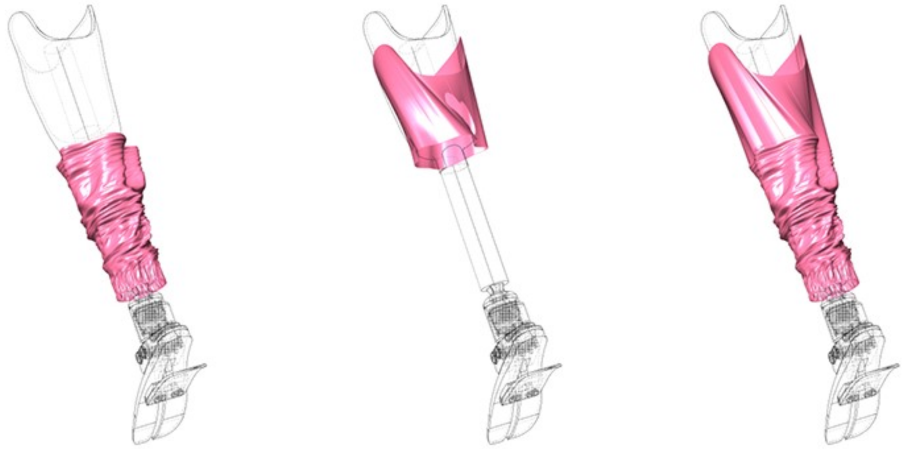


Figure 3.20: Integrating the 3D geometry by lofting scaled contours of the aesthetic seed with the socket cover.

3.4 Algorithm 03 – optimisation of additive manufacturing

The conceptual design of the prosthetic cover has been produced by extending the aesthetic seed through the algorithm 02 – leg sculpting. In order to then manufacture the design, it will need to be applied to a particular manufacturing process which may, in turn, require some further modifications to it. In this case, we are working with Additive Manufacturing, which requires that the cover designs produced by Algorithm 2 are further modified in specific ways as we now discuss.

Due to additive manufacturing being a process of an accumulation from bottom to top, higher layers always requires support from the lower layers. However, the higher layers are not always the same as the lower layers. When the lower layer can not support the higher layers, there is a requirement to print extra structures for supporting the higher layers. Printing supporting structures to support overhanging parts during the additive manufacturing process takes a noticeable proportion of the entire printing time and materials consumption. In order to improve printing efficiency,

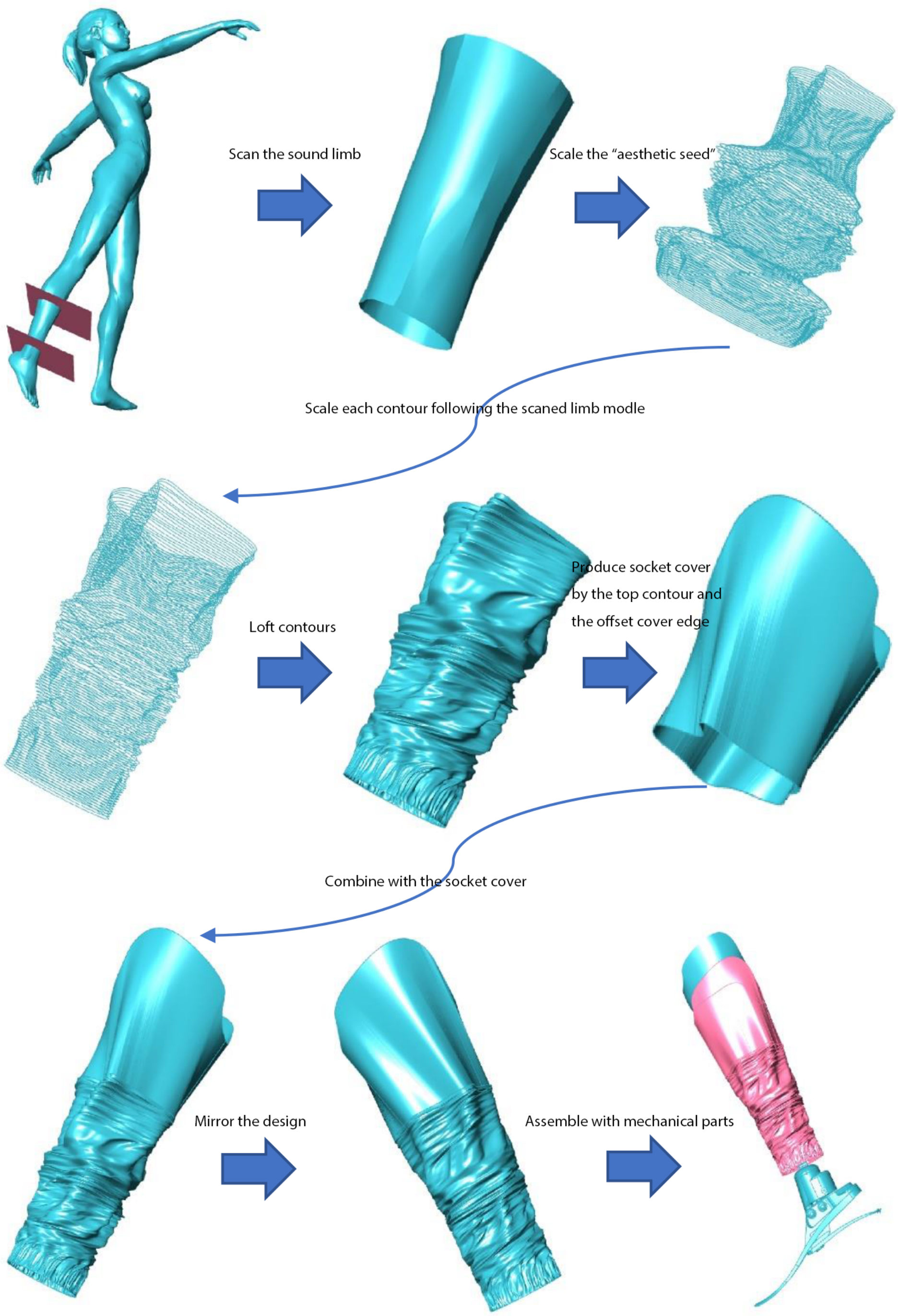


Figure 3.21: Simplify the process of producing the conceptual design of the aesthetic prosthetic cover with aesthetic seed by the algorithm 02 – leg sculpting.

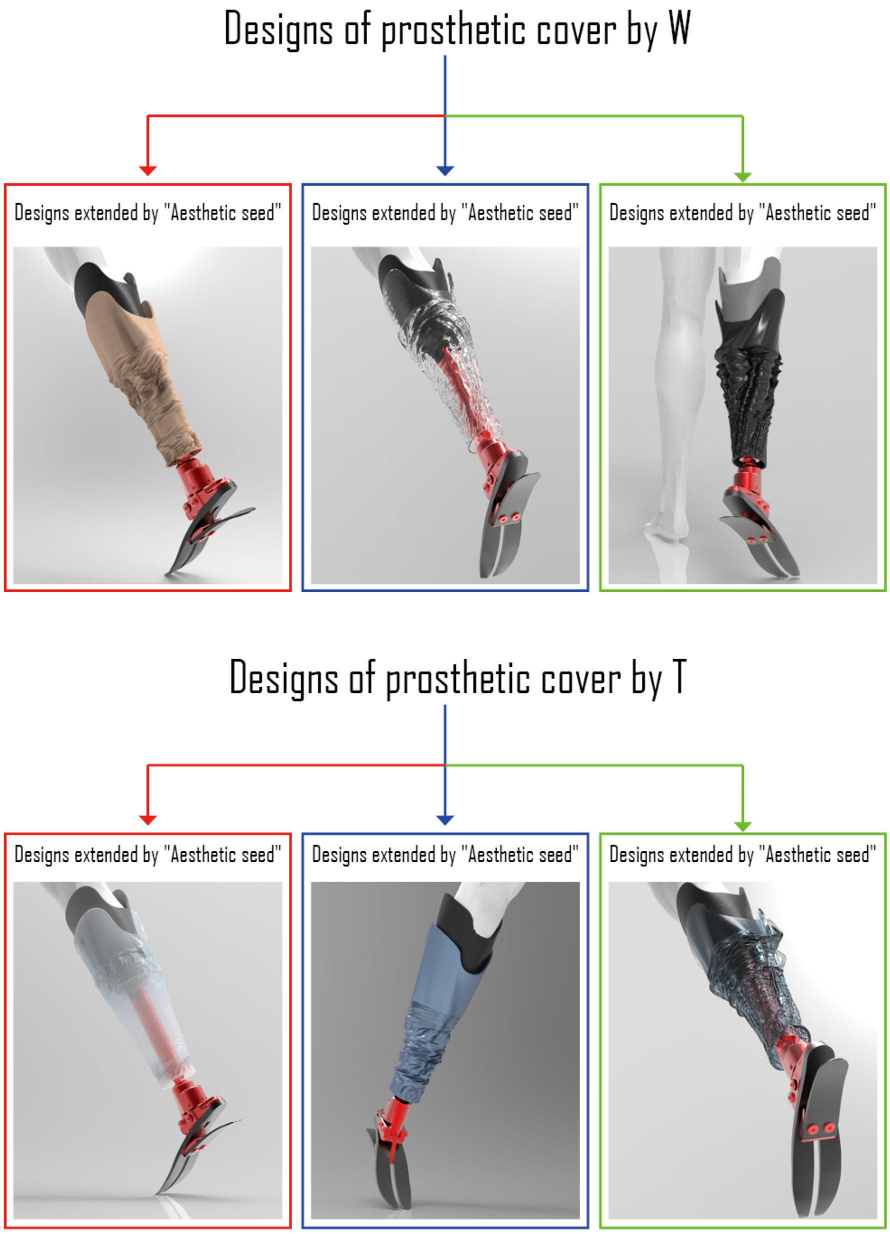


Figure 3.22: Designs of prosthetic cover.

overhanging parts on the prosthetic cover were eliminated using algorithm 03 – optimisation of additive manufacturing. It enables automatic scanning and adjusting of 3D models until the overhanging parts disappear. This subchapter will demonstrate the approach to optimise the conceptual designs to improve the efficiency of additive manufacturing in three sections: reason of overhanging, logic of the algorithm 03, and experiment.

3.4.1 Forming of overhanging

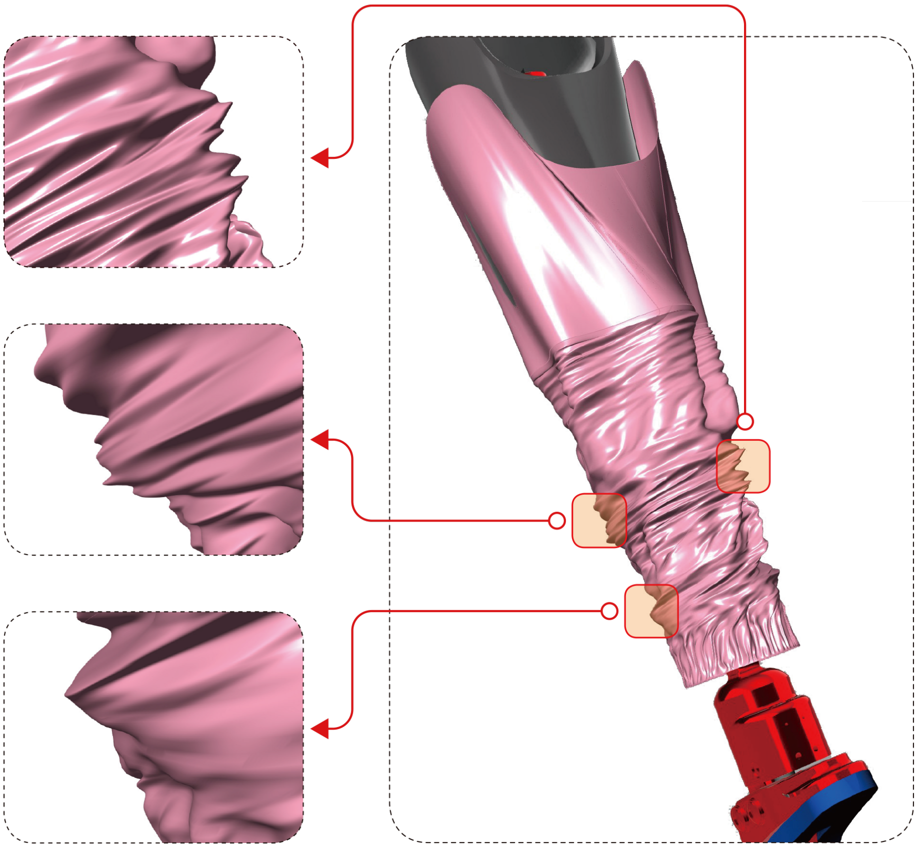


Figure 3.23: The overhanging state on the conceptual design of the aesthetic prosthetic cover designed by T.

Since the aesthetic seeds generated by Mogrow consist of 2D contours stacked from bottom to top, which record the transforming history of a dynamic particle-spring closed chain at a fixed interval, every two neighbour contours record this dynamic curve before and after states of a constant short time. The faster the transforming speed of this dynamic curve is, the more significant difference between the two adjacent contours is, and the more likely overhanging will occur. On the contrary, the slighter difference between adjacent contours, the less likely it will produce overhanging. Similarly, if ejection or shrinking behaviours occur, the two adjacent closed contours will also have significant differences in shapes, resulting in overhanging. Although the conceptual design of the aesthetic prosthetic cover is produced by the scaled contours of the aesthetic seed, the transforming of the contours happens on the overall scale, in which the details are not changed. Thus, the conceptual design of the aesthetic prosthetic cover shares quite a similar overhanging state with its aesthetic seed. Figure: 3.23 illustrates the overhanging state of the conceptual design of the aesthetic prosthetic cover designed by T. All of the following studies about the efficiency of additive manufacturing are illustrated based on this model. Therefore, in order to eliminate overhanging for increasing printing efficiency but simultaneously retain its aesthetic details, Algorithm 03 – optimisation of additive manufacturing was developed.

3.4.2 Logic of the algorithm 03 – optimisation of additive manufacturing

This section will demonstrate the logic of optimisation of additive manufacturing. It starts with slicing the conceptual design of the prosthetic cover into contours at 1.5 mm intervals, which is also the layer height for additive manufacturing of the present research. And the contours represent the printing toolpath of additive manufacturing. As the same set as the conventional 3D printers, the maximum overhang angle limit is set to 55 degrees, which means unprintable without supporting structure, when

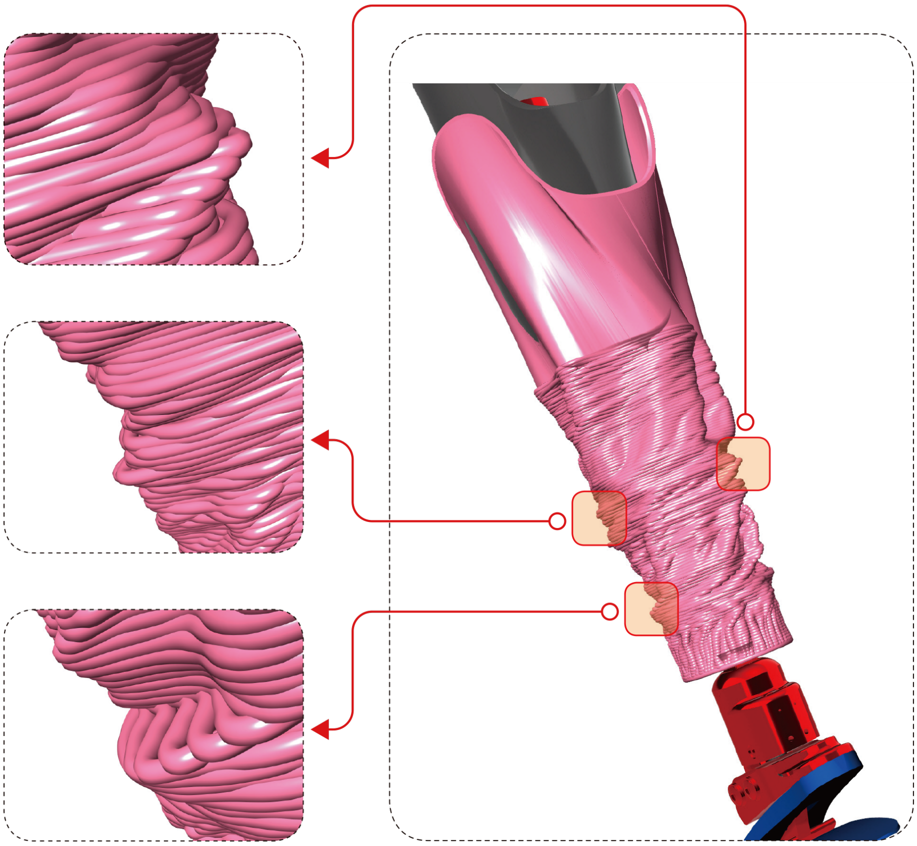


Figure 3.24: The overhanging state on the sliced conceptual design of the aesthetic prosthetic cover designed by T.

the Angle of overhanging is bigger than 55 degrees. Figure: 3.24 illustrates three overhanging parts on the sliced 3D model of the prosthetic cover.

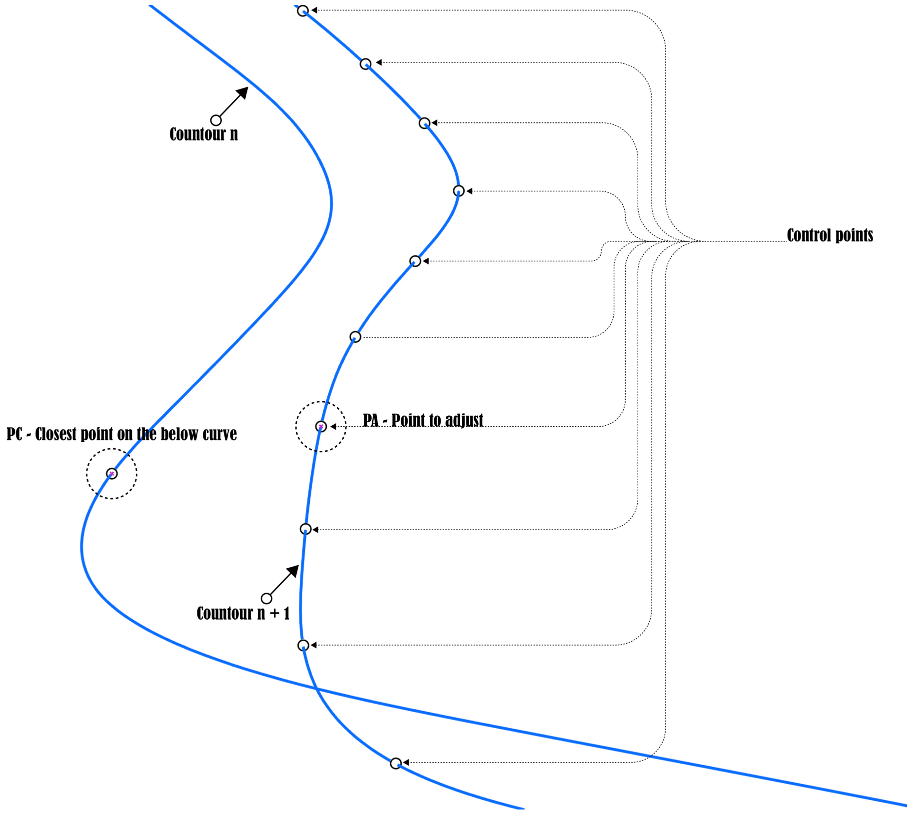


Figure 3.25: Top view of two neighbour contours.

In order to analyse the overhanging challenge, two adjacent contours are selected as research objects (Figure: 3.25). They are named contour n (the lower contour) and contour n+1 (the upper contour). To measure the overhanging angle and adjust the parts exceeding the overhanging limited angle, contour n+1 was divided into control points by the same distance. Since the density of control points is usually too high to illustrate, the control points in figure: 3.25 are to represent these controlling points for easy illustration. PA represents a control point on Contour N +1 that is being tested for overhanging angle and under adjustment. Then the point PC represents the PA's nearest point on Contour n.

Figure: 3.26 illustrates a perspective view of Contour n and Contour n+1. Since each contour is a 2D curve, each PA will have a projection "PP" on

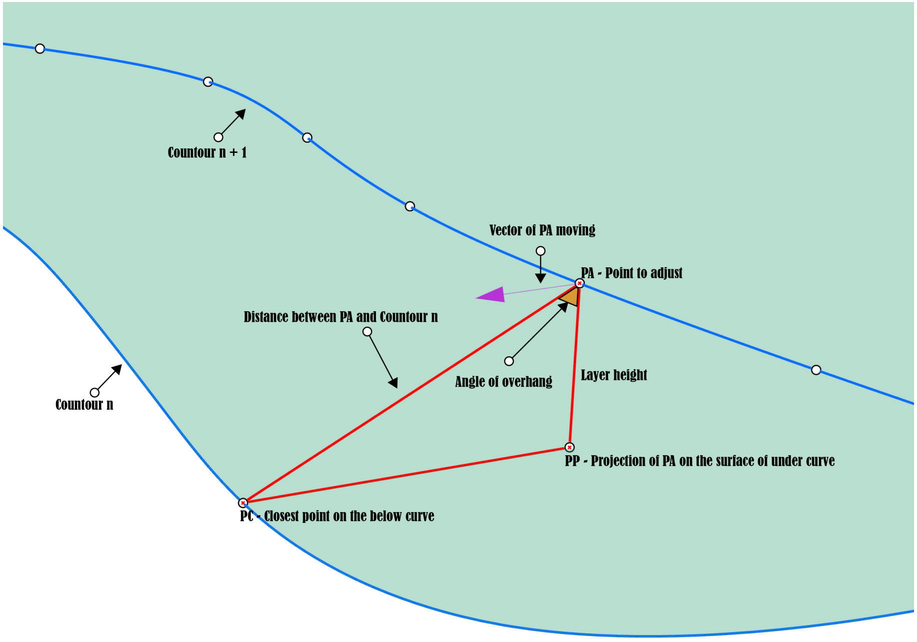


Figure 3.26: Illustration of overhanging adjustment during the bottom-up scanning.

the plane of its lower contour. Thus, the linking of point to adjust – "PA", projection of "PA" on the surface of under contour – "PP" and closest point of "PA" on the below counter – "PC" produces a rectangular triangle. Then when the "Angle of overhanging" illustrated in figure: 3.26 is bigger than the overhanging angle limit – 55 degrees, this "PA" needs to be adjusted. It will move for a short distance, namely "toleranceStep", which is set as 0.05mm in this study, following the direction of the "Vector of PA moving". This vector has the same direction as the vector from "PP" to "PA". Conversely, if the "Angle of overhanging" is less than the overhanging angle limit, "PA" will remain unchanged. When all control points on Contour n+1 have completed a test and adjustment, a new contour will be rebuilt according to the new control points to replace the previous Contour n+1. Thus, this completes the adjustment of one of all contours composing the design. A "bottom-up scan" would be completed when this adjustment runs from the second contour to the last in the order from bottom to top.

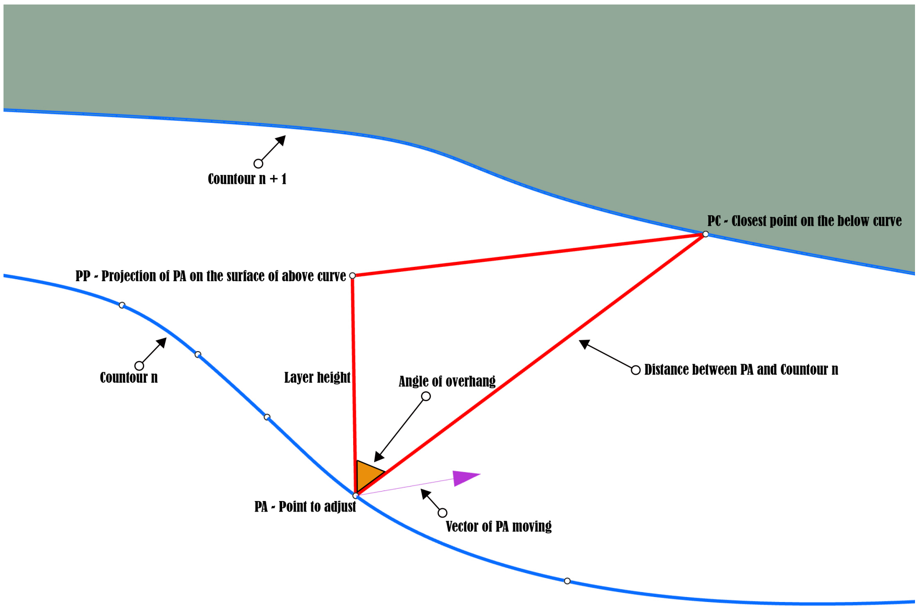


Figure 3.27: Illustration of overhanging adjustment during the top-down scanning.

Because the adjustment always happens on the upper contours and the lower contours keep constant in the process of "bottom-up scan", the form of the final design will be more likely to tend to the geometry of the lower part of the design, after multiple iterations of "bottom-up scan". Therefore, after a "bottom-up scan", "top-down scan", which is contra with the "bottom-up scan" is conducted. As shown in Figure: 3.27, the Contour n+1 is kept invariant, and the overhanging measurement and adjustment happen on the Contour n. This process prompts an adjustment of lower contours and keeps upper contours constant. Thus, waving "bottom-up scan" and "top-down scan" with multiple iterations achieves eliminating the overhanging with the slightest modification on the overall design. Figure: 3.28 illustrates this waving and iteration of "bottom-up scan" and "top-down scan". And the white points in this diagram represent points being adjusted. Figure: 3.29 demonstrates the morphological comparison between the original contours (green curves) and the ones (red curves) after multiple iterations of the "scan".

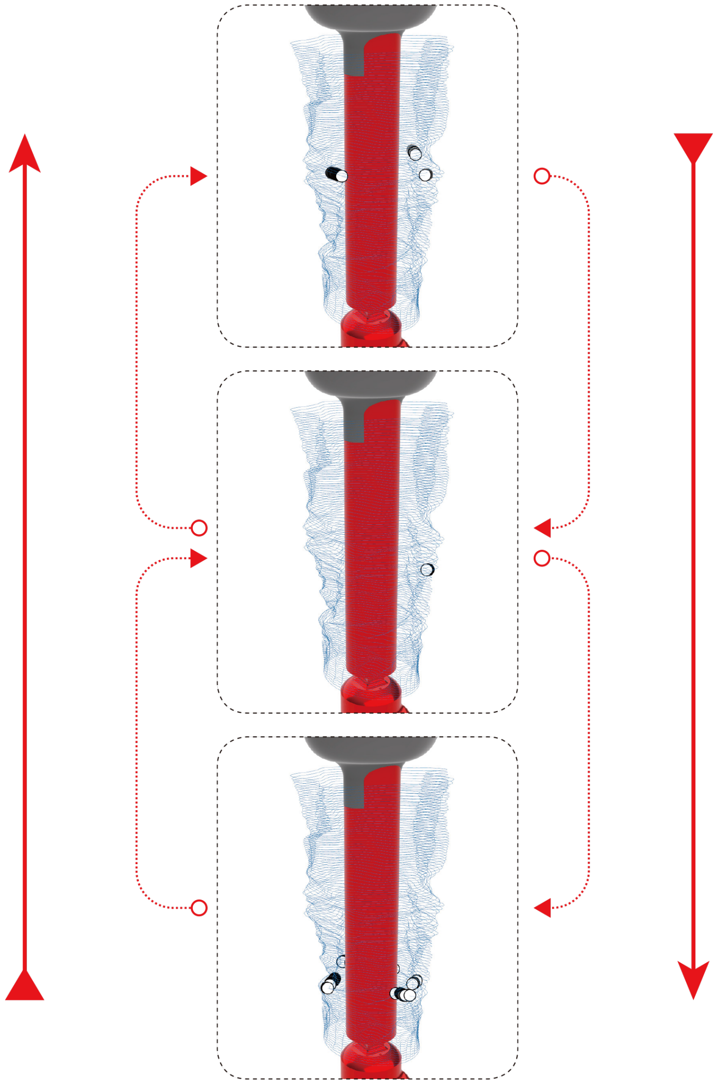


Figure 3.28: Waving "bottom-up scan" and "top-down scan".

In order to conveniently modify the details of this algorithm, an process as developed as demonstrated in Figure: 3.30. There are four steps to make the algorithm work and modify details. Step 1: Pick up contours. Before conducting Step 1, all of the contours need to be 2D curves on the XY plane. Step 2: To avoid decreasing the efficiency of the following calculation, right-click on the component and select "internalise data", then disable all the components before this one. Step 3: There are two parameters and one button. One parameter, namely "constraintAngleDegree", determines the overhanging angle limit, which is set at 55 degrees here. Then the

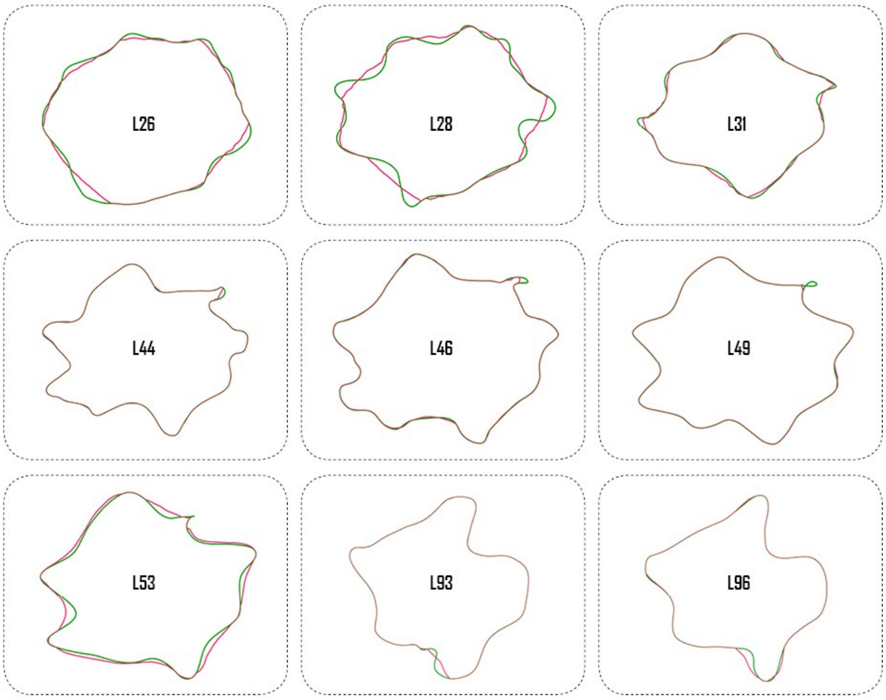


Figure 3.29: Comparison between the original contours and the ones after multiple iterations of "scan".

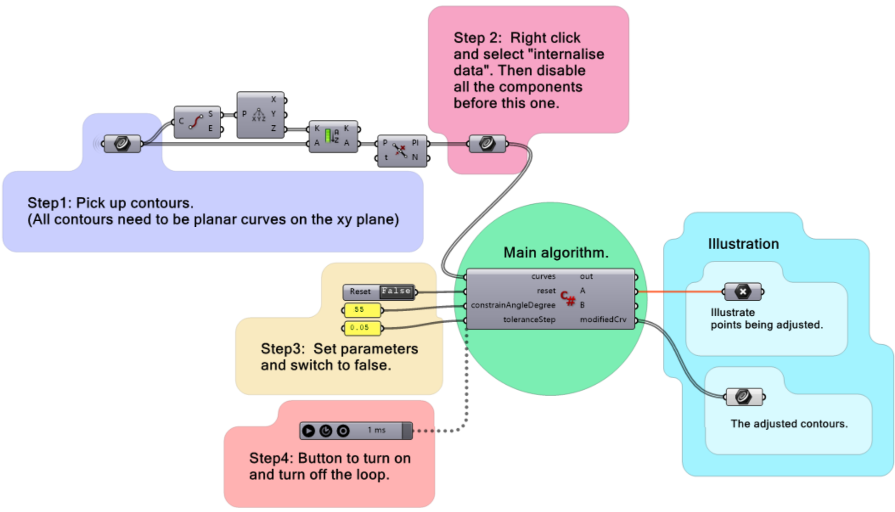


Figure 3.30: Illustration of parameters controlling overhanging adjustment.

controlling points with overhanging angle over 55 degrees will be adjusted until it is smaller than this. Considering different materials or printing layer heights may have various maximum overhanging degrees, one adjustable parameter is set here to modify this data efficiently. The other parameter, namely "toleranceStep", controls the moving distance of the controlling points under one adjustment. The smaller the value set is, the smoother the final adjusted model is, but more iterations are required to eliminate the overhanging. In this study, the value was set at 0.05mm. The button in Step 3 is named "reset", which determines whether to reset the adjusted contours. Before operating the "Main algorithm", this value needs to be set as False. Step 4: here is a button to turn on or off the "Main algorithm" loop. In addition, there are also parameters to control the illustration of points being adjusted and the contours after adjustment.

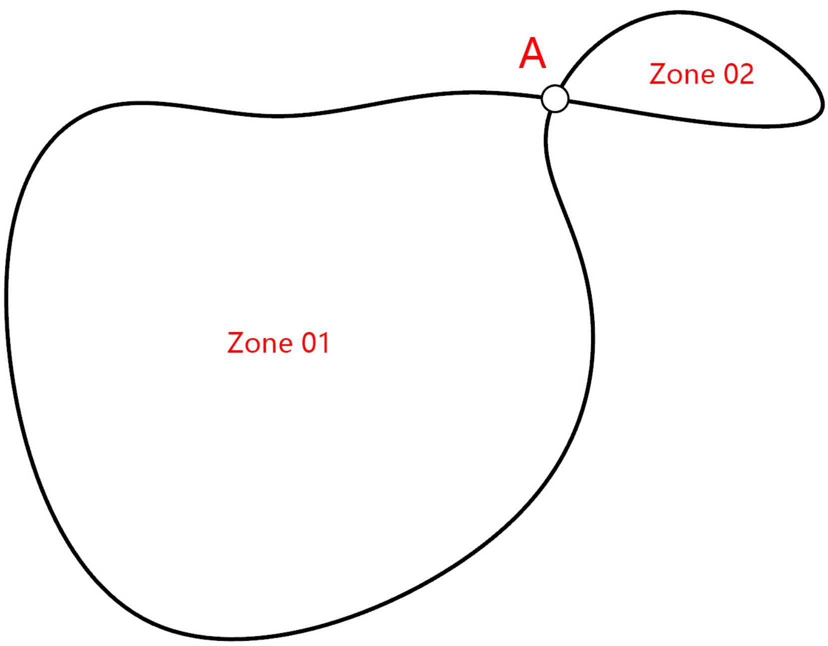


Figure 3.31: Phenomenon of self-intersection.

However, there is another problem – self-intersection emerges, after "scan" and adjustment to eliminate overhanging parts. Self-intersection on 2D curves is a phenomenon illustrated in Figure: 3.31. Point "A" is the point

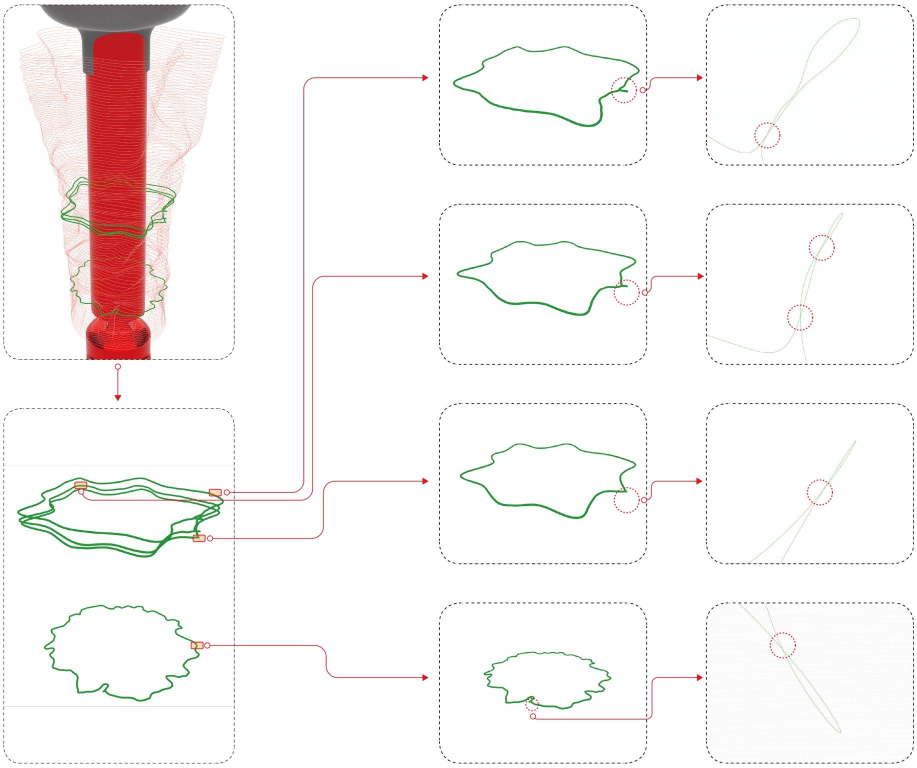


Figure 3.32: Illustration of self-intersection on the contours composing the design of the prosthetic cover.

where the intersection occurs. “Zone 01” and “Zone 02” are two closed spaces created by self-intersection. If the 3D printing path is this curve, the printer’s nozzle will go through the point of intersection twice. Suppose the extrusion speed of the material is kept constant in the printing process, when the nozzle goes over this intersection point for the second time, the material will accumulate. In the other case, stopping material extrusion when it passes the intersection point the second time adds complexity to the printing path programming. In addition, in this research, the size of Zone 02, one of the two spaces generated by intersection, is significantly smaller than that of Zone 01. Even deleting Zone 02 will not produce a significant impact on the design. Therefore, direct deleting Zone 02 was chosen to deal with the self-intersection of the print path. Figure: 3.32 illustrates the contours happening self-intersection in green colour. While the red circles in this figure show the details of self-intersection enlarged, the second green contour appears twice self-intersection, and the other three appear once each.

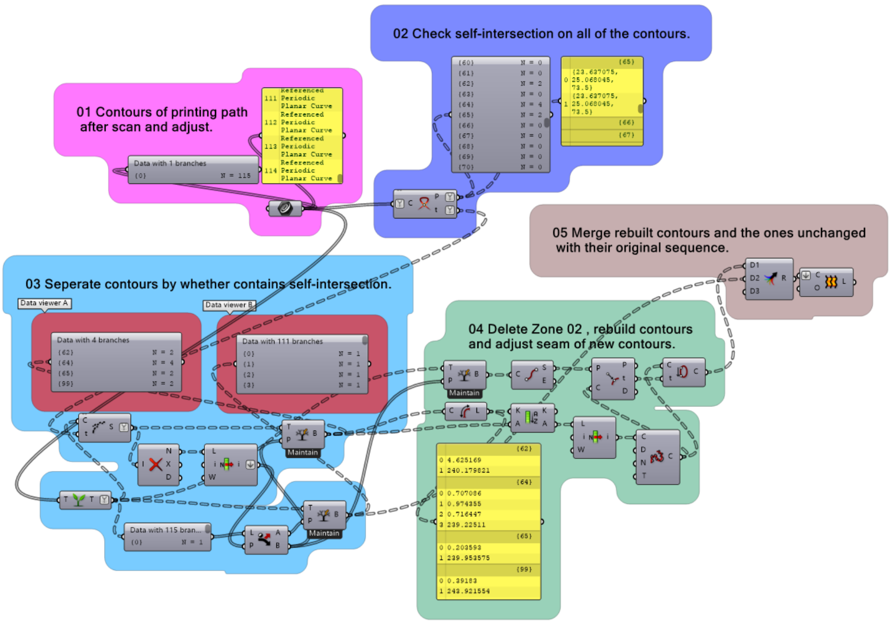


Figure 3.33: Grasshopper program removing self – intersections.

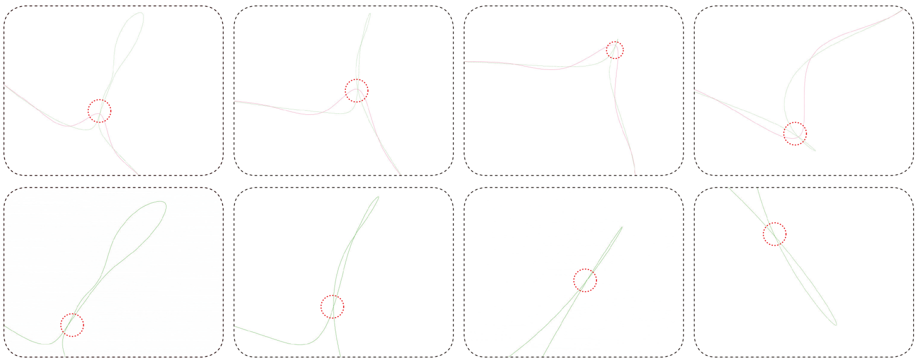


Figure 3.34: Rebuild the contours after modification of self-intersection.

The procedure that implements the elimination of self-intersection is shown in Figure: 3.33. First, contours that have been tested and adjusted for eliminating overhanging parts are picked up into the algorithm by right-clicking the curve component in step 01 (Figure: 3.33). The yellow panel shows a total of 115 planar curves. Second, the self-intersection test is performed on all contours. The test results are shown in Step 02 of Figure: 3.33: counters without self-intersection are displayed as an empty list; counters with the corresponding self-intersection show the exact position where the self-intersection occurs. Third, contours are separated by whether they contain self-intersection while maintaining the original sequence of contours (as shown in data viewer A and data viewer B in Step 03). Fourth, splits contours that have self-intersection at the point where the intersection occurs. In this case, the small closed curve (Zone 02) generated by self-intersection is much smaller than the overall length of the curve. The data viewer in step 04 shows the length of these segmented curves. For instance, on contour 65, the length of the two segmented curves are 0.203593mm and 239.953575mm. Removing these short segmented curves will have little impact on the overall appearance. Thus, the algorithm chooses to remain the longest segmented curve and delete the short ones. However, sharp corners are left after splitting the original contour and deleting the short segmented curves. In order to make it smooth, the modified contours are rebuilt by their controlling points. In Figure: 3.34, the red curves are the reconstruction results after modification for self-intersection, and the green ones are the original contours. Last, the self-intersection modification is completed by combining all contours modified by self-intersection and the list of curves that do not need to be modified in their original order.

Figure: 3.35 illustrates the comparison between the original design and the improved design by Algorithm 03 – optimisation of additive manufacturing. Notably, the overhanging angle is significantly reduced. Meantime, the aesthetic features remain.

3.4.3 Experiment

A simple experiment was conducted to evaluate algorithm 03 – optimisation of additive manufacturing. The experiment was operated on the 3D printer Flashforge Creator 3 (Flashforge Creator 3 FDM 3D Printer Large Build

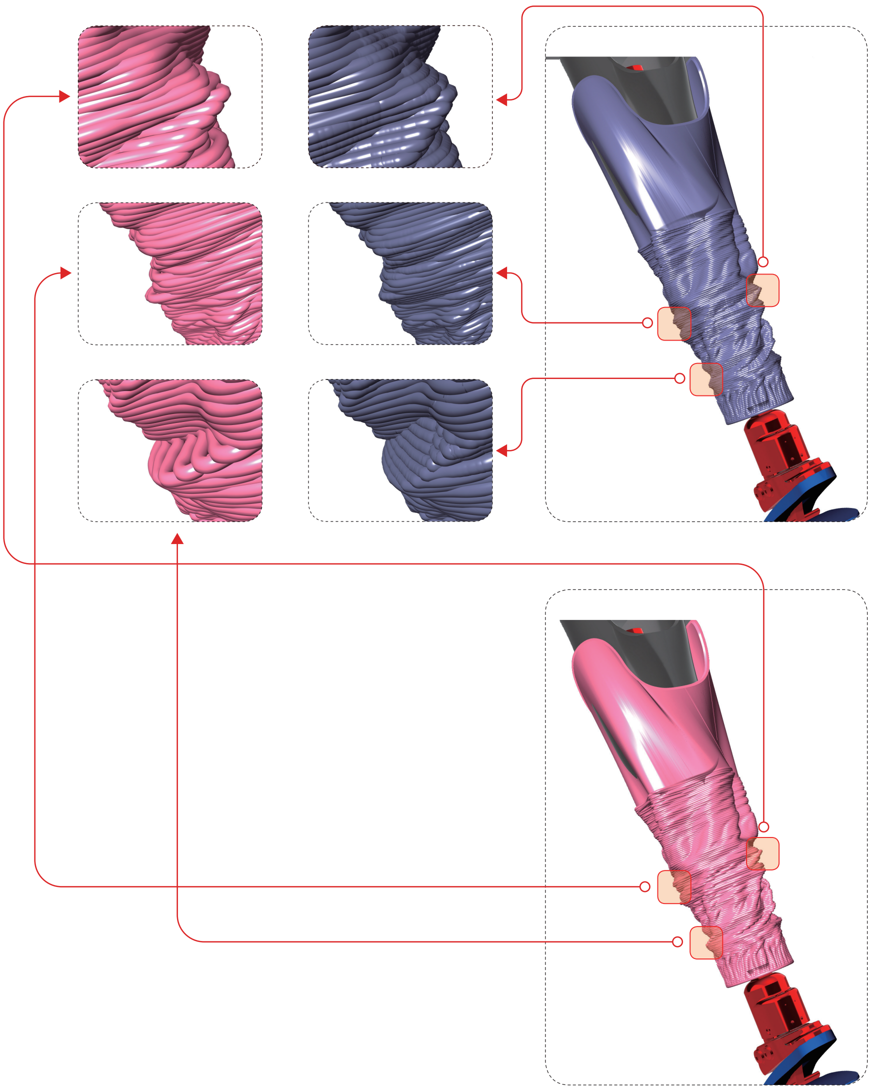
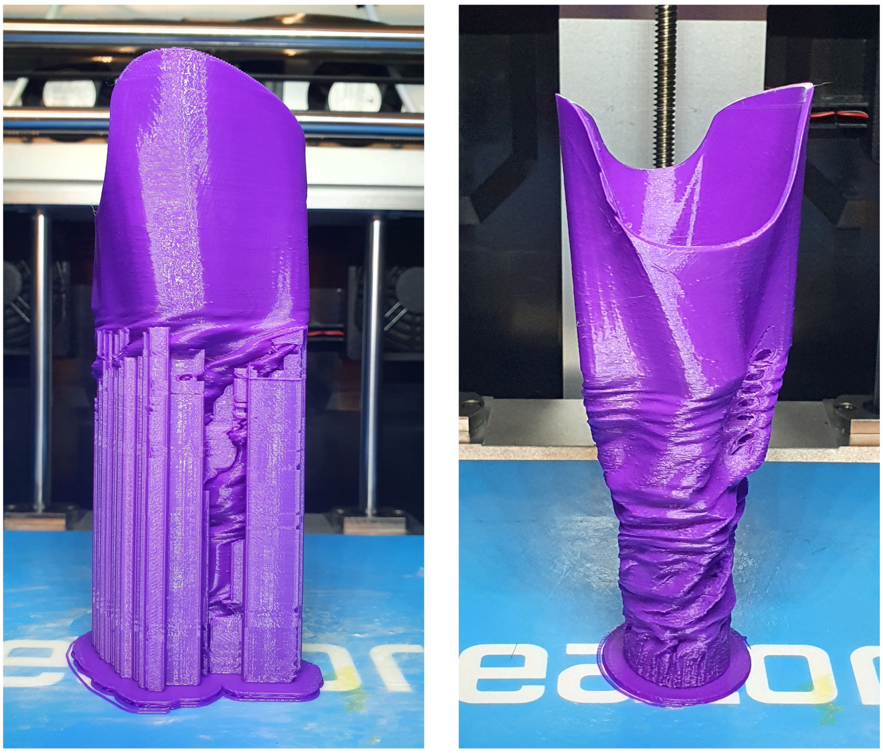


Figure 3.35: Comparison between the original design and the optimised design by algorithm 03.

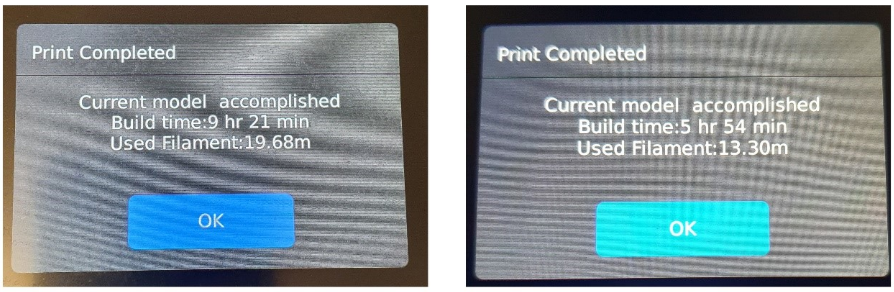
Volume - FlashForge, n.d.) with the material of 1.75mm purple PLA. The model applied to this experiment is the same one being applied to illustrate the logic of algorithm 03 in the above content. However, limited by the size of the printer, the model is scaled as half size of the original model. Two different stages of this design are printed. One is the conceptual design produced by algorithm 02 – leg sculpting. This one is defined as model A. The other is the final design after optimising by the algorithm 03 – optimisation of additive manufacturing. This model is defined as model B. Due to the existence of overhanging on model A, it requires printing supporting structure to support these overhanging parts. In contrast, there is no demand for printing supporting structure for model B, since the overhanging has been eliminated by algorithm 03. Figure 3.39 illustrates the printed models of model B and model A without removing supporting structures. Figure 3.40 illustrates the comparison of time and material consumption of printing model A and model B. It demonstrates that model B without overhanging saves 36.5% printing time and 32.4% material than model A requiring supporting structure.

In summary, the design phase of the present research attempted to fill the identified research gap inefficient approaches for customising personalised aesthetic designs for prostheses. Specifically, three algorithms are developed for this aim. Algorithm 01 - Mogrow was developed based on co-design, generative design and motion capture principles to produce customised archetypes – aesthetic seed, which enables dancers to customise their own aesthetics for designs by dancing-interaction. Algorithm 02 – leg sculpting aimed to further develop the aesthetic seed into a specific conceptual design – prosthetic cover, that was personalised by personal data to fit users' personal body features and simultaneously retain the aesthetic details of the aesthetic seed. At last, algorithm 03 – optimisation of addi-



Model A Model B

Figure 3.36: Comparison of printed models: Model A is the original design, which has to print supporting structures, while model B is the optimised design based on algorithm 03.



Time and material consuming of model A

Time and material consuming of model B

Figure 3.37: Comparison of manufacturing time: Model A is the original design, which has to print supporting structures, while model B is the optimised design based on algorithm 03.

tive manufacturing was developed to increase the manufacturing efficiency by eliminating overhanging parts without obvious modification on appearance. These three algorithms accomplished customising aesthetic designs on the prosthetic cover, by dancer's interaction and without demand on the involvement of professional designers.

As a new approach trying to explore aesthetic customisation of prosthetics, evaluation of aesthetics of design and interacting-design experience is essential. This evaluation was conducted by three user studies, which will be demonstrated in the following chapters.

Moreover, this chapter primarily focuses on aesthetics. However, prosthesis usually has rigorous requirements on their mechanical properties and weight control, which are easy to conflict with aesthetics. A non-planar additive manufacturing platform was developed for balancing requirements of mechanical properties, weight control, and aesthetics, which is the primary aim of the manufacturing phase. These contents will be stated in the next chapter.

Chapter 4

Non-planar additive manufacture platform

4.1 Introduction

The previous chapters presented a co-design approach to producing aesthetic prostheses designs by using the interaction between dancers and the algorithm - Mogrow. The "aesthetic seeds" were firstly produced to capture the dancers' unique interactive experiences. They were applied to aesthetic prosthetic covers. After that, the designs were revised to be made printable without support by eliminating all overhanging parts. The resulting designs were ready to be manufactured. This chapter aims to explore the non-planar additive manufacturing platform as a method of manufacturing customised prostheses with high geometric freedom for aesthetics and light-weighting whilst retaining sufficient mechanical properties.

Figure: 4.1 illustrates the framework of the explored non-planar additive manufacturing platform. It consists of three sections: 6DOF robot (yel-

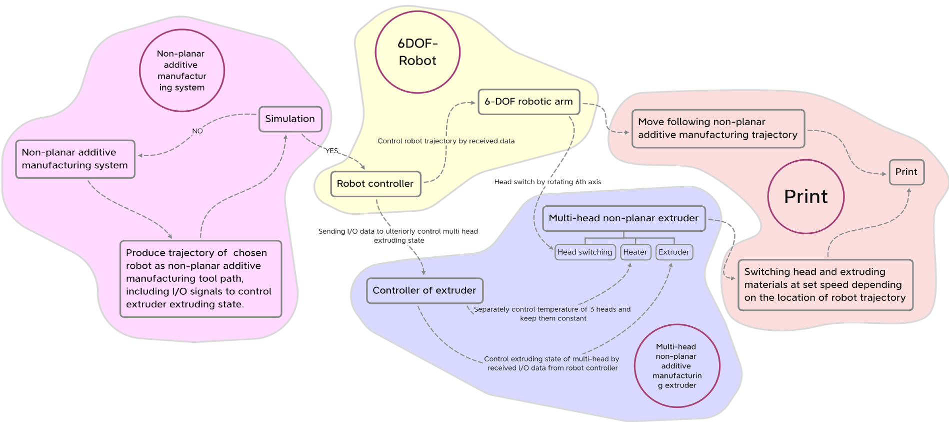


Figure 4.1: Framework of non-planar additive manufacturing platform.

low circle), multi-head non-planar additive manufacturing extrusion system (purple circle), and non-planar additive manufacturing controlling system (pink circle). The red circle in Figure: 4.1 shows the printing operation (experiment). This chapter presents the non-planar additive manufacturing platform by four corresponding sub-chapters: 6DOF (Degree of freedom) robot, multi-head non-planar additive manufacturing extrusion system, non-planar additive manufacturing control system, and experiment, for which, the 6DOF robot represents the commercial industrial 6DOF robot in the market, such as ABB, UR, Kuka etc; the multi-head non-planar additive manufacturing extrusion system represents the printing head and its controller attached to the 6DOF robot to melt, extrude materials and communicate with the controller of 6DOF robot, this device was developed by the author; and the non-planar controlling system is also developed by the author to control the operation of 6DOF robot arm and the multi-head non-planar additive manufacturing extrusion system to conduct non-planar addtive manufacturing.

4.2 6DOF (Degree of freedom) robot

The literature on additive manufacturing by 6DOF robot arms demonstrates the benefits of the high flexibility of 6DOF, long reach, and various payloads, hence, there is an increasing interest in additive manufacturing by 6DOF commercial robot arms in both academy and industry.

In physics, the degree of freedom (DOF) of a mechanical system is the number of independent parameters that define its configuration or state (Degrees of Freedom (Mechanics) - Wikipedia, n.d.). Robot arms are described by their degrees of freedom. This is a practical metric, in contrast to the abstract definition of degrees of freedom which measures the aggregate positioning capability of a system (Paul, 1981). Most conventional 3D printers are based on a 3DOF system, whose tool-paths only contain XYZ coordinates. As the tool head only has a single orientation in which it can reach any given coordinate, this information fully constrains the tool head (Kubalak et al., 2019). On the other hand, a mobile unit's six degrees of freedom are divided into two motional classes (Six Degrees of Freedom - Wikipedia, n.d.). One class is the same as the 3DOF system that consists of translational envelopes: moving forward and backwards on the X-axis (Surge), moving left and right on the Y-axis (Sway) and moving up and down on the Z-axis (Heave) (Figure 4.2). The other one consists of rotational envelopes: tilting side to side on the X-axis (Roll), tilting forward and backward on the Y-axis (Pitch), and turning left and right on the Z-axis (Yaw) (Figure 4.2). Compared with the fact that the 3DOF 3D printer can only move following XYZ coordinates without orientation of the print-head, the 3D printer based on the 6DOF robot arm enables the same translation movement following XYZ coordinates and rotation of the print-head. This is how the 6DOF robot brings higher flexibility to benefit non-planar additive manufacturing.

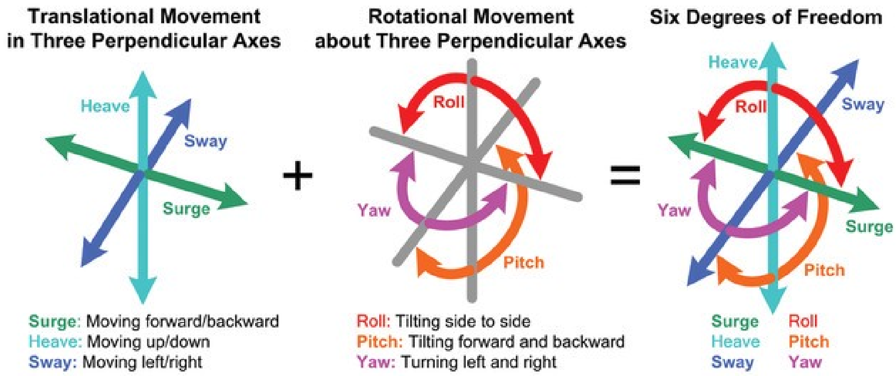


Figure 4.2: Illustration of Six Degrees of Freedom (Narmontas, 2016).

The present research used a Universal Robots UR3e, a collaborative robotic arm with a payload of 3KG, operating radius of 500mm, ±360-degree rotation on all wrist joints, and infinite rotation on the end joint (UR3e Collaborative Robot Arm That Automates Almost Anything, n.d.). As with most other 6DOF commercial robotic arms, it consists of a robot arm and robot controller (Figure: 4.3).

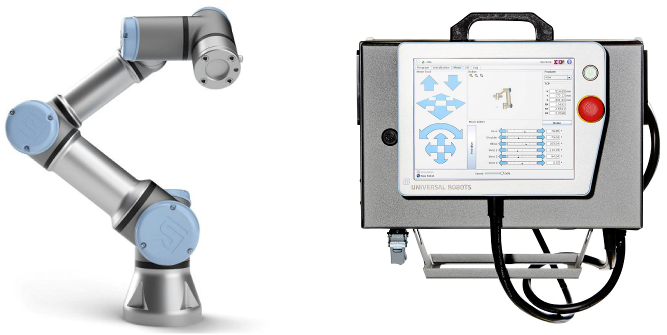
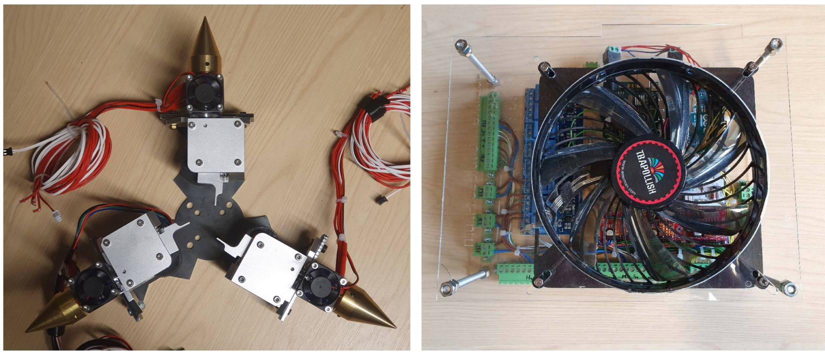


Figure 4.3: Unversal Robots UR3e.



A B

Figure 4.4: Multi-head non-planar additive manufacturing extrusion system.

4.3 Multi-head non-planar additive manufacturing extrusion system

4.3.1 Introduction

There are many commercial 6DOF robotic arms from various brands, e.g. ABB, KUKA, Universal Robots, in the market, which makes it easy to obtain a 6DOF system that is potentially suitable for non-planar additive manufacturing. The next step, then is to fit extrusion and control systems to these commercial robotic arms.

In robotics, an end effector is a device at the end of a robotic arm designed to interact with the environment (Robot End Effector - Wikipedia, n.d.). The exact nature of this device depends on the application of the robot. So for non-planar additive manufacturing, the end effector is an extruder for 3D printing. Specifically, the present research developed a novel multi-head non-planar additive manufacturing extrusion system as an end effector (Figure: 4.4). This consists of an extruder (Figure: 4.4 A) and a controller (Figure: 4.4 B). The extruder was designed as multi-head, which enables multi-material. Recent research in multi-material additive manufacturing has focused on improving mechanical strength, printing speed, and reducing costs associated with the process. Studies have explored various techniques, such as optimizing material combinations, incorporating functionally graded materials, and utilizing novel composite materials to enhance mechanical strength (Liu, Chua, Leong, Lim, 2019). Efforts to increase printing speed have investigated the potential of high-speed sintering and parallel processing techniques, which can significantly reduce the time required for producing multi-material components (Chen, Zhao, Liu, 2020). Additionally, research on reducing costs involves exploring more affordable materials and refining production processes to minimize waste and optimize efficiency (Raz, 2020). These advancements are essential for expanding the applications and accessibility of multi-material additive manufacturing to manufacture aesthetic prosthetics.

The multi-head extruder is attached to the flange at the end of the robotic arm. Then the robotic arm moves it to follow the pre-set toolpath for the 3D printing. Simultaneously, the extruder melts and extrudes filament with a specific speed at a specific location of the toolpath, under the control of the controller. The control of the extrusion speed is conducted by linking the controller of the robotic arm with the controller of the multi-head non-planar additive manufacturing extrusion system. The controller of the extrusion system receives digital I/O signals and then controls the extrusion state of three nozzles, depending on the received digital I/O signals.

This subchapter states the Multi-head non-planar additive manufacturing extrusion system by two sections: multi-head extruder and controller of multi-head non-planar additive manufacturing extrusion system.

4.3.2 Multi-head Extruder

The multi-head extruder is designed following three requirements: compatible with common commercial robotic arms in the market, high flexibility to print different materials, and collision-free. These three requirements permeate the whole design of the multi-head extruder. This section will present the design of the multi-head extruder, starting with its primary components: mounting structure, nozzle, heat-sink & heat-break, and gearbox (Figure: 4.5), then describe the collision avoidance features and finally incorporated them into the extruder design.

Figure 4.5: Multi-head extruder.

Mounting structure

The aim of designing the mounting structure was to support components of the extruder such as gearboxes, heat-sinks & heat-breaks, nozzles etc. and to attach the print head to the flange of the robotic arm. In order to ensure compatibility with the common, commercial robotic arms, this study gathered product information from three primary makers in the

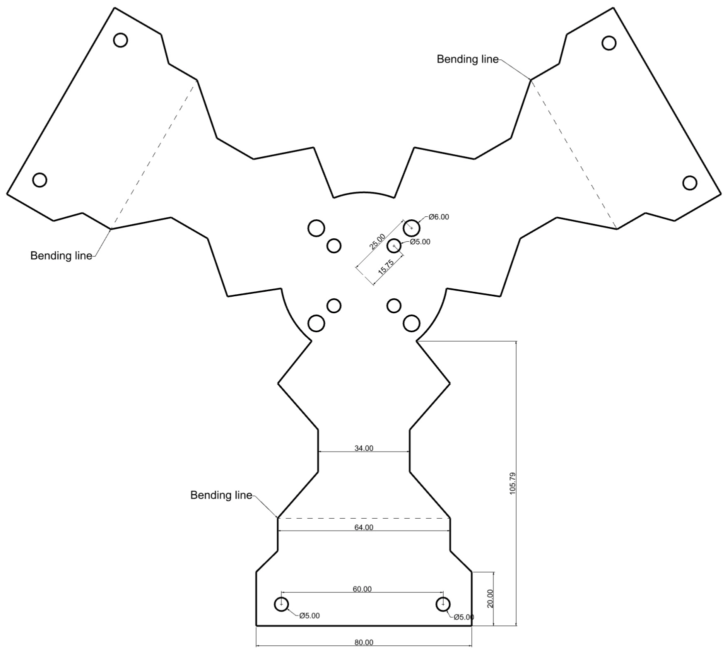


Figure 4.6: Mounting structure.

European market: ABB, KUKA, and Universal Robotics. The mounting structure was designed to fit two sets of robotic mountings: one has four M6 mounting holes located evenly on a circle with a radius of 25mm. The other is connected via four M5 mounting holes located evenly on a circle with a radius of 15.75 mm (Figure: 4.6). This design enables the multi-head extruder to fit the following models of commercial robotic arm: all of the models from Universal Robots (Collaborative Robots from UR — Start Your Automation Journey, n.d.), all models under 16kg payload from ABB(Industrial Robots — ABB Robotics, n.d.) and KR 4 AGILUS, KR AGILUS (Payload 6-10kg, reach 706.7 – 1101 mm, 18 models), LBR iiwa (LBR iiwa 7 R800, LBR iiwa 7 R800 CR, LBR iiwa 14 R820, LBR iiwa 14 R820 CR), KR CYBERTECH nano (Payload 6-10kg, reach 1420 – 1840 mm, 8 models), KR CYBERTECH (Payload 8-22kg, Reach 1612 – 2013mm, 10 models) from KUKA(Industrial Robot — KUKA AG, n.d.).

Hot-end and nozzle

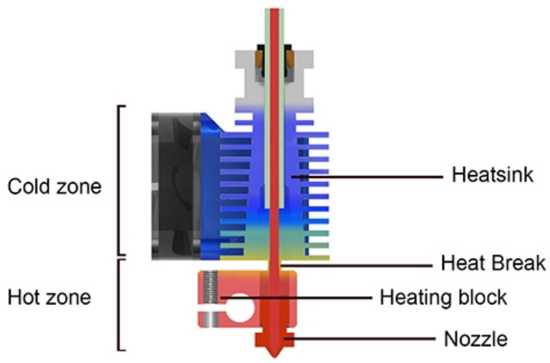


Figure 4.7: Structure of hot-end on the conventional 3D printer.

The hot-end and nozzle elements of the print head are used to melt the filament and deliver material to the work surface. A conventional nozzle is usually designed separately from the heating components (Figure: 4.7). The nozzle for the multi-head extruder was designed to be integrated with the heating components to make a much longer melting tunnel for melting efficiency and shaper nozzle angle was employed to avoid collision (Figure: 4.8).

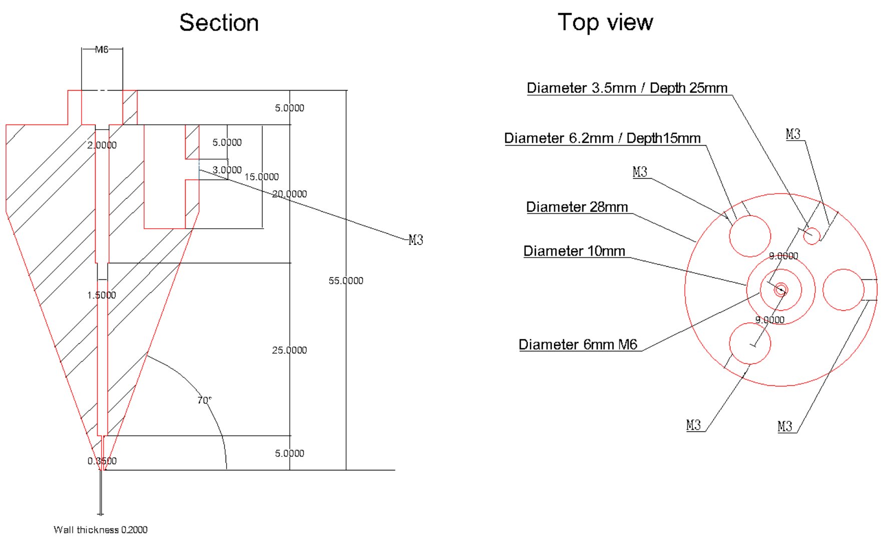


Figure 4.8: Nozzle of the multi-head extruder.

Filament melting in the nozzle follows the process in which the nozzle obtains the heat from the heaters and then conducts to the filament and melt it. The heat conduction between the nozzle and the filament via thermal conduction, which follows the formula for the rate of heat flow:

Q/x= -kA*T/x

Where:

- Q is the net heat (energy) transfer,
- t is the dwell time in the nozzle,
- T is the difference in temperature between the cold (the filament) and hot (nozzle) sides,
- x is the thickness of the material conducting heat (distance between hot and cold sides),
- k is the thermal conductivity, and
- A is the surface area of the surface-emitting heat.

For the same 3D printing filament and nozzle material and design, the values of T and x are constant, once equilibrium has been reached, if k can be assumed to be temperature independent. Then the value Q, the net heat transfer to the filament, only varies with the time taken and surface area. It can be seen from the equation that Q is proportional to the dwell time in the nozzle/hot-end unit and A, the contact area between the filament and the surface-emitting heat. Melting the same amount and type of material requires the same net heat (energy) transfer – the value Q. Thus if A increases t should decrease, and vice versa. In other words, a longer hot end reduces the time taken to melt the filament, thus the melting efficiency is increased. Moreover, rather than a single heater, as used on the conventional hot end of a 3D printer, three heaters are used for each nozzle here to further improve melt efficiency.

The conventional three nozzles of the multi-head extruder were made of brass, which has good thermal conductivity. This material was found to be suitable for tests on various thermal polymers e,g, PLA, ABS, and PETG. Extrusion diameters investigated were 0.35mm, 0.8mm, and 1.2mm, which enabled printing at various different resolutions. The multi-head system also has the capability to incorporate nozzles of other materials, such as stainless steel and hardened steel for printing more abrasive or higher melting point materials, such as Nylon, PEEK, metal filled filaments and continuous carbon fibre.

The heat-sink & heat-break

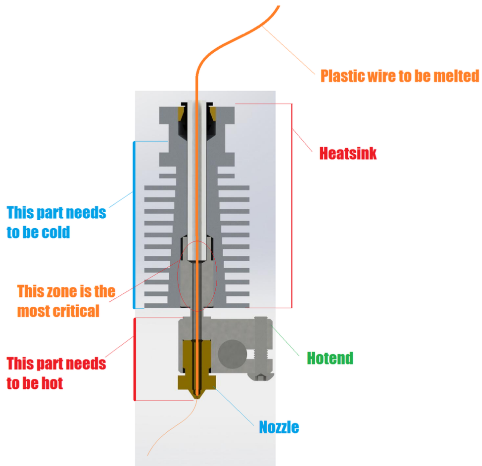


Figure 4.9: Heat-sink and heat-break (Water Cool a 3D Printer Nozzle for Cheap and Easy!: 6 Steps (with Pictures) - Instructables, n.d.).

The heat-sink & heat-break element of the print head is designed to link the gearbox and the nozzle. As described above, the filament is melted in the nozzle/hot-end element of the print head and it is important it doesn't melt before this as half-melted materials can easily block the extruder. Thus the primary function of the heat-sink & heat-break is to isolate the thermal conduction between the cold tunnel (in the gearbox and upper

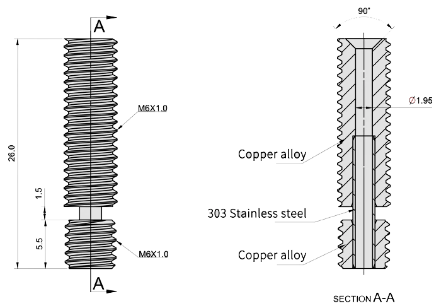


Figure 4.10: Heat-break pipe from E3D V6 Dragon Hot-end (BIQU High Quality Bi Metal Heat-break MK10 MK8 Throat For E3D V6 Dragon Hot-end Heater Block 1.75mm 3D Printer Parts Heat-Break—3D Printer Parts & Accessories— - AliExpress, n.d.).

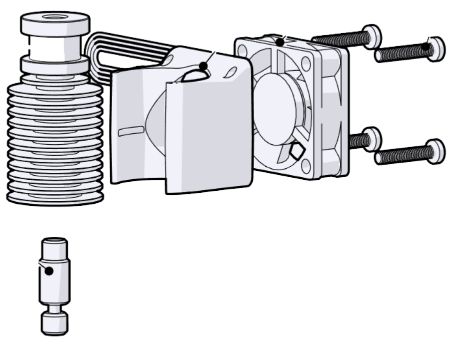


Figure 4.11: Heat-sink and heat-break from E3D V6 (V6 All-Metal Hot-End – E3D Online, n.d.).

part of the heat-break pipe) and the hot tunnel, which is inside the nozzle (Figure: 4.9). In order to achieve heat isolation, the heat-break pipe is usually designed with a thin wall on the connection between cold and hot tunnels. Figure: 4.10 illustrates the heat-break pipe from an E3D V6 Dragon Hot-end, in which the connection between cold and hot tunnels is made of 303 stainless steel. This material has strong mechanical properties to avoid breaking from the thin wall and poor thermal conduction to achieve thermal isolation between cold and hot tunnels. In order to dissipate heat passing to the cold tunnel, a heat-sink and fan are used. The heat-sink & heat-break components of an E3D V6 were used in the present extruder (Figure: 4.11). Moreover, the multi-head extruder was designed to fit most heat-sinks & heat-breaks on the market to enable easy switching to fit various materials. For instance, the heat-break of Dragon Hot-end WHF from Pheatus enables printing materials with high-temperature requirements like PEEK.

Gearbox & motor

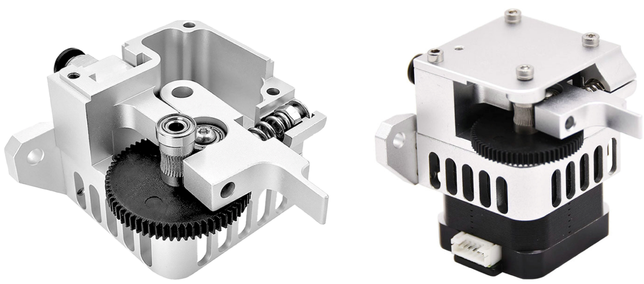


Figure 4.12: Gearbox for the multi-head extruder.

The gearbox was designed to push the filament into the nozzle for melting and extrusion. A gearbox was developed based on the Titan extruder from E3D ((Titan Extruder – E3D Online, n.d.) Figure: 4.12 illustrates the gearbox for the multi-head extruder. It consists of a 3:1 gearing ratio allowing lighter motors to apply a stronger pushing force on the filament. The gearbox is mainly made of aluminium, which can operate at higher temperatures than plastics. This design aims to match the requirement of high-performance materials, such as PEEK, requiring a chamber temperature of 120℃. The feeder gear is the component directly contacting with the filament. There are two types of feeder gears for the gearbox of the multi-head extruder. One is for 1.75mm filament (Figure: 4.13 A). It consists of concave teeth to increase the touch area with filament and avoid sliding even at high pressure. The other one is for continuous fibres reinforced filament, which is much thinner than standard filament, with a diameter of 0.6mm. So the feeder gear in this case is straight teeth to make sure the thinner filament can be touched (Figure: 4.13 B).

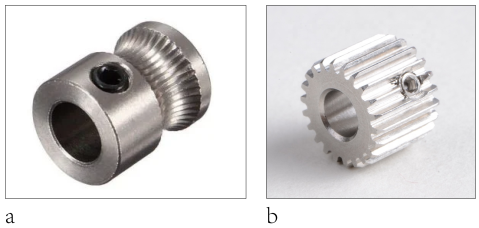


Figure 4.13: Feeder gears with concave teeth and straight teeth.

The mounting structure enables the multi-head extruder's broad applicability to commercial 6DOF robotic arms. At the same time, its broad adaptability to various materials is achieved by the nozzles made from various materials, the broad adaptation to various heat-sinks & heat-breaks for 1.75mm filament in the market, the gearbox made of aluminium with two types of feeder gears, and three print-heads for multi-material manufacturing. For instance, continuous carbon fibre reinforced PEEK additive manufacturing can be applied by the multi-head extruder with the following components. The nozzles are made from hardened steel, avoiding erosion by carbon fibre. Furthermore, the heat-sink & heat-break of Dragon Hotend WHF from Pheatus is applied for higher temperature resistance. In addition, the feeder gear with straight teeth is applied to extrude the carbon fibre reinforced thin filament. Moreover, the three heads enable carbon fibre reinforced PEEK additive manufacturing by applying supplementary materials, e.g. material for printing support.

Design adaptations for collision-free printing

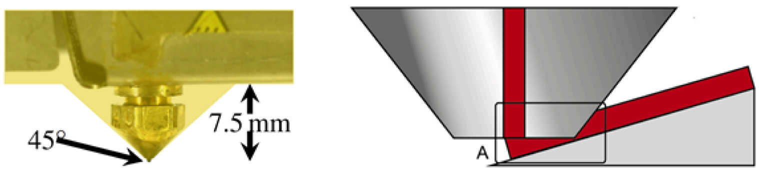


Figure 4.14: Two factors affect collision in non-planar additive manufacturing application by the conventional three-axis 3D printer (Ahlers et al., 2019; Pelzer & Hopmann, 2021).

Collision is a non-negligible problem in multi-axis non-planar additive manufacturing. There are three features of conventional 3D printing logic: the print-head remains vertical, all layers are two-dimensional and keep constant heights within the same layers, and layers are built from bottom to top. These three features ensure a collision-free printing process. However, for non-planar additive manufacturing, the layers are usually 3D surfaces that cross various heights, which makes for easy collision between the print-head and printed object. Moreover, the print-head is rotating in multi-axes (five axes or more), which aggravates the likelihood of a collision.

Some researchers have explored solutions to this problem from both printing logic and hardware design. For printing logic, Wu et al.(2016) explored an algorithm for generating collision-free toolpaths for wireframe models. Huang et al. (2016) considered stability constraints in the manufacturing process together with collision-free constraints. Dai et al. (2018) developed a convex-front governed approach that can always ensure collision-free working surfaces for material accumulation. For hardware design, researchers explored two factors that affect collision in non-planar additive manufacturing by traditional three-axis 3D printers. One is the angle of printing that takes the whole extruder into account, including the nozzle, heat sink and gearbox (Ahlers et al., 2019), as illustrated in Figure: 4.14. This angle of printing affects applying materials into valley geometries. When this angle is bigger, the issue of collision with neighbouring geometry is less and highly curved layers are allowed. The other factor on hardware is the wall thickness of the nozzle tip. Conventional nozzles are built with a flat bottom to flatten any excess material. Applying it to non-planar additive manufacturing, it easily interferes with and scratches previously manufactured slopes (Pelzer & Hopmann, 2021) (Figure: 4.14). Considering these two factors affecting collision in three-axis non-planar additive manufacturing, the present research analyses the problem of collision in additive manufacturing by the 6DOF robotic arm and proposes strategies to avoid these collisions in terms of hardware design.

The nozzle remains vertical while printing with a three-axis machine. In contrast, the nozzle can rotate to remain perpendicular to the work-surface in the non-planar additive manufacturing process with a 6DOF robotic arm. Thus the collision state relative to the printing angle is different in non-planar additive manufacturing by a 6DOF robotic arm. The other factor – wall thickness is less of a problem with six-axis non-planar additive manufacturing as nozzle rotation can usually ensure it is perpendicular to the work-surface. However, there are some situations where this is not possible, such as printing in a deep valley, which requires the nozzle to be angled to the work-surface to avoid the collision. Thus, to minimise this problem, the wall of the nozzle tip was designed as thin as possible at 0.2mm (Figure: 4.8)

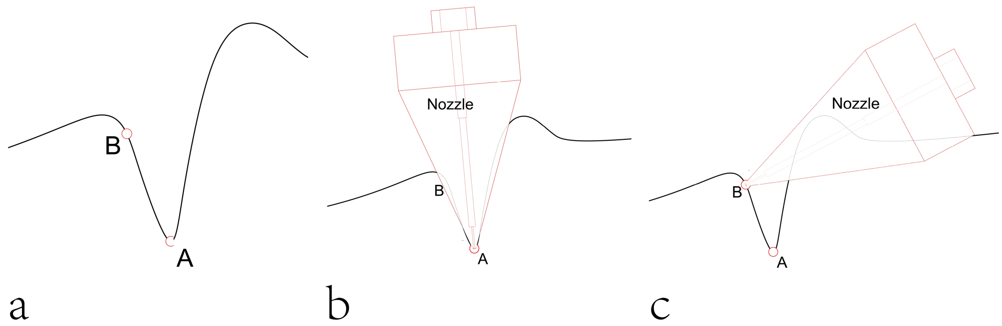


Figure 4.15: Illustration of bottom collision and side collision.

As stated above, the factors that affect collision in six-axis non-planar additive manufacturing are partly different from those with a three-axis machine. Figure: 4.15 illustrates the two collision situations in six-axis non-planar additive manufacturing: bottom and side collisions. The curve in Figure: 4.15a represents a side view of a non-planar 3D printing toolpath. Point A in Figure: 4.15a represents the lowest point in the valley geometry, while point B represents the points on the side of the valley. Figure: 4.15b illustrates the collision situation at point A, which shows no accessibility to the valley's lowest point because the nozzle angle is wider than the valley. It is defined as a bottom collision. While Figure: 4.15c illustrates the collision that happens during printing the sides of valley geometries – when the nozzle remains perpendicular to the printing path on the side of the valley geometry, the collision happens between the nozzle or extruder and the printed parts. This collision state is defined as a side collision. The bottom and side collisions this defined can classify most collision situations in six-axis non-planar additive manufacturing. The bottom collision is triggered by the valley being narrower than the nozzle or extruder, which is not adjustable with printing logic and requires mechanically modifying the nozzle geometry. In contrast, the side collision is triggered by attempting to maintain a perpendicular print angle, which is adjustable by changing the print angle to avoid collision.

Terms definition		
Feature name	Feature symbol	Value
Valley angle	Va	34°
Valley depth	Vd	16.49 mm
Side collision distance	Scd	10.37mm
Nozzle angle	Na	40°
Effective nozzle distance	End	88.47 mm
Effective extruder distance	Eed	
Extruder angle	Ea	49.9°

Figure 4.16: Terms definition.

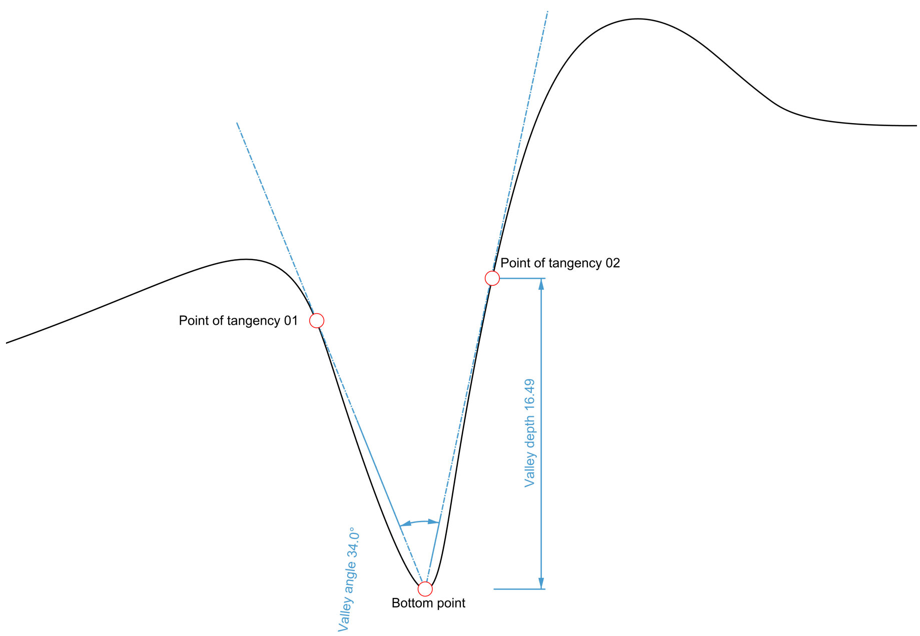


Figure 4.17: Valley angle and valley depth.

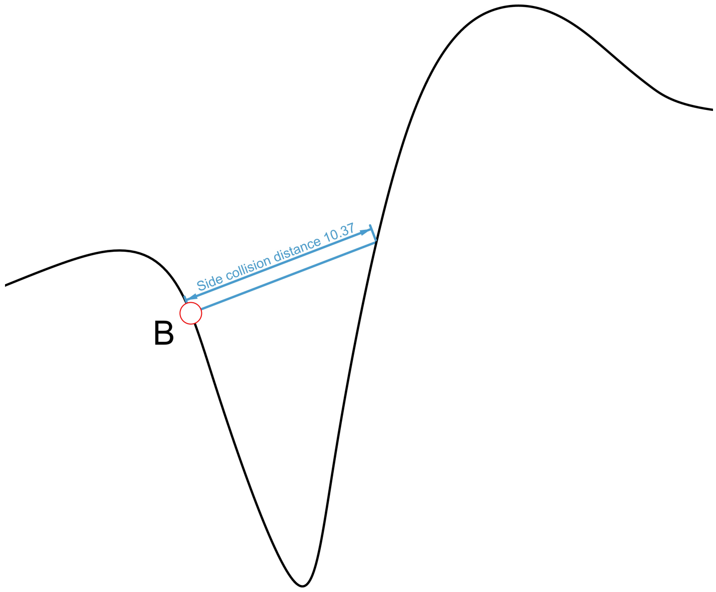


Figure 4.18: Side collision distance.

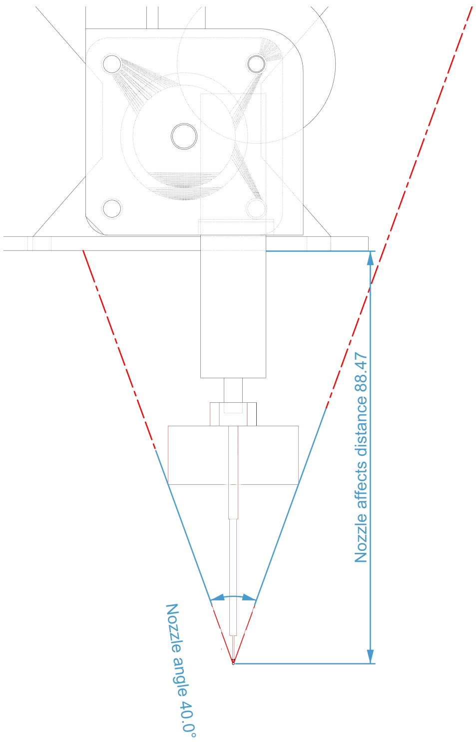


Figure 4.19: Effective nozzle distance and nozzle angle.

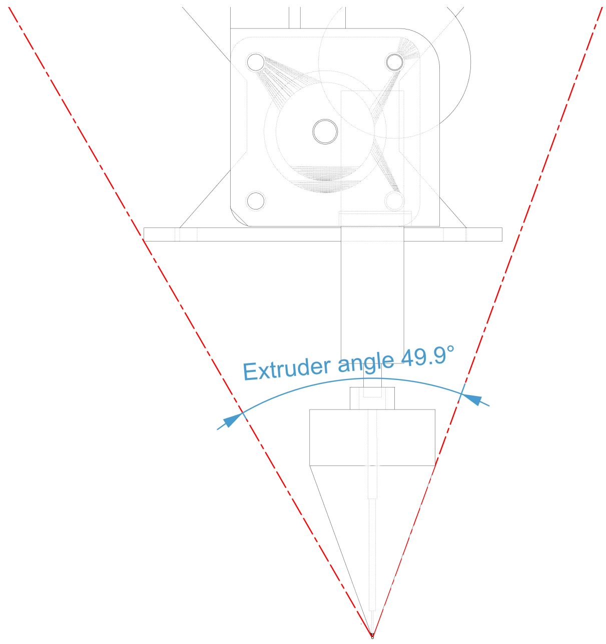


Figure 4.20: Extruder angle.

Several values need to be defined to illustrate the requirements of collision free printing, as illustration of Figure: 4.16. Figure: 4.17 illustrates the values of valley angle (Va) and valley depth (Vd). The valley angle is the angle between two tangent lines of both sides of a valley geometry that start from the bottom point. The valley depth is the distance between the bottom point and the higher point of tangency in the vertical direction. The side collision distance (Scd) is the length of the line starting at a point on one side of a valley and ending at the cross point produced by the intersection between the vertical line of the printing path starting at this side point and the other side of the valley (Figure: 4.18). Several values relative to the nozzle and extruder also need to be defined. Figure: 4.19 illustrates the nozzle angle (Na), and the effective nozzle distance (End). The nozzle angle means the angle of the nozzle tip. At the same time, the effective nozzle distance represents the distance in the vertical direction between the nozzle tip and the highest point that nothing over the angle of the nozzle. The distance exceeding the effective nozzle distance is defined as effective extruder distance (Eed). Figure: 4.20 illustrates the extruder angle (Ea) representing the smallest angle starting with the nozzle's tip covering the whole extruder.

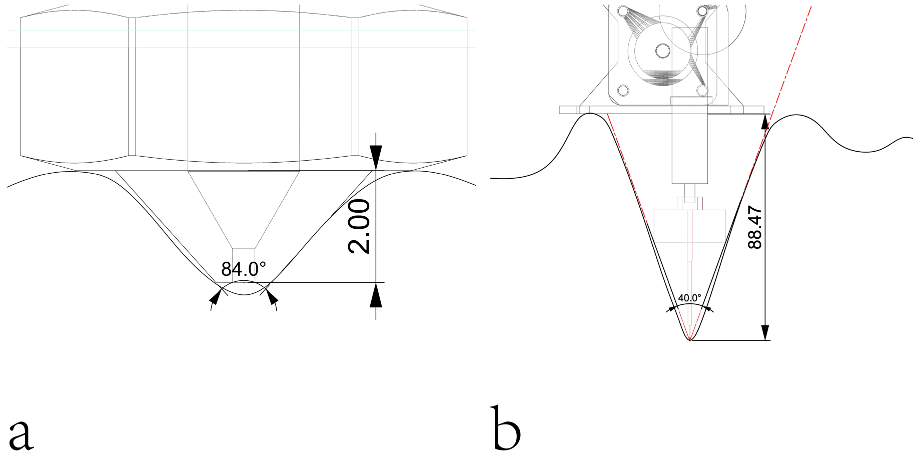


Figure 4.21: The narrowest and deepest valley geometric toolpath within the effective nozzle distance.

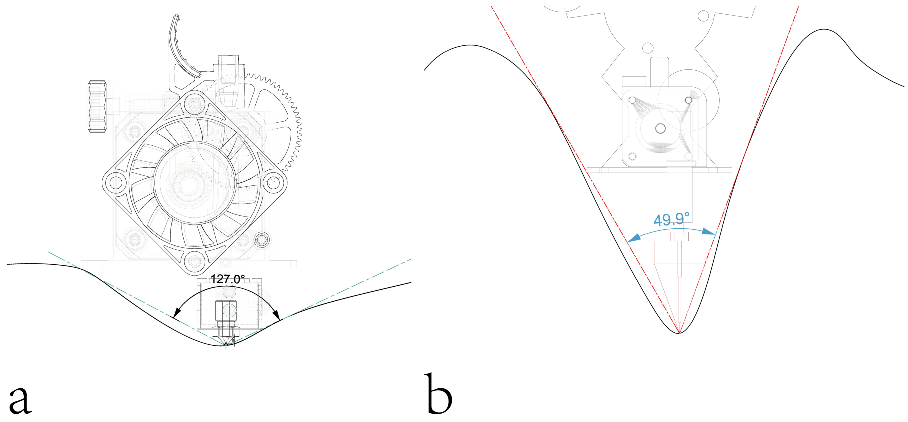


Figure 4.22: The narrowest valley geometric toolpath within the effective extruder distance.

For the bottom collision, there are two different situations. One is within effective nozzle distance, meaning the Vd is smaller than the End. In this situation, the collision only happens when the Na is larger than the Va. The other is within the effective extruder distance meaning the Vd is bigger than the End, in which the collision happens when the Ea is bigger than the Va. Figure: 4.21A illustrates the narrowest and deepest valley that can be printed by conventional extruder within the effective nozzle distance. In contrast, Figure: 4.21B illustrates the narrowest and deepest valley that can be printed using the multi-head extruder designed in this work. It shows that the valley that can be printed by the multi-head extruder is much deeper and narrower than the one that can be printed with the conventional extruder. The following strategies bring this freedom of printing, avoiding the bottom collision. The integrated design of the nozzle and heat component enables a much longer nozzle, allowing a sharp tip. In addition, the separated heat-sink from the gearbox significantly extends the effective nozzle distance. Figure: 4.22 illustrates the valley angle of the narrowest valley geometric toolpath with the effective extruder distance of the conventional extruder – E3D Titan Aero Extruder and the multi-head extruder. It is noticeable that when it is within the effective extruder distance, the conventional extruder can only print valley geometry with the Va of 127°. In contrast, the multi-head non-planar extruder can print the valley geometry with the Va of 49.9°. Therefore, the printing flexibility avoiding the bottom collision of the multi-head extruder is much higher than the conventional 3D printing extruders within both of the effective nozzle distance and effective extruder distance.

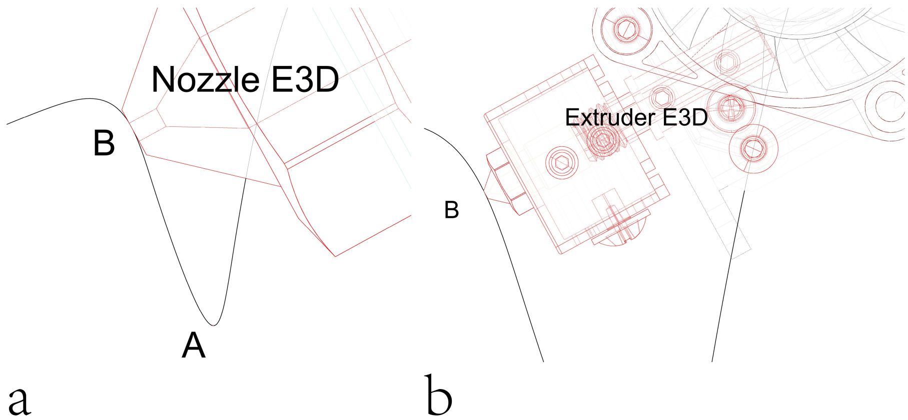


Figure 4.23: Side collision of the conventional extruder.

The side collision also happens within the effective nozzle distance, and the effective extruder distance. Figure: 4.23 illustrates the side collision of the

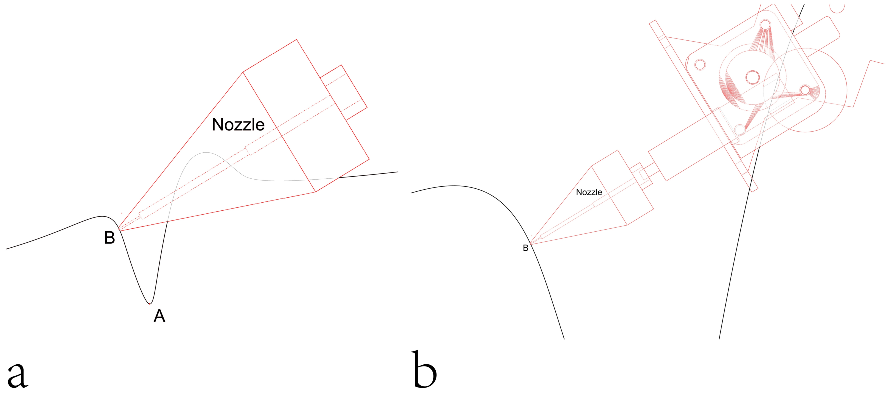


Figure 4.24: Side collision of the multi-head non-planar additive manufacturing extruder.

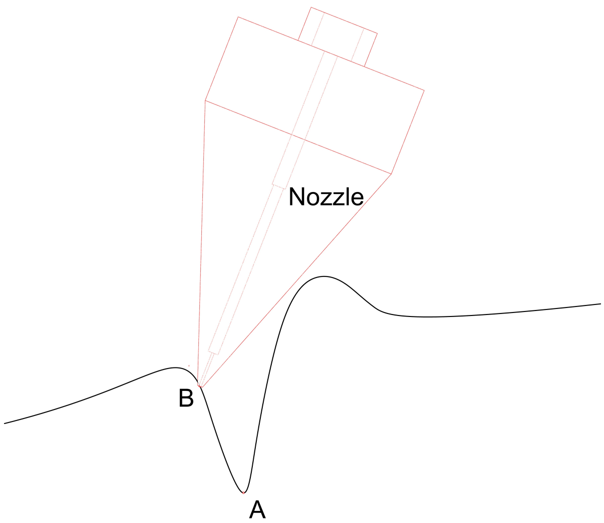


Figure 4.25: Lean nozzle to avoid the side collision.

conventional extruder. It is noticeable that the conventional extruder can rarely print vertically with the toolpath on the valley side, neither within the effective nozzle distance nor the effective extruder distance, since the Na and the Ea are both too big to avoid collision with the other side of the valley. Figure: 4.24 illustrates the side collision of the multi-head extruder. When the End is bigger than the Scd, the side collision needs to consider the nozzle itself (Figure: 4.24a). When the Ned is smaller than the Scd side collision, the side collision should consider the whole extruder (Figure: 4.24b). However, if the nozzle constantly keeps vertical with the printing path, even the nozzle angle is as sharp as 0°, a collision can still occur on the valley side. Thus, to avoid the side collision, the nozzle has to lean to make it printable (Figure: 4.25). This was achieved in this work through toolpath calculation. The toolpath with nozzle verticle with printing path is maximised to eliminate the collision effect of the wall thickness of the nozzle tip. At the same time, the nozzle is angled to avoid side collision.

To summarise, collision-free printing is achieved by maximising the nozzle effect distance, minimum the nozzle's angle by integrating the heat component with the nozzle, and leaning nozzle at the valley side.

4.3.3 Controller of multi-head non-planar additive manufacturing extrusion system (Figure: 4.26)

The previous section describes the mechanical part design of the multi-head non-planar additive manufacturing extrusion system. This section will present its controller, which was designed to separately control the temperature of the three nozzles, read the digital I/O signal from the robotic arm's controller and separately control the extrusion speeds of three mo-

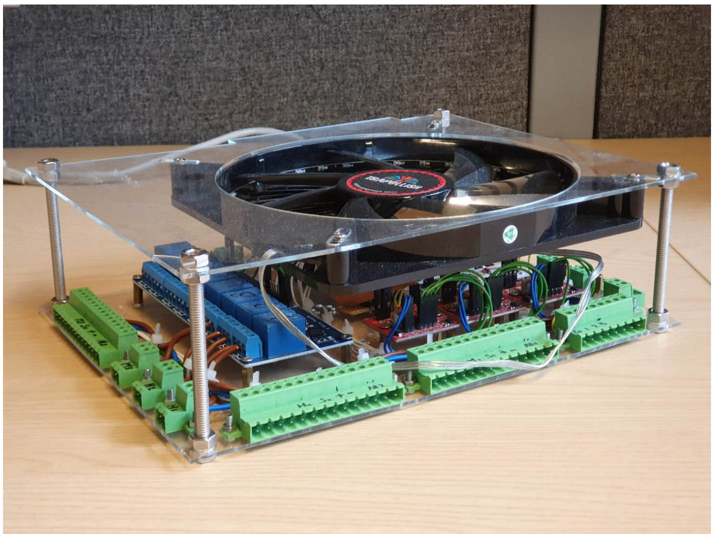


Figure 4.26: The controller of multi-head non-planar additive manufacturing extruder.

tors, depending on the received I/O signal.

Arduino

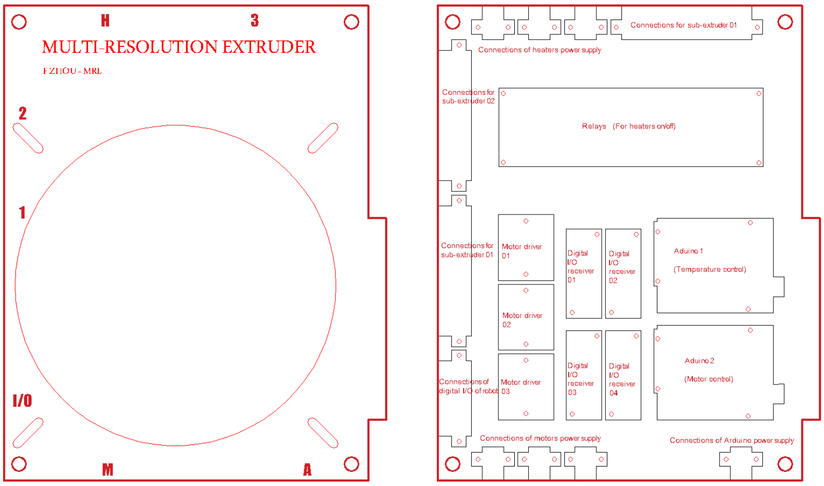


Figure 4.27: Design of the controller of the multi-head non-planar additive manufacturing extrusion system.

Figure: 4.27 illustrates the design of the controller. It is designed based on two Arduinos. One is for temperature control, while the other is for extrusion control. Arduino is an open-source electronics platform based on easy-to-use hardware and software (What Is Arduino? — Arduino, n.d.).

Temperature control circuit

The temperature control circuit is used to individually maintain constant temperatures for the three nozzles. Their temperature must be constant for melting material and continuous extruding. However, the constant temperatures for the three nozzles can vary to accommodate multi-material printing. The temperature control circuit consists of the following components. Nine heaters at 40W 12V (three for each nozzle) to supply sufficient heat to keep nozzles at a constant temperature. Three PT100 temperature sensors are used to measure the temperatures of the three nozzles. These can work with temperatures as high as 500℃, which is applicable to high-performance polymer, e.g. PEEK requiring printing temperature of 350 to 400℃. The working procedure of the temperature control circuit is as follows.

- 1, When the temperatures of nozzles change, the corresponding PT100 thermal sensors' value of resistance changes.
- 2, Once the resistance values of thermal sensors change, the voltage on the other resistors connected with the corresponding thermal sensor will change.
- 3, Arduino reads these voltages and calculates the current temperature.
- 4, Three target temperatures for the three nozzles are preset and constantly compared with the corresponding measured temperatures.
- 5, When any measured temperature is larger than the corresponding target one, the corresponding relay is turned off. When the measured temperature is smaller than the corresponding preset one, the corresponding relay is turned on to start heating. Thus the three relays

are continuously turned on and off to keep the constant temperatures of the three nozzles.

Motor control & I/O signal read

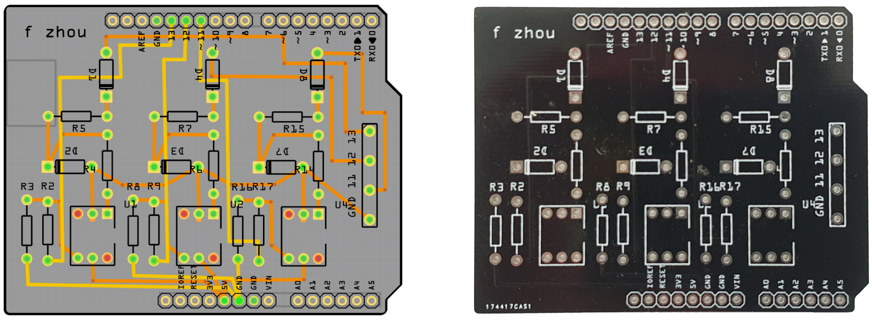


Figure 4.28: PCB design for reading I/O signal from commercial robotic arm controller.

In order to control the extrusion state of the three print-heads, there is a need for constant data exchange between the robot controller and the controller of the extrusion system. Different parts of the print toolpath will have different requirements for material depositing speed, which needs to be controlled by sending data from the robot controller to the extruder controller to ensure extrusion at a specific velocity at a specific location. The same logic is also applied to head switching. When there is a requirement for switching print heads (for material or printing resolution switching), data needs to be sent from the robot controller to the controller of the extruding system. The current nozzle will then stop extruding material and after the nozzle is switched, the new nozzle will start extruding. Hence, enabling the extrusion system to exchange data with most commercial 6DOF robotic arms is a significant factor in ensuring broad applicability to various robotic arms. Through analysis of commercial 6DOF robot arms, it is noticeable that most of them conduct data communication with exterior facilities by 24V Digital I/O. For instance, there are dedicated eight digital outputs, with the possibility to expand with eight configurable and additional two outputs at the tool flange, on Universal Robots: UR3e, UR5, and UR10. (Universal Robots - Connecting Internal Inputs and Outputs (I/O) on the Robot's Controller, n.d.) For the brand of the robot – ABB, IRC5C Compact Controller that is applied to various models of ABB robotic arm, has a built-in expandable 16 in, 16 out I/O system (ABB, 2019). Thus, the controller of the multi-head non-planar additive manufacturing extruding system is designed to receive 24V I/O signals.

The motor control circuit was built based on the Arduino, which only reads 5v digital I/O signals. Thus enabling Arduino to read the digital I/O signals from the robotic arm requires transferring the 24v digital I/O signals into 5v. Figure: 4.28 illustrates the PCB of the digital I/O board designed for this aim. It contains three cells of voltage transformer, which allow reading 24v digital I/O signals from three digital output pins of the robotic arm. Each digital output pin has two states as On and Off, which means that three digital I/O pins can produce eight different combinations as follows: ON/ON/ON, OFF/ON/ON, ON/OFF/ON, ON/ON/OFF, OFF/OFF/ON, OFF/ON/OFF, ON/OFF/OFF, and OFF/OFF/OFF, calculated as $2\hat{3}$=8. Thus, the Arduino can set eight combinations of three motors' extrusion speeds. When two I/O boards are applied to communicate with the controller of the robotic arm, there are six transformer cells, which means 64 combinations of three motors' extrusion speed. The present research applies two I/O boards, which can be increased as needed.

Components for motor control include three 42 step motors, three big easy drivers from Sparkfun for motor control, and an Arduino Uno. The process of controlling extrusion speed is present as follows:

- 1, I/O boards receive 24V digital I/O signals from the robotic arm's controller.

- 2, I/O boards transfer the 24V digital I/O signals into 5V digital I/O signals and send them to the Arduino through Arduino's Digital pins.
- 3, The Arduino reads the digital I/O signals and sends the pulse signals to the corresponding big easy drivers to control the motor rotating speed with the corresponding preset speed.

4.4 Non-planar additive manufacturing control system

The non-planar additive manufacturing control system developed in this work aims to create an integrated system for the application of non-planar additive manufacturing by a 6DOF robotic arm. Its integrated function consists of slicing 3D models following a non-planar logic, producing a non-planar additive manufacturing toolpath for a commercial 6DOF robotic arm and providing an interface for controlling print details and conducting print simulation (yellow components in Figure: 4.29).

4.4.1 Platform

The non-planar additive manufacturing control system was developed based on the platform Rhino and Grasshopper (Rhino - Features, n.d.-b). Rhino is popular with 3D designers. It was chosen as the fundamental platform by evaluating four factors: accuracy, modelling, visualisation and plugin of Grasshopper. As an engineering application, accuracy is the primary requirement for 3D printing. Modelling in Rhino is based on Non-uniform ra-

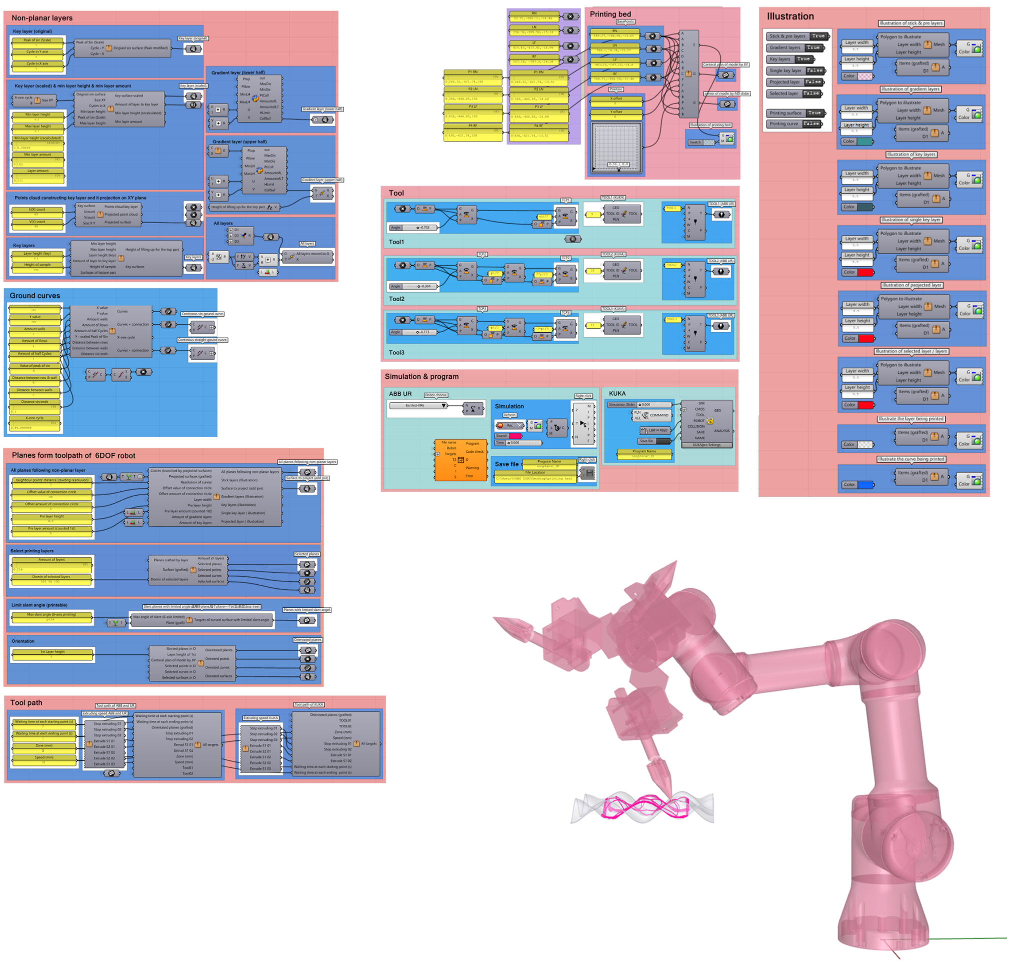


Figure 4.29: Non-planar additive manufacturing control system

tional basis spline (NURBS), a mathematical model using basis splines (B-splines) that is commonly used in computer graphics for representing curves and surfaces. It offers great flexibility and precision for handling both analytic (defined by common mathematical formulae) and modelled shapes. NURBS curves are commonly used in computer-aided design (CAD), manufacturing (CAM), and engineering (CAE). They are part of numerous industry-wide standards, such as IGES, STEP, ACIS, and PHIGS (Non-Uniform Rational B-Spline - Wikipedia, n.d.). So Rhino is accurate enough to represent design for additive manufacturing. The second factor is modelling. The first job before conducting additive manufacturing is modelling, editing or directly importing the existing models. Rhino can create, edit, analyse, document, render, animate, and translate NURBS curves, surfaces and solids, subdivision geometry (SubD), point clouds, and polygon meshes (Rhino - Features, n.d.-a). In addition, real-time visualisation is required during the process of designing a 3D printing toolpath and virtual simulation. As a mature modelling software, the display response of Rhino is fast. (Rhino - Features, n.d.-a)

A significant advantage of using Rhino over similar software packages is a plugin application called Grasshopper. Grasshopper is a visual programming language and environment that runs within the Rhinoceros 3D computer-aided design (CAD) application. In computing, a visual programming language (VPL) is any programming language that lets users create programs by manipulating program elements graphically rather than by specifying them textually. (Jost et al., 2015) Grasshopper was created by David Rutten at Robert McNeel & Associates. (Rutten, 2021) Programs are created by dragging components onto a canvas. The outputs to these components are then connected to the inputs of subsequent components. Besides, VB, C#, Python programming language is also supported for more flexibility in programming. Grasshopper is primarily used to build generative algorithms (Loomis, 2010) (Loomis, 2011). Using Grasshopper, users can make rapid changes or explore many variations of 3D models using algorithms or simple commands. The automatic process of non-planar model slicing, printing toolpath calculation, and modification of printing details by parameters are all programmed in Grasshopper.

Grasshopper's interface simplifies the creation of complex models, and with the right plugins – it allows for other abilities such as robot control. (Donovan, 2020) According to incomplete statistics, Grasshopper includes 131 Addons and 6084 components of various fields. Each of the Addons consisting of multiple components is a package of a specific application such as Geometry & Meshes, AI Agent simulation, AI Machine learning, Animation & Physics, Electronic Robot Control, Structural Analysis & FEM, 3D printing & Fabrication and so on (Rodricks, n.d.). Specifically for 6 DOF robot arm control, there are 15 Addons (Figure: 4.30) (Godwyll, 2021). Two of these Addons – Robots and KUKA PRC were used in this research. The Addon–Robot can broadly work with ABB, KUKA and UR robots. While the KUKA PRC only works with KUKA robots. However, KUKA PRC is the only Addon of Grasshopper that can control the seven-axis robot arm KUKA IIWA. Thus the combination of two Addons – Robot and KUKA PRC can work with all of the 6 DOF and 7 DOF robots from ABB, KUKA and Universal Robots. Figure: 4.29 illustrates the integrated control system for robotic arm additive manufacturing, developed based on Robots and KUKA PRC.

NAME	PRICE	KUKA	ABB	UR	other robot brands	Operating systems*	Link
Robots	**Free** (open source)	✅	✅	✅	Staubli	Win MacOS	github
MACHINA	**Free** (open source)	✅	✅	✅	❌	Win	Food4Rhino github
Furobot	**Free**	✅	✅	✅	custom Robot creation inside gh	Win	Food4Rhino Website
HAL Robotics	£800/yr £60/yr (academic) Free trial	✅	✅	✅	❌	Win	Food4Rhino(old) Food4Rhino(new) Website
Axis	**Free** (open source)	❓	✅	❌	custom Robot creation inside gh	Win	github
Robot Components	**Free** (open source)	❌	✅	❌	❌	Win	github Food4Rhino Documentation
KUKA PRC	Free (limited) 450€/yr 95€/yr (Student)	✅	❌	❌	❌	Win	Food4Rhino Website
Taco ABB	**Free**	❌	✅	❌	❌	Win	Food4Rhino Website
Taco HIWIN	**Free**	❌	❌	❌	HIWIN	Win	Food4Rhino Facebook
RoboDK	Free trial 145€(Edu) 2995€(Pro)	✅	✅	✅	many others see here	Win + Others (standalone App)	Food4Rhino Website
Cobra	**Free** (open source)	KR6-10R900	❌	❌	❌	Win	Food4Rhino github
Robot Fabrication Design	**Free**	KR 120 R2500	❌	❌	❌	Win	Food4Rhino Website
Scorpion	**Free** (open source)	❌	❌	✅	❌	Win	Food4Rhino
~~Rapcam~~	150€/month Free trial	✅	✅	❌	Fanuc	Win	~~Food4Rhino Website~~
~~ROBOTS IO~~	£166 /yr (Edu) £1999 /yr (Pro)	✅	✅	✅	Fanuc	Win	Developer Website Forum Archived Website

Figure 4.30: Grasshopper plugins for 6DOF robotic arm control (Godwyll, 2021).

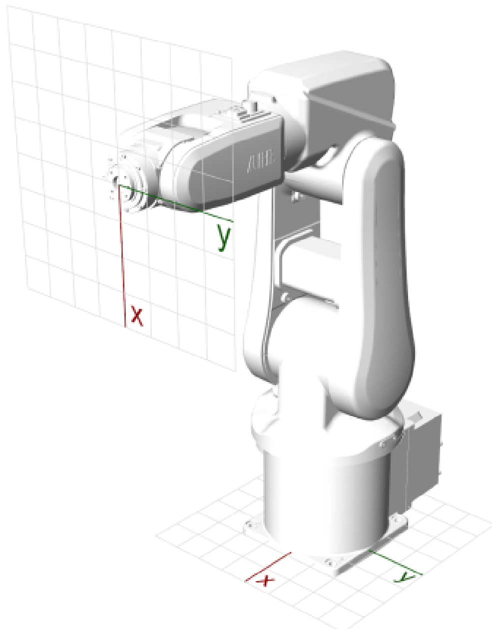


Figure 4.31: Coordinate system of the 6DOF robotic arm (Home Visose / Robots Wiki · GitHub, n.d.).

4.4.2 Coordination system and robot kinetics

Coordination and robot navigate

Robotic arms in the automated manufacturing industry can perform their tasks with extreme accuracy. They can do so under the guidance of a controller monitored coordinate system. The coordinate system is used to help the robot navigate in 3-dimensional space (Goodwin, 2020). Three coordinate systems are applied in the non-planar additive manufacturing control system (Figure: 4.31). The world coordinate system is the Rhino document's coordinate system. Cartesian robot targets are defined in this system. They have transformed into the robot coordinate system during post-processing. The Robot coordinate system is used to position the robot in reference to the world coordinate system. By default, robots are placed in the world XY plane. The X-axis points away from the front of the robot, and the Z-axis points vertically. The present research set the Robot coordinate system as the same as the World coordinate system, shown as the coordinate at the base of the robotic arm in Figure: 4.31. The Tool coordinate system is used to define the position and orientation of the Tool Centre Point (TCP) relative to the flange. The Z-axis points away from the flange (normal to the flange), and the X-axis points downwards, shown as the coordinate at the top of the robot in Figure: 4.31.

Tool centre point (TCP)

Without anything attached to the robot, the end of the arm is used as a reference point for navigation. The controller can move each of the joints in a coordinated manner to make the reference point move through space to predetermined or “taught” positions. When a tool or gripper is added to the robotic arm, the reference point should change to reflect the offset the tool makes. Using the tool as the focus of movement makes programming the robot much easier and allows for more versatility in what functions can be added to a program. A tool centre point (TCP) is used to create the necessary adjustment. This allows the controller to shift the coordinate system to keep track of the tool instead of the arm's end (Goodwin, 2020).

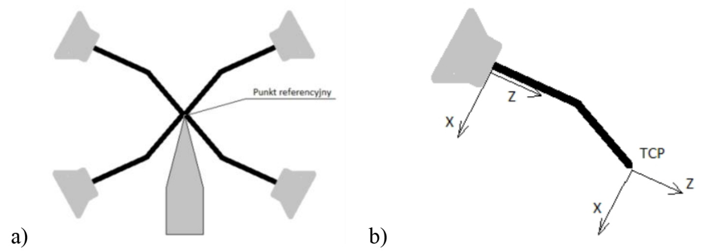


Figure 4.32: The 4-point calibration method for measuring TCP.

The 4-points calibration method is implemented in most industrial robots to measure the TCP (Figure: 4.32). The algorithm is as follows. Find a reference fixed point in the robot workspace. Next, determine the reference point on the tool, which is the nozzle tip in the present research. Finally, indicate the reference robot point from four different directions by moving the manipulator tool, as shown in Figure: 4.32a (one position, four orientations). The robot control system calculates the TCP based on the different positions with respect to the robot mounting flange. It is crucial that reference points should be as close as possible to obtain the best accuracy. Figure: 4.32b shows a defined TCP. (Zwierzchowski, 2017)

The TCPs of the multi-head extruder are all measured using the 4-point coordination method in this work. Since there are three extrusion heads on the multi-head extruder, three corresponding TCPs are required to be measured. The switching of print-heads during the multi-head printing process is achieved by switching corresponding TCPs in the control system.

Move by overlapping coordinates of Target and TCP

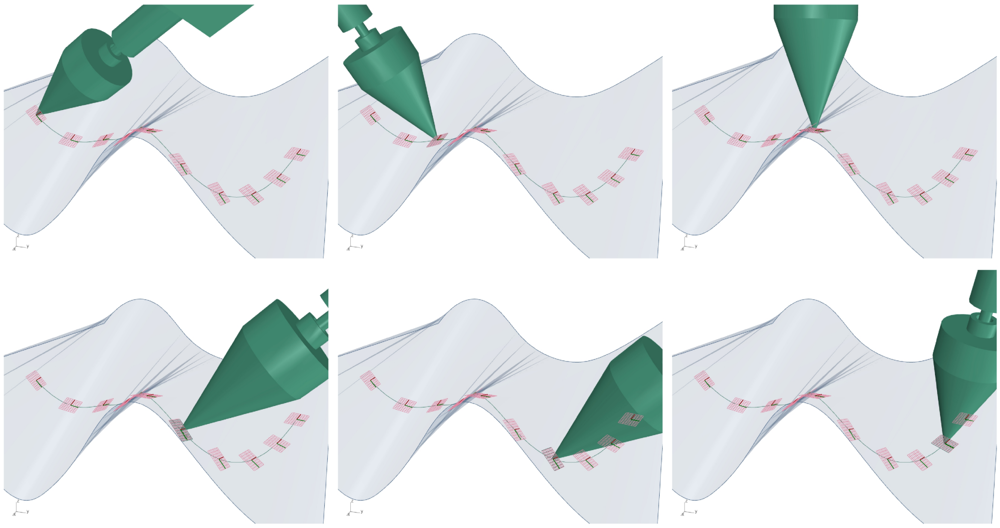


Figure 4.33: Move by overlapping coordinates of Target and TCP.

The position of the print-head in a conventional three-axis 3D printing system is represented by X, Y, Z values. Its print-head constantly points to the ground during the printing process, and the only change is its position, which X, Y, Z values can describe. However, in the environment of non-planar additive manufacturing with a 6DOF robot, besides the X, Y, Z values describing the print-head's position, there is a requirement for more values to describe the nozzle orientation information. The Target coordinate is applied to achieve this aim. The X, Y, Z value of the target coordinate's original point based on the world coordinate system represents the position of the print-head. The rotation of the target coordinate's X, Y, Z axes represents the print-head's rotation. The strategy to control the 6DOF 3D printer's movement is based on overlapping the TCP coordinate with the Target coordinates. Figure: 4.33 illustrates the movement of the 6DOF 3D printer following a curve by overlapping target coordinate with TCP coordinates.

Kinematics

Move by overlapping coordinates of Target and TCP

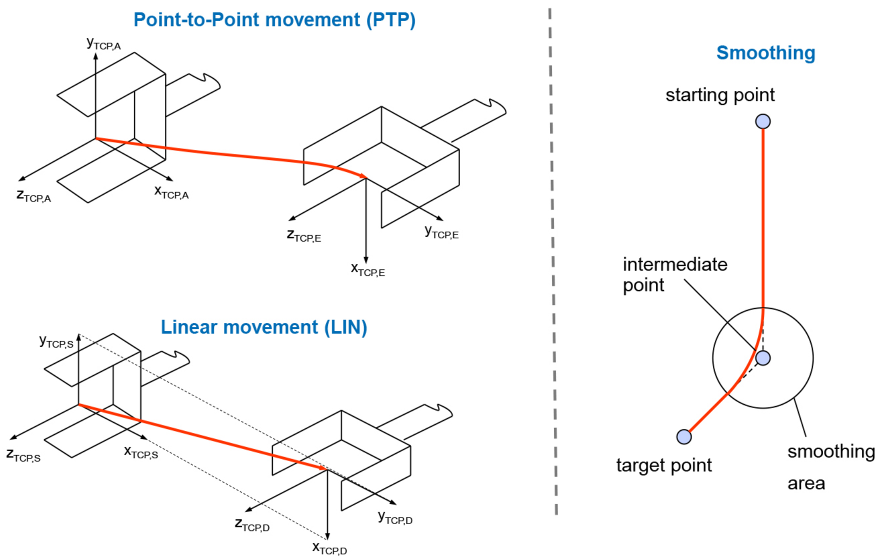


Figure 4.34: Movement types of the 6DOF robotic arm (Brecher et al., 2013).

Kinematics in robotics is concerned with the study of the relationship between a robot's joint coordinates and its spatial layout and is a fundamental and classical topic in robotics. Kinematics can yield very accurate calculations in many problems, such as positioning a gripper at a place in space, designing a tool that can move from point A to point B, or predicting whether a robot's motion would collide with obstacles (Kinematics, n.d.).

Two movement types, Point-To-Point (PTP) or Linear (LIN), are typical for 6DOF commercial robotic arms (Figure: 4.34, left). The PTP command provides the fastest movement between two points, but the trajectory is random and can not be predicted between the two points. Conversely, the trajectory is the straight-line path between starting and target positions in a LIN movement. For high accuracy, the Linear movement was applied to additive manufacturing in the present study. If a movement is comprised of more than two points with Linear movement, e.g. in out of plane 3D printing, smoothing can be applied to increase the smoothness of a movement (Figure: 4.34, right). If smoothing is enabled, the robot does not need to reach the exact intermediate point but enters the smoothing area defined by the intermediate point and a maximum smoothing distance. (Brecher et al., 2013)

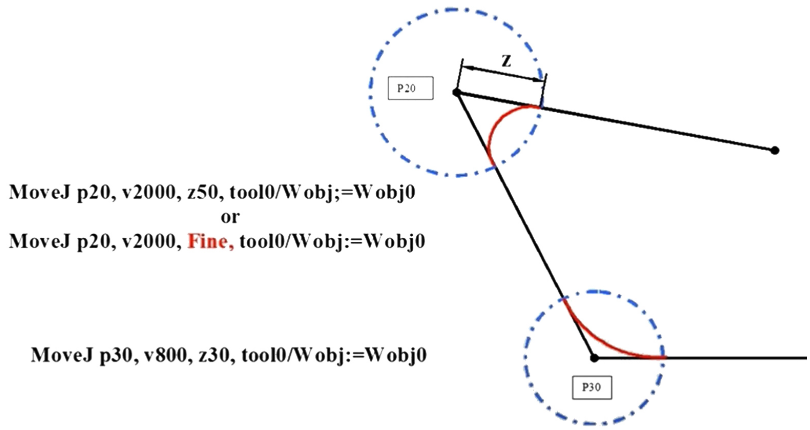


Figure 4.35: Illustration of Zone (ABB IRC5 Programming Zones Data Approximation Continuous Motion Advance Read Run - YouTube, n.d.).

The value describing the range of smoothing area is termed Zone. It gives the robot the ability of continuous motion by cutting the corner to bypass targets. Figure: 4.35 illustrates an ABB robot path that starts from target P10 and then goes through two more targets with Zone values – P20 and P30. This figure demonstrates that the Zone value puts a circle around the targets – P20 and P30 with radiuses specified by the distance. Specifically, the Zone value of P20 is z50, representing the approximation zone or range at the target P20 with a radius of 50mm, and 30mm at P30. Zone gives the robot permission to leave the program path at the target. Once the robot crosses into the approximation zone, it veers off the program path and returns once it leaves the approximation zone. After leaving the approximation zone of P20, it will be back on the program path and remain until it reaches P30. P30 is also a target that contains a Zone value. It enables the robot to continuously move without ever having to stop moving through P20 and P30If this is not desirable, a Fine move command can be used to prevent the continuous motion.

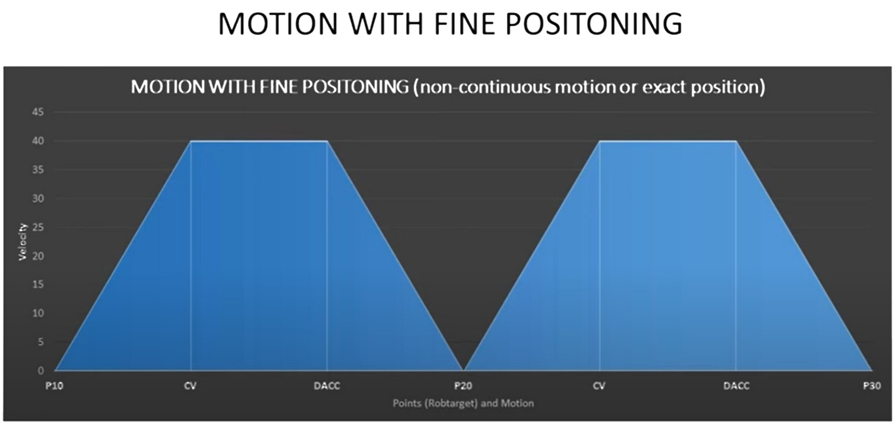


Figure 4.36: Motion with fine positioning (ABB IRC5 Programming Zones Data Approximation Continuous Motion Advance Read Run - YouTube, n.d.).

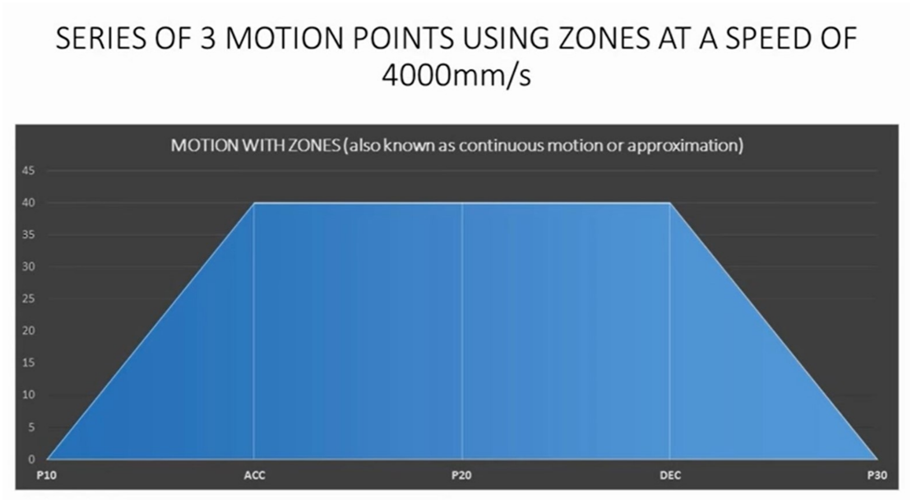


Figure 4.37: Motion points using Zones at a speed of 4000mm/s (ABB IRC5 Programming Zones Data Approximation Continuous Motion Advance Read Run - YouTube, n.d.).

Figure: 4.36 illustrates the procedure of the robot going through P10, P20, and P30 with Fine value (rather than Zone). CV represents the robot reaching its constant (preset) velocity, and DACC represents deceleration. The robot leaves P10 with acceleration until it reaches constant velocity, decelerates and comes to a complete stop at P20, then reaccelerates and decelerates until it completely stops at P30. In this procedure, the robot applies deceleration, stop, and acceleration at each target of a continuous robot path. When there are more targets in a continuous robot path, vibration can occur due to intermittent decelerations, accelerations and stops.

Figure: 4.37 demonstrates the same set of three motions with a Zone setting. It shows the same series P10, P20 and P30. The robot starts to move and accelerate from target P10 until it reaches the constant velocity. Unlike the Fine setting motion, there is no deceleration, stop and reacceleration at target P20. The robot just continuously goes past P20 and then decelerates, and finally stops at P30. Thus for a continuous long robot path with many targets, e.g. additive manufacturing, the acceleration only happens at its first target and deceleration and stop only happen at the last target. The robot moves continuously and smoothly through all of the targets in the middle.

4.4.3 Non-planar slicing

Strategy

Literature Review indicated that the weak connection between layers triggers anisotropy in 3D printed objects (Riddick et al., 2016), where the strength in the build direction is significantly weaker than the strength in the filament direction. However, the application of slicing with sinusoidal layers potentially improves the building direction strength by dividing the force into a parallel and a normal sub-force, allowing non-planar layers to partly redistribute the load away from inter-layer adhesion (Figure: 4.38) (Khurana et al., 2020; Pelzer & Hopmann, 2021). Thus, sinusoidal slicing was selected as the primary slicing approach for the non-planar additive manufacturing control system developed in this work.

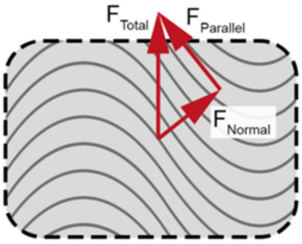


Figure 4.38: Forces applied to the component are divided into parallel and normal parts, allowing non-planar layers to redistribute the load away from inter-layer adhesion. Sinusoidal slicing (Pelzer & Hopmann, 2021).

The other slicing strategy investigated in the present study was gradient transform. The Literature review demonstrates relevant research on improving printing quality by non-planar additive manufacturing (Llewellyn-Jones et al., 2016) (Etienne et al., 2019). They sliced the 3D model following the surface geometry of the printing object to eliminate the staircase effect. The present study also aims to increase the printing quality using a similar approach, a key difference is that in our case the slicing starts with a layer following the geometry of the printing object, but then gradient layers are produced to transform the surface geometry of the printing object to constant sinusoidal layers. Therefore, the combination of sinusoidal slicing and gradient transform theoretically improves mechanical properties in the build direction and improves printing quality by eliminating the staircase effect.

The foundation of the gradient transform is printing with variable layer heights. Some researchers have conducted relevant research. Pelzer & Hopmann (2021) presents an algorithm for non-planar path planning with variable layer height, enabling the accurate representation of freeform surfaces and introducing the potential for increasing the parts' mechanical properties by tailoring the layers to the load case. Furthermore, Fang et

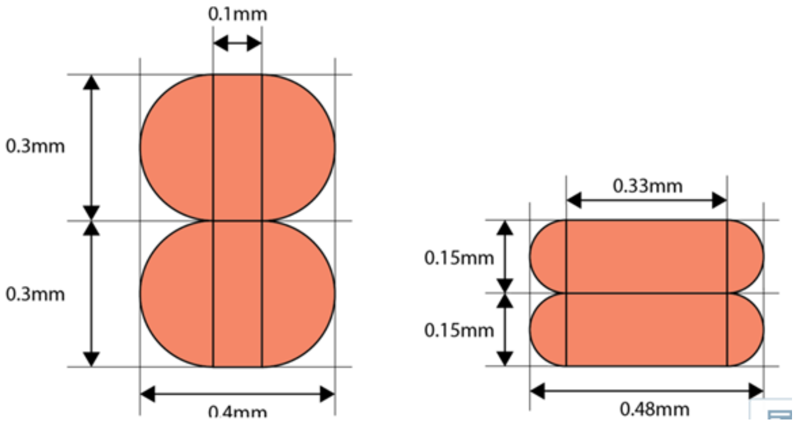


Figure 4.39: Various layer heights for a specific material, nozzle diameter, printing tolerance and printing speed.

al. (2020) presented a new computational framework to generate specially designed layers and toolpaths of multi-axis 3D printing for strengthening a model by aligning filaments along the directions of largest stress. In the FFF 3D printing process, the printing layer height is not constant for a specific nozzle size. For example, a standard 3D printer nozzle is 0.4mm in diameter, but once the plastic is pushed through the nozzle and down onto the layer below it, it expands to between 0.42 and 0.48mm wide. Accordingly, layer height would be from 0.15mm to 0.3mm. (Figure: 4.39) Based on specific material attributes, nozzle diameter, printing tolerance and printing speed, the applicable layer height should be a range.

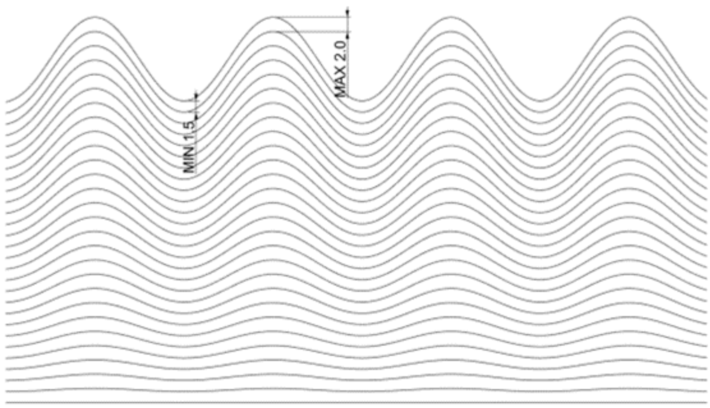


Figure 4.40: Side view of the gradient transform from a flat layer to a sinusoidal layer by various layer heights.

Figure: 4.40 Illustrates a transformation from a flat layer to a sinusoidal layer by gradient transform. This printing has a minimum layer height of 1.5mm and a maximum layer height of 2.0mm. During the whole printing process of this model, the layer height needs to change progressively. The valley bottom points of all layers need to be printed at 1.5mm layer height. In contrast, the peak points of all layers need to be printed at 2.0mm layer height. The gradient transforming from 1.5mm to 2.0mm layer height happens every time printing goes from the bottom to the next peak of the valley. Thus, the aimed sinusoidal layer is gradually produced by accumulating the different layer heights applied to different parts of the printing layers. To summarise, the slicing strategy is to maximum sinusoidal slicing layers and simultaneously match the surface geometry of the printing object by gradient transform.

Slicing algorithm

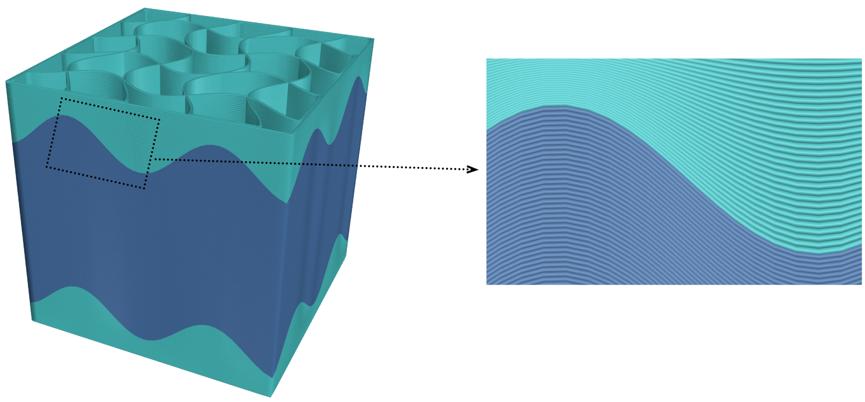


Figure 4.41: Layers classification.

The slicing algorithm was developed based on a cube for simplification. Slicing surfaces are firstly produced based on the slicing strategy ,i.e. to maximise sinusoidal slicing layers and simultaneously match the surface geometry of the printing object by gradient transform. Then, a two-dimensional continuous curve is projected separately to all of the slicing surfaces. As a result, these projected continuous curves form a printing toolpath. All toolpath layers are classified into three groups (Figure: 4.41): bottom gradient layers, constant sinusoidal layers, and top gradient layers. Correspondingly, there are also three groups of slicing surfaces: bottom gradient slicing surfaces, constant sinusoidal slicing surfaces, and top gradient slicing surfaces.

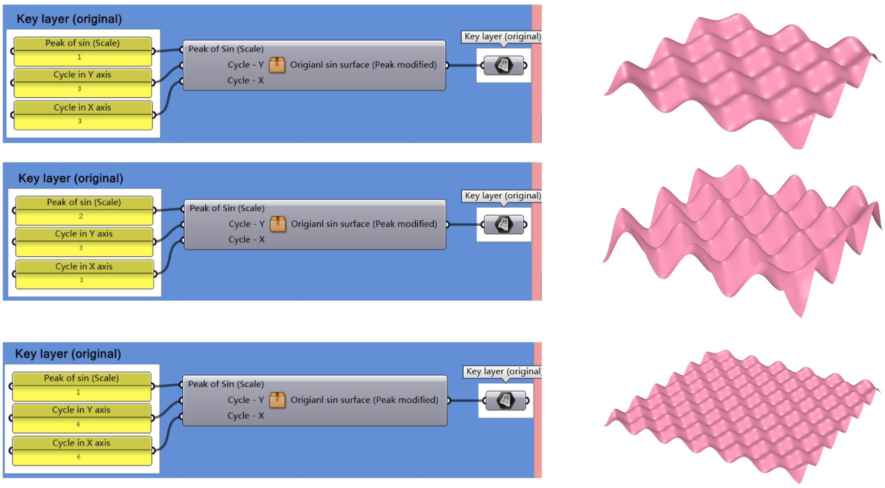


Figure 4.42: Interface to produce the aimed surface.

The lowest constant sinusoidal slicing surface is defined as an aimed surface, while the lowest slicing surface of the model is a flat two-dimensional layer, which is defined as the original surface. The process from the original surface to aimed surface is the “Bottom gradient transform”. The first job to generate “Bottom gradient transform” is configuring the features of the aimed surface. It is conducted as Figure: 4.42 illustrates. The cycles in the x-axis and y-axis direction and amplitude scale can be modified directly by the corresponding parameters: “Cycle in X axis”, “Cycle in Y axis” and “Peak of sin (scale)”. Comparison between the first row and second row of Figure: 4.42 shows the waves on the aimed surface are deeper when increasing the value “Peak of sin (scale)”. While the comparison between the first row and third row of Figure: 4.42 indicates that the weaves are denser when the cycles in the x and y direction increase.

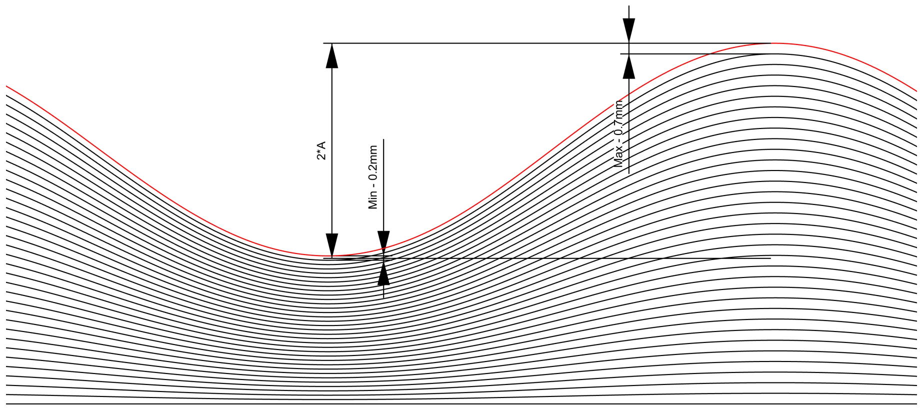


Figure 4.43: Section view of the bottom gradient slicing surfaces.

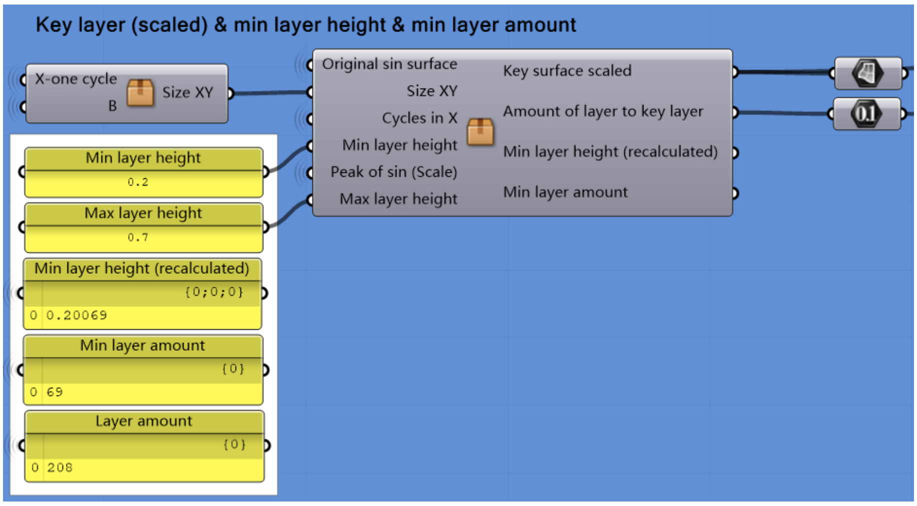


Figure 4.44: Interface to calculate the number of gradient layers.

After configuring the aimed surface's features, the number of the bottom gradient slicing surfaces is calculated. The amount of bottom gradient slicing surfaces is defined as 'n', which defines how many layers is required to accumulate the height difference on different parts of the slicing surfaces to achieve the sinusoidal geometry of the aimed surface. Figure: 4.43 illustrates a sectional view of the bottom gradient slicing surfaces. The value A represents the amplitude of the sinusoidal geometric aimed surface. So the difference in vertical distance between peak and valley of the aimed surface is 2*A, which is also the maximum difference of vertical distance on the aimed surface between random two points. Then the maximum layer height (MaxLH) is set as 0.7mm, and the minimum layer height (MinLH) is set as 0.2mm (Figure: 4.43). The value “MaxLH – MinLH” represents the maximum vertical distance difference that a single layer can produce. Thus, the result of calculating how many times of vertical distance difference on a single layer (MaxLH-MinLH) is the maximum vertical distance difference on the aimed surface (2*A) produces the minimum amount of the bottom gradient slicing surfaces. Since the calculated result has not to be an integer, the result needs to be rounded up to an integer. The formula is shown as follows:

n= 2A/(MaxLH-MinLH)

Figure: 4.44 illustrates the interface used to modify the minimum and maximum layer’s height values. Since producing the top gradient slicing surfaces is an opposite process of producing bottom gradient slicing surfaces, these two groups share the same layer amount and surface geometries but have an opposite order. Utlilising this fact, the interface also shows the value of the minimum layer amount of the whole sample, which is calculated by doubling the minimum number of bottom gradient slicing surfaces. In addition, there is a requirement to compare the whole layer amount and minimum layer amount. If the former value is bigger than the latter one, it requires modifying values such as the peak or the value “Height of sample”, presented by the following contents.

After calculating the number of bottom gradient slicing surfaces, the next step is to produce these slicing surfaces based on this value. This starts with producing a point cloud of the aimed and the original slicing surfaces. The point cloud of the aimed surface is produced by dividing the surface following X Y axes. Shown as the mid image of Figure: 4.45, the values

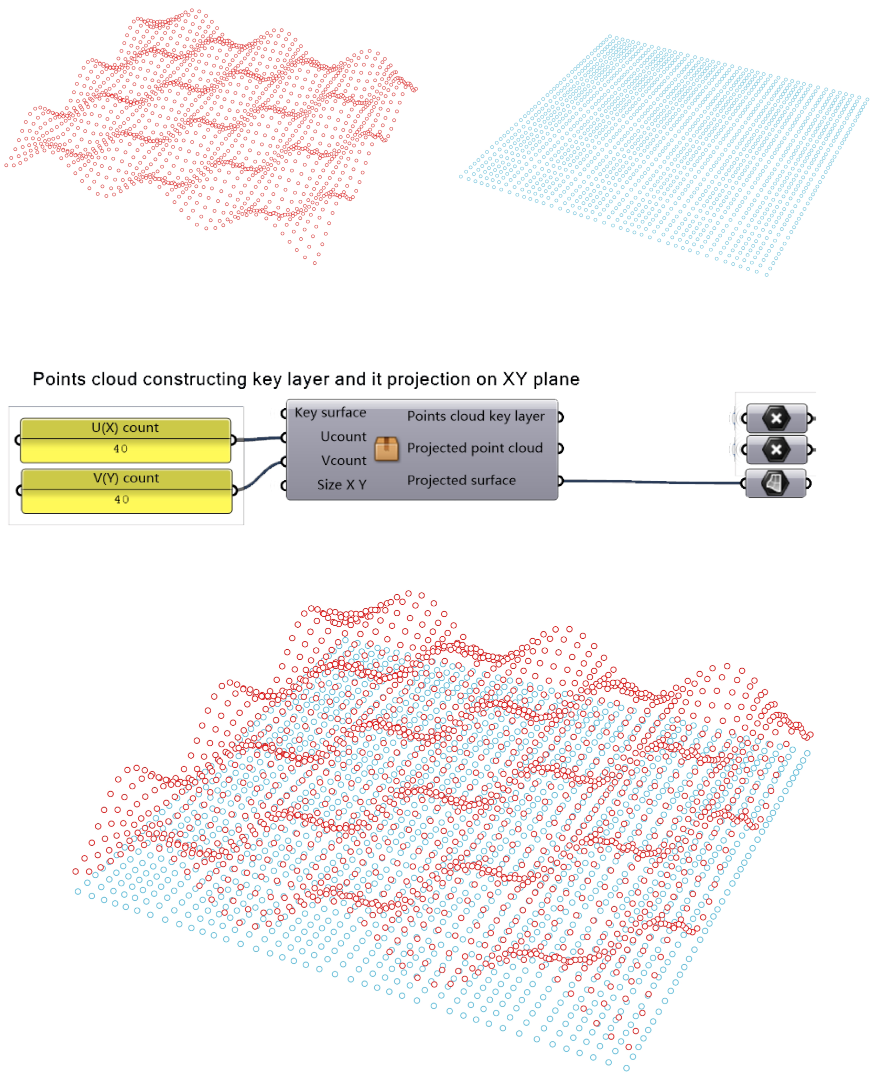


Figure 4.45: Points cloud of the original and aimed slicing surfaces.

"U(X) count" and "V(Y) count" separately represent the amount of the segments in the X and Y axes direction. The top left image of Figure: 4.45 illustrates the points cloud produced by the aimed surface. The point cloud of the original surface is produced by projecting the points cloud of the aimed layer vertically downward (top right image of Figure: 4.45). As a result, the points clouds of the original and the aimed surfaces are produced, as illustrated by the bottom image of Figure: 4.45.

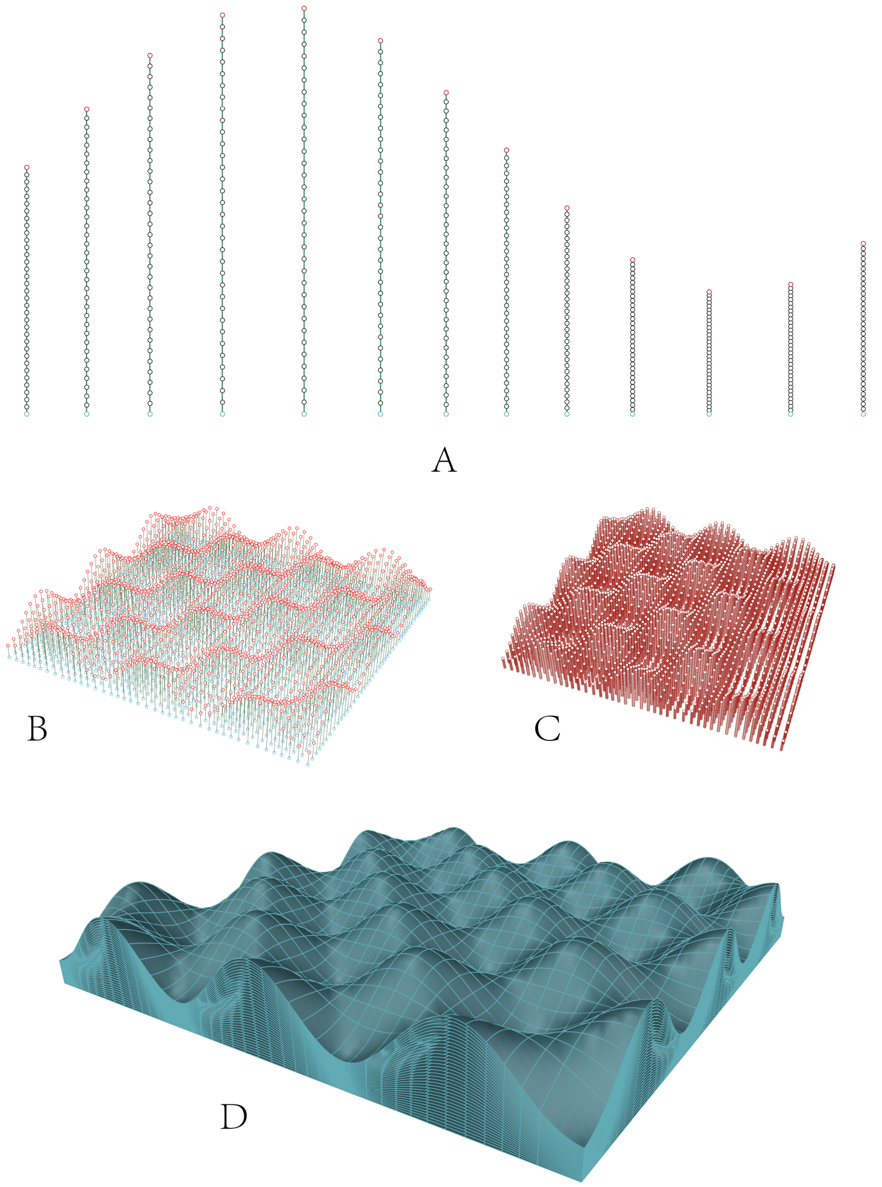


Figure 4.46: The process of generating gradient slicing surfaces.

The generated point clouds of the original and aimed slicing surfaces are then used to produce the bottom gradient slicing layers. This starts with vertically linking the corresponding points of point clouds on the aimed and original surfaces (Figure: 4.46B). These vertical lines are then equidistantly divided into segments by the value n – the number of the bottom gradient layers, which has been calculated above (Figure: 4.46A). After that, the division of all of the lines linking corresponding points in points clouds of aimed and original surfaces generates points cloud for each gradient layer (Figure: 4.46C). Finally, the point clouds for each layer are applied as control points to produce the corresponding gradient slicing layer. All of the bottom gradient slicing layers are produced, as shown by Figure: 4.46D.

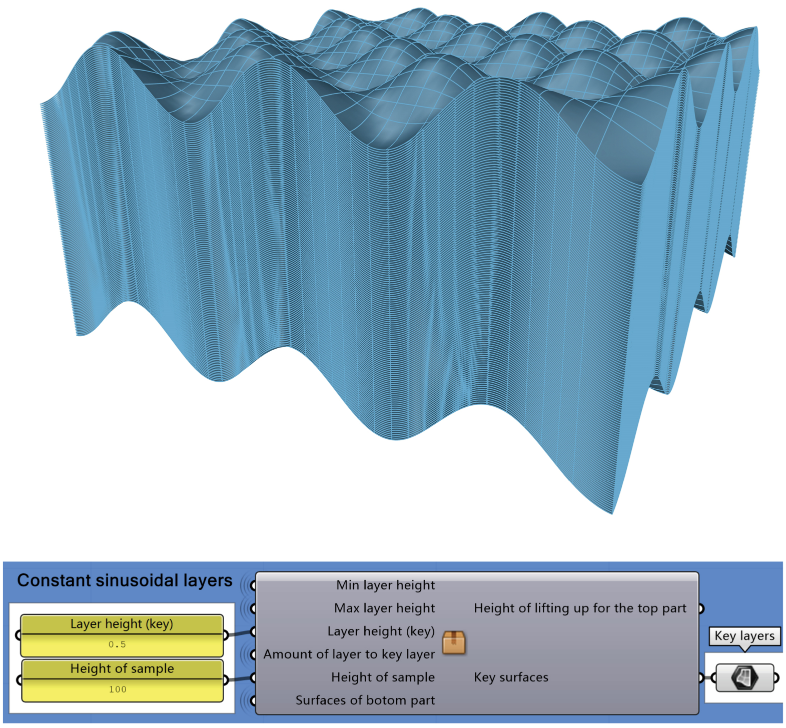


Figure 4.47: Constant sinusoidal layers.

The above process produces the bottom gradient slicing surfaces. Meanwhile, the aimed surface, also referred to as the last gradient slicing surface, shares the same geometry with the constant sinusoidal slicing surfaces. Thus, constant sinusoidal slicing surfaces can be produced by simply duplicating and moving up the aimed surface with a constant layer height (top image of Figure: 4.47). The bottom image of Figure: 4.47 illustrates the parameters controlling the features of the constant slicing surfaces. The value “Layer height (key)” controls the distance between every two adjacent layers, which is set as 0.5 mm in the present study. While the value “Height of sample” determines the height of the whole cube sample. It is easy to calculate the heights of the groups of bottom gradient slicing surfaces and top gradient slicing surfaces by the calculated layer amount and preset minimum and maximum layer height. Then the height of the constant sinusoidal slicing surface group can be calculated by the height of the sample reducing the heights of groups of the bottom and top gradient slicing layers. After that, the amount of the constant sinusoidal slicing surfaces can be confirmed with the confirmed layer’s distance between adjacent layers. Therefore, all constant sinusoidal slicing surfaces can be generated by duplicating and moving up the aimed surface with the calculated number and preset adjacent layers’ distance (Figure: 4.47).

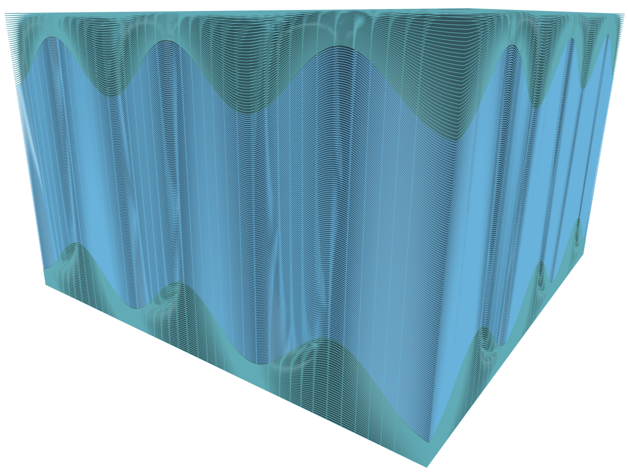


Figure 4.48: All slicing layers.

Moreover, the top gradient slicing surfaces share the same layer amount and geometry with the bottom gradient slicing surfaces but in the opposite order. So the top gradient slicing surfaces are easily produced by reversing the layer order of the bottom gradient slicing surfaces and moving to the top of the constant sinusoidal slicing surfaces. Figure: 4.48 illustrates three groups of slicing layers: bottom gradient slicing surfaces, constant sinusoidal slicing surfaces, and top gradient slicing surfaces.

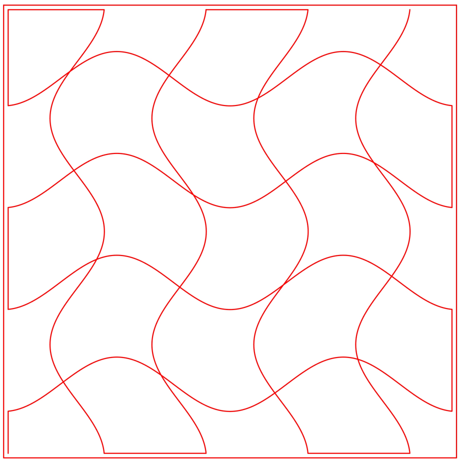


Figure 4.49: The basic layer- a continuous two - dimensional curve.

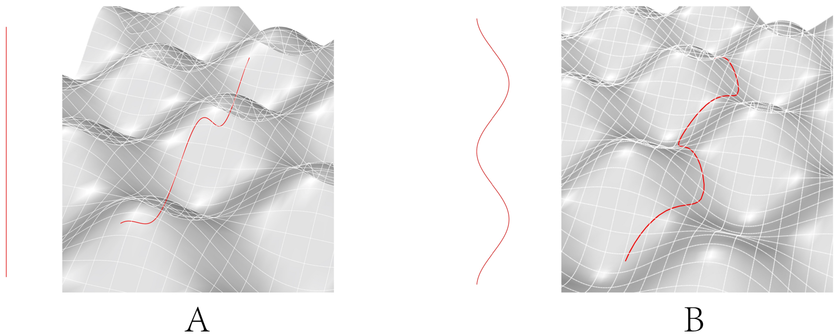


Figure 4.50: Projection of straight line and 2D sinusoidal curve to a 3D sinusoidal slicing surface.

The logic to produce a printing toolpath using the non-planar additive manufacturing control system developed in this work is, hence, by projecting a two–dimensional continuous curve (basic layer) to the slicing surfaces. The approach generating all slicing surfaces has been presented above. The following paragraphs will state the details of producing a two-dimensional continuous curve (basic layer) and generating target coordinates for the

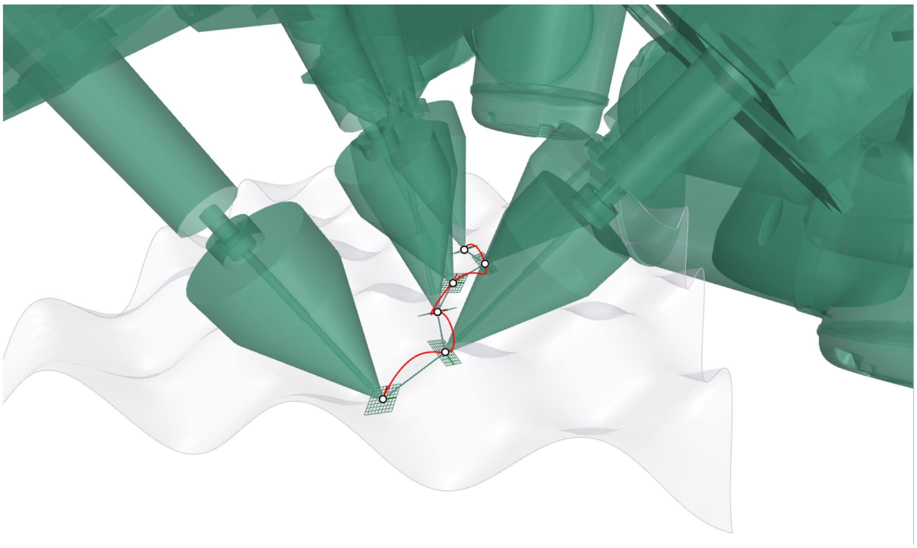


Figure 4.51: Print-head rotation following a 3D curved toolpath.

toolpath by projecting this basic layer to the slicing surfaces. The basic layer consists of the outer wall and two groups of cross sinusoidal curves as infills (Figure: 4.49). Unlike the 2D sinusoidal curve obtained by projecting a straight line to a sinusoidal slicing surface (Figure: 4.50A), projecting a 2D sinusoidal curve to a 3D sinusoidal slicing layer produces a 3D curve (Figure: 4.50B). Applying this 3D curve as a non-planar 3D printing toolpath will bring more challenges to the flexibility of printers since the print-head is rotating in 3D space rather than a 2D surface (Figure: 4.51). It is expected that this will challenge the flexibility of the non-planar additive manufacturing platform. The other requirement on the basic layer design is to maximise continuousness. This is a fundamental requirement of continuous fibre printing since continuous fibres provide the greatest advantages in improved mechanical properties when using fibre reinforced material. The basic layer integrates the outer wall and two groups of sinusoidal curves for infill as a continuous curve. A designed interface can modify configurations such as wall thickness, infill density, sinusoidal cycles, size and so on (Figure: 4.52).

Projecting the basic layer to slicing surfaces can produce target coordinates

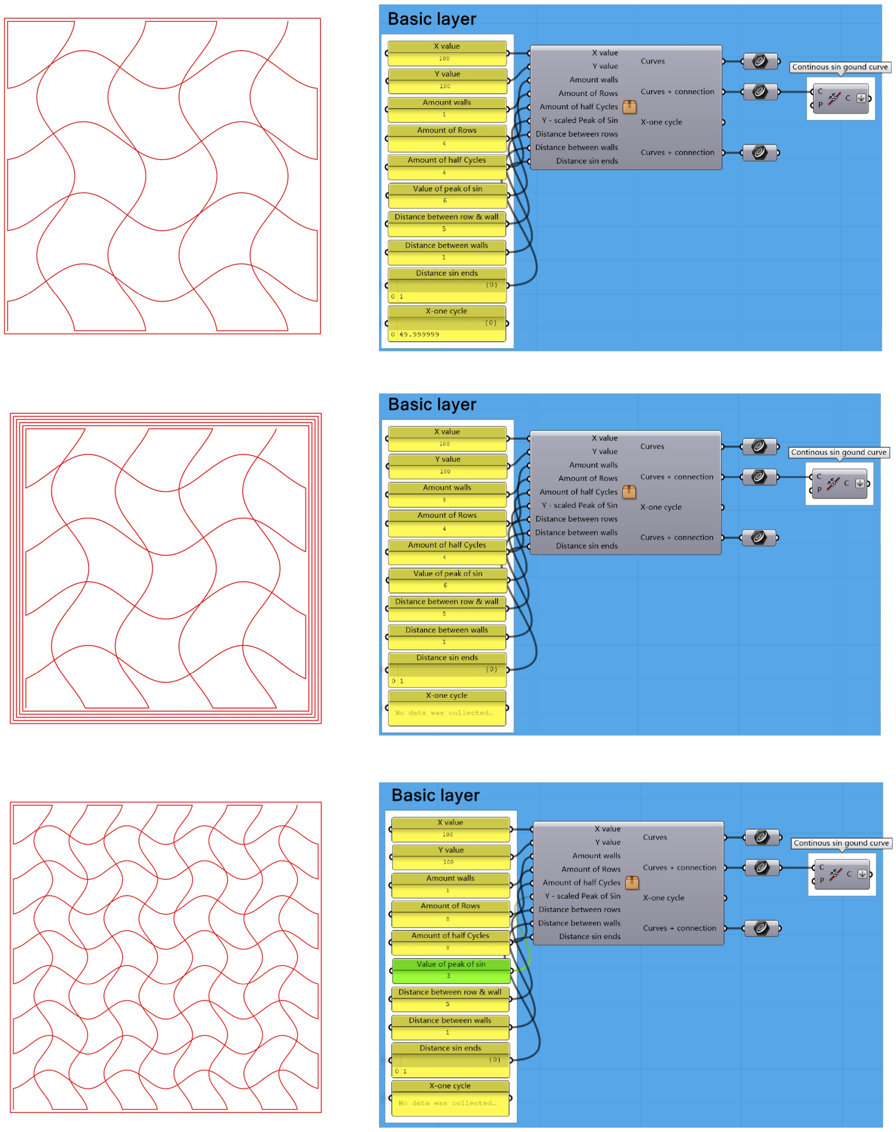


Figure 4.52: Interface to control the basic layer.

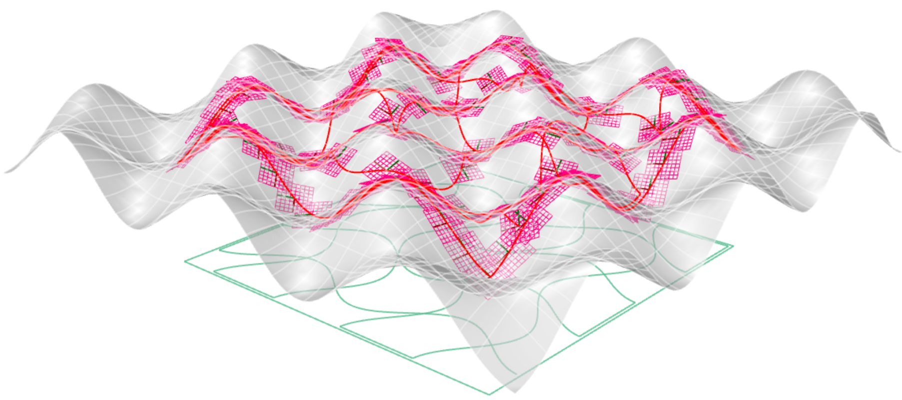


Figure 4.53: Project the basic layer to a 3D sinusoidal slicing surface to produce target coordinates for additive manufacturing toolpath generation.

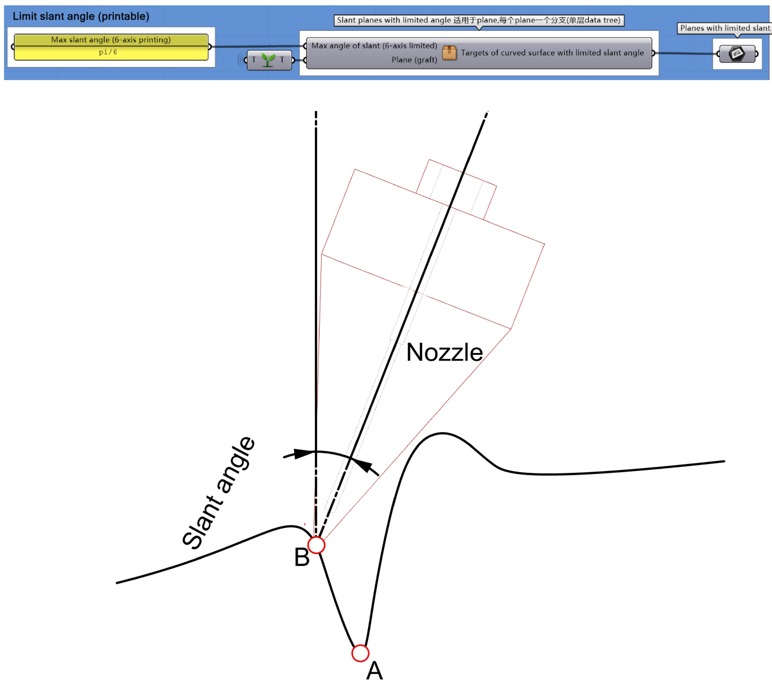


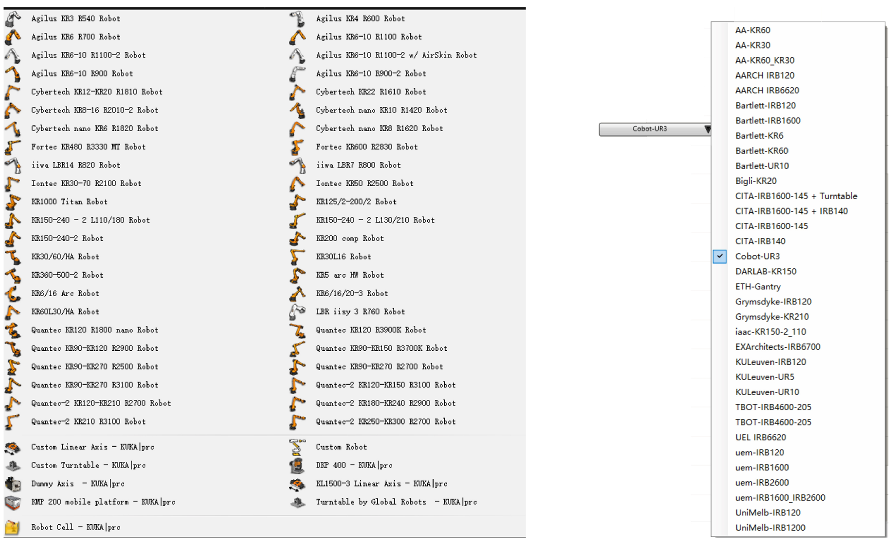
Figure 4.54: Limiting slant angle.

for toolpath generation. Figure: 4.53 illustrates this process. The green line represents the basic layer, projected to a sinusoidal slicing surface (grey) and forms a 3D sinusoidal curve (Red). Then the 3D sinusoidal curve is divided into polygon control points. A control polygon is a sequence of control points (nodes) in space used to manipulate an object's shape (Control Polygons - 2018 - SOLIDWORKS Help, n.d.). After that, these polygon control points are applied to produce target coordinates (pink coordinate in Figure: 4.53 based on their corresponding tangency planes on the slicing surface. These target coordinates can be applied to produce the 6DOF additive manufacturing toolpath. The logic of controlling the trajectory of the robotic arm is to overlap the coordinate of TCP with the target coordinates. Thus, the nozzle will constantly keep vertical with the printing path when the target coordinates are tangent with the printing path and the slicing surface. As demonstrated in the previous section: collision-free, the print-head keeps vertical with the printing path as much as possible. However, the print-head has to be angled when facing a side collision risk. Thus, there is a parameter to limit the slant angle of the print-head (Top image of Figure: 4.54). The value Max slant angle (6-axis printing) determines the maximum slant angle between nozzle and vertical direction (Bottom image of Figure: 4.54). After projecting the basic layer to all of the slicing surfaces, all target coordinates for generating toolpath are achieved.

4.4.4 Toolpath producing and interface

All target coordinates have been produced by projecting the basic layer to the slicing surfaces. This section presents how are these target coordinates are applied to produce the final toolpath in order to control the additive manufacturing trajectory using the 6DPF robotic arm.

Selection of robot arm



A B

Figure 4.55: Robotic arms from KUKA PRC and Robot.

The non-planar additive manufacturing by 6DOF robotic arm is conducted by applying the ordered target coordinates to a specific printing environment, including a specific robotic arm model, measured printing bed, extrusion head configuration, and defined kinetics configurations. Specification of the robotic arm can be conducted by directly selecting the appropriate option from the control interface. KUKA PRC includes all models of KUKA robotic arm in the market (Figure: 4.55A). The plugin Robot supplies several models from various brands of KUKA, ABB and Universal Robotics (Figure: 4.55B). This also allows customisation to a specific robotic arms by supplying 3D model and data of each axis. The present research applies Universal Robots UR3e as the robotic model.

Setting the print bed

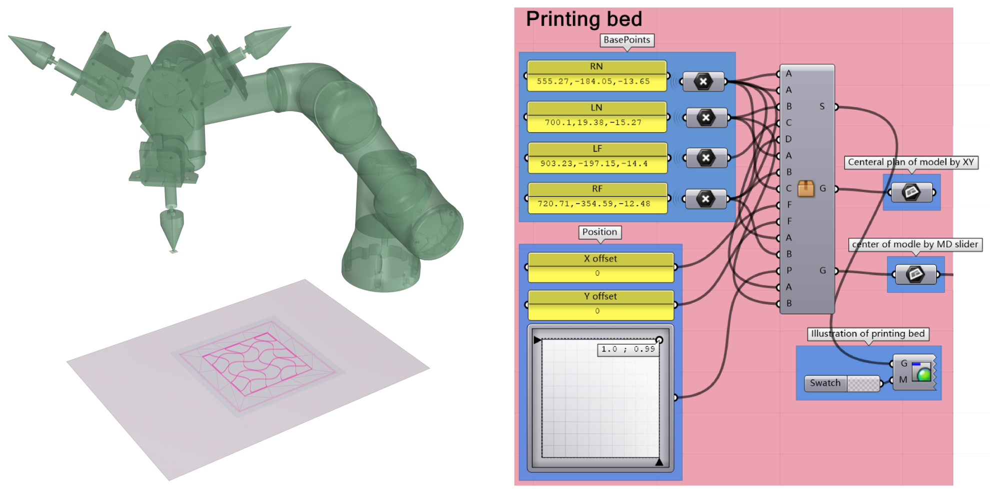


Figure 4.56: Interface setting printing bed.

A print bed is a platform that provides the base for the the accumulation of printed material. The print bed for a conventional 3D printer is typically integrated with the other components of the printer. It is usually located vertically downward of the print-head and has a fixed size based on the fixed printing reach. However, the 6DOF robotic arm brings more flexibility than the conventional 3-axis 3D printer, and the position of the printibed for 6DOF robot printing can also be defined more flexibly. It can be located on the robotic arm's right, left, front, or back to fit complicated environments. Thus the print bed needs to be configred for a specific print. Figure: 4.56illustrates the interface to configure the printing bed. The coordinates of four corners are used to determine the print bed for a specific print. The coordinates can be easily input by manually operating the robotic arm. After that, the print object can be oriented to the printing bed by its original reference coordinate – world coordinate and the aimed coordinate produced by three points on the printing bed. In addition, the MD slider or X and Y values can easily modify the position of the printed object on the print bed, which makes it easy to modify the printing position depending on requirements.

Setting of printing tool (Figure: 4.57)

The TCP also needs to be set for the multi-head extruder. Since there are three heads, three TCPs must be set. The pre-mentioned 4-Point calibration approach is used to do this. Switching of the tool is achieved by setting the corresponding TCP (Figure: 4.57). In addition, there is another parameter in the TCP interface, namely "Angle of tool", which controls the rotation of TCP within the X, Y plane. This parameter does not affect the position or orientation of the print head. It only affects the "gesture" of the robotic arm to reach the target coordinates. Figure: 4.58 illustrates four different "gestures" to reach the same target coordinate. This setting is meaningful for print reach since the same target coordinate is reachable by some "gestures" but not by others.

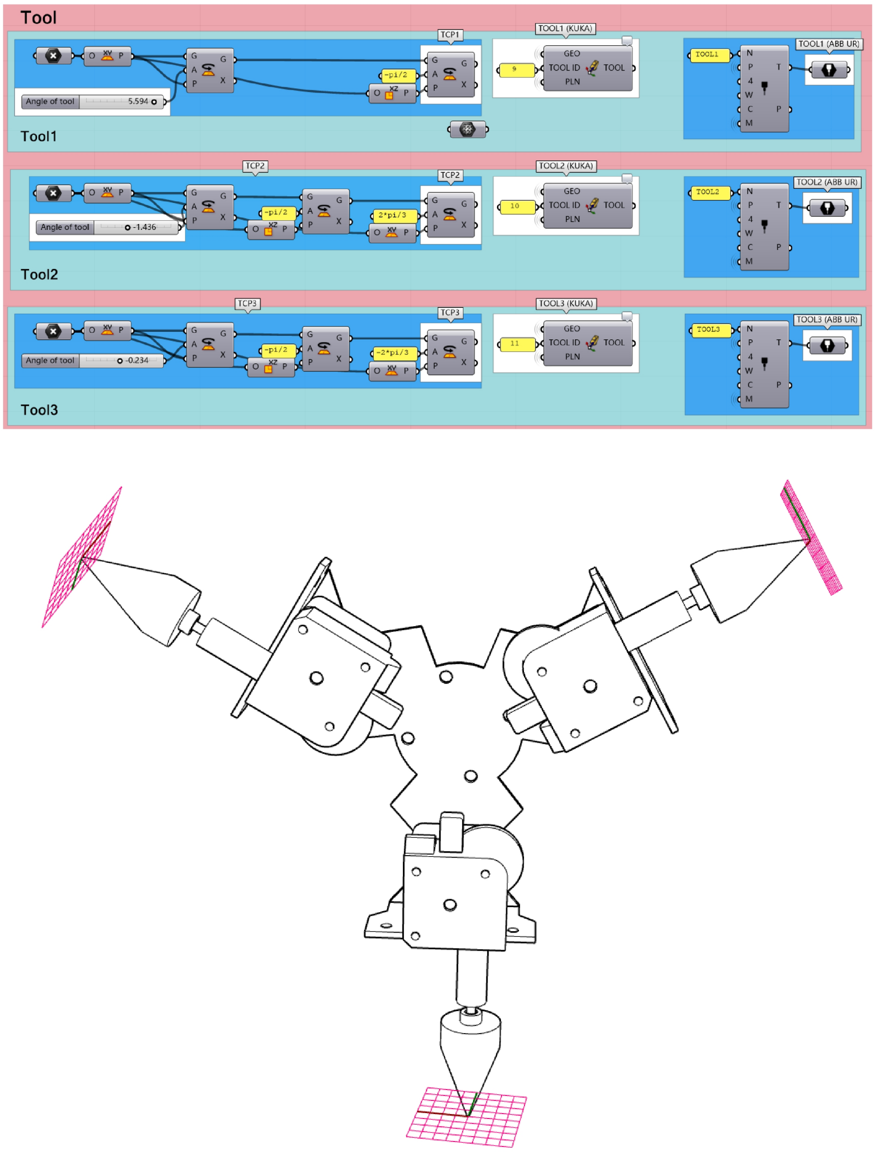


Figure 4.57: TCP setting.

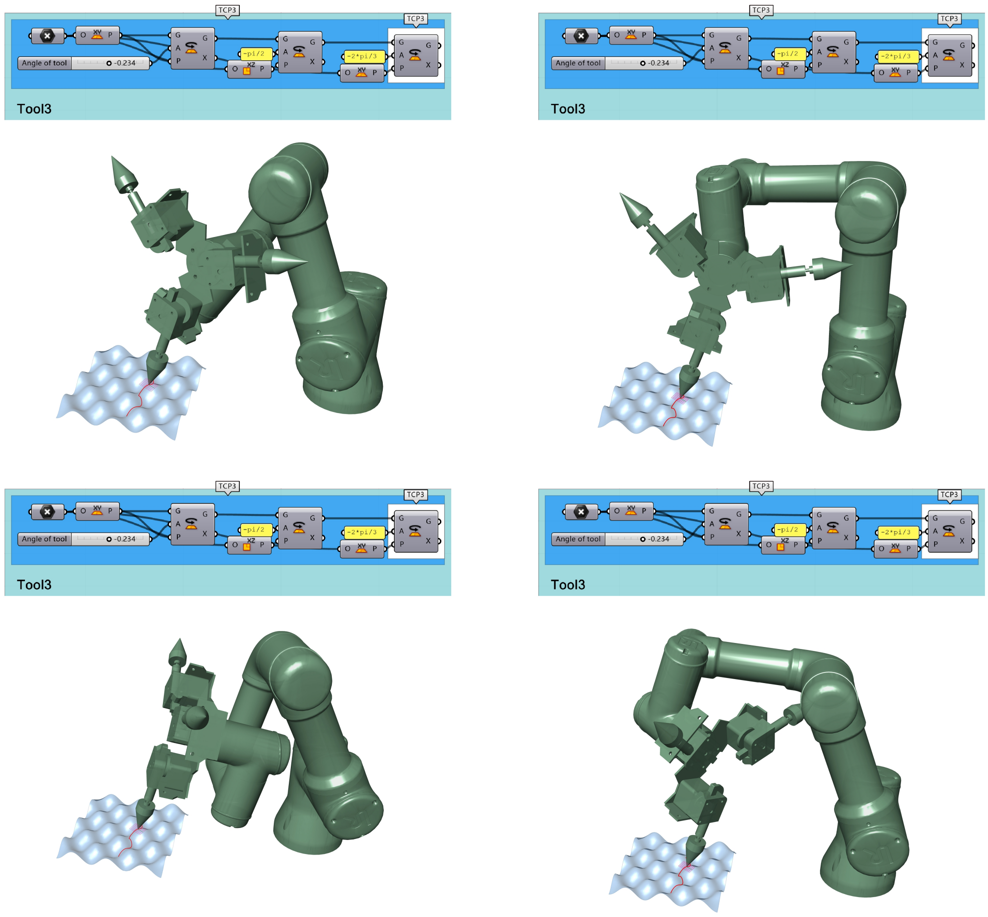


Figure 4.58: Effect of the parameter "Angle of tool".

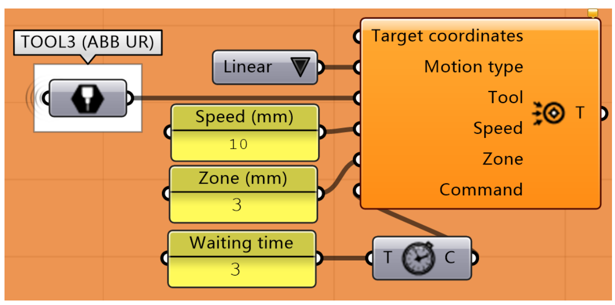


Figure 4.59: Setting configurations of robotic printing kinetics.

Kinetic configurations

After configuring the model of the robotic arm, print bed and print tool, the print kinetics need to be defined. Integration of the target coordinate and kinetic configurations is defined as Target, which can be applied to control the robotic trajectory. The kinetic configurations consist of movement type, zone, printing speed, and wait. The two primary movement types of the 6DOF robotic arm are PTP and Linear. As stated previously, PTP allows robots to move from point to point in the fastest way. However, the path between points is random and not predictable. This feature of PTP makes it not an appropriate movement type for 3D printing due to its poor accuracy. By contrast, Linear movement can ensure the paths between Targets are always straight lines, which is stable and predictable. Combining with the other configuration – zone (discussed previously), which allows smooth movement between targets, an accurate but smooth print trajectory can be achieved. The setting of Linear movement type and Zone value is shown as parameters – movement type and Zone in Figure: 4.59. Figure: 4.59 also illustrates the setting of print speed. The set value is 10mm, meaning the print head moves at a velocity of 10mm/s. Another kinetic configuration is waiting time, illustrated as parameter "Waiting time" in Figure: 4.59, which determines the time the robot stops at the set Target. All of the kinetic configurations are set with each Target. Kinetic configurations could be set the same for all Targets by setting them together. They can also be different by specifying selected Targets with special requirements. For instance, a robot 3D printer is required to stay at the starting point of the whole printing toolpath to make sure the material sticks well with the printing bed. Then, there are no requirements of the wait at all left target coordinates. Thus the waiting command needs to be only added to the Target at the beginning point.

Digital I/O setting

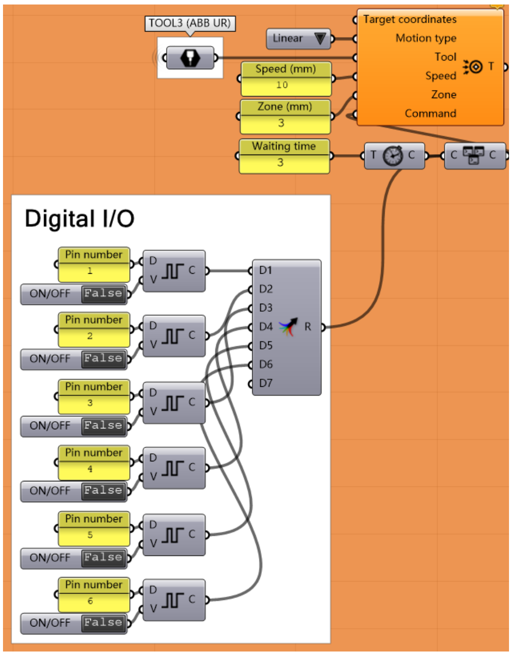


Figure 4.60: Digital I/O setting.

As with the command of waiting time, the digital I/O can also be set as a command attached to any Target (Figure: 4.60). The set digital I/O is sent to the I/O board on the controller of the multi-head non-planar extrusion system. Then it extrudes materials with the corresponding printhead and velocity under the control of the Arduino. For instance, there are six Digital I/O pins: Pin 1,2,3,4,5,6 on the robot controller controlling the extrusion speed of the multi-head extruder. All three print-heads stop extruding when all of the Digital I/O pins are set as OFF. When Pin 1 is set On, and all other five pins are set OFF, print head A extrudes materials at velocity a.

Simulation

After setting all of the parameters, a virtual simulation is used to check the print path before sending the code to the robotic arm controller. Due

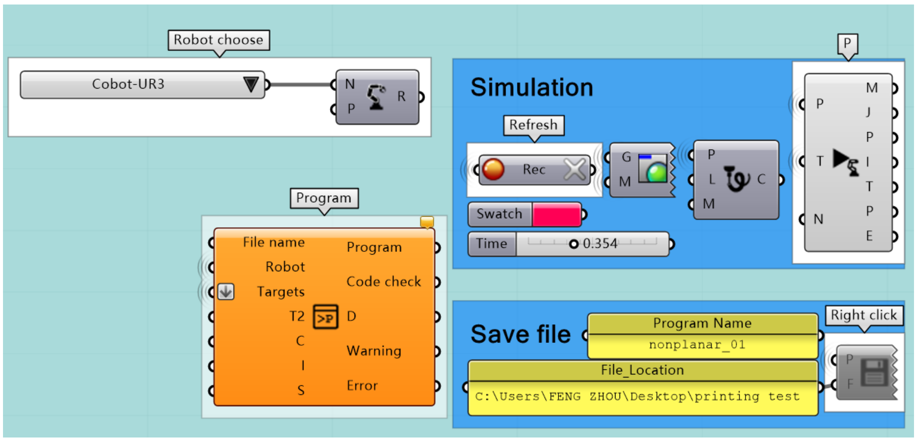


Figure 4.61: Printing simulation and generating the print file.

to the complexity brought by 6DOF, the collision of the print-head and printed object, print-head and printing bed, print-head and robotic arm easily happen. In order to avoid these collisions, a virtual simulation is essential. Powered by the fast visualisation by Rhino and robot path simulation component by Robot and KUKA PRC, the virtual simulation of the whole printing process can be easily conducted by simply right click on the component "p" (Figure: 4.61). When a collision or other errors are found by simulation, the program producing toolpath needs to be revised. When the simulation goes through, and no errors are found from the process, the printing code is ready to save by right-clicking on the saving component, and then the robot code will be produced under the setting path (Figure: 4.61)

Printing operation

Reflecting the integrated framework of the non-planar additive manufacturing platform illustrated in Figure 4.1, its working flow is stated as follows:

- 1, The target 3D model is built or imported into the Non-planar additive manufacturing control system.

- 2, Parameters controlling printing details are set.
- 3, The control system automatically slices the 3D model and produces the corresponding printing toolpath following the set parameters.
- 4, Printing simulation is run in the non-planar additive manufacturing control system. If any error is found in the simulation, it needs to check the 3D model or the parameter settings.
- 5, When there is no error during the simulation, the corresponding code fitting the selected robotic arm is generated by the control system and sent to the controller of the robotic arm.
- 6, Robot moves following the received code.
- 7, At the points where extruding velocity is changed or print-heads need to be switched, the I/O signal is sent to the controller of the multi-head non-planar additive manufacturing extruding system.
- 8, The extruding speed of extruding system changes based on the received I/O data.

4.5 Experiment

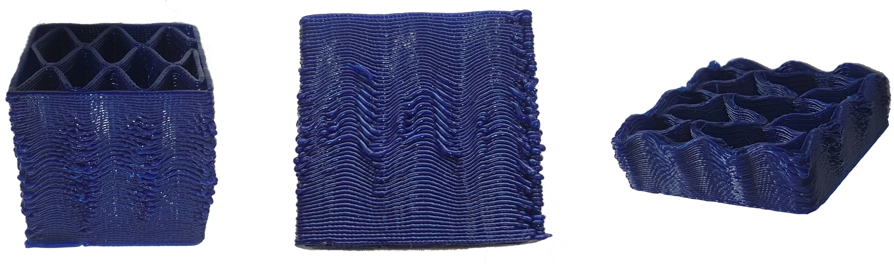


Figure 4.62: Sample from a practical printing test by the non-planar additive manufacturing platform.

A practical printing has been conducted to test the non-planar additive manufacturing platform. Figure: 4.62 shows the sample from the test.

The first and second images in Figure: 4.62 illustrate the finished sample's perspective and side views. While the third image of Figure: 4.62 shows the sample during the printing process. The printing test was conducted by following settings:

- 6DOF robot arm: Universal Robots UR3e.
- Dimension of the sample: height -100mm, width-100mm, length-100mm.
- The material for printing: 1.75mm PLA filament.
- Extrusion diameter of nozzle: 1.2mm.
- Minimum layer height: 0.5mm.
- Maximum layer height: 0.9mm.
- The layer height of the constant sinusoidal layer: 0.7mm.
- Printing speed: 10mm/s.
- Zone setting: 3mm.
- Maximum slant angle: pi/6.

As shown by Figure: 4.62, the non-planar additive manufacturing platform successfully manufactured a sample. However, the printing quality is not enough to conduct further research on mechanical properties tests. There are poor connections between layers and over extruding on many parts of the sample. The poor printing quality was speculated by chatter vibration.

During the printing process, it was noticeable that there were frequent vibrations referred to as chatter vibrations. The structural rigidness contributes to preventing the chatter vibration. Due to the limited access to the industrial 6DOF robotic arm, the present study applied Universal

Robots UR3e to the printing test. Universal Robots UR3e is a collaborative robotic arm primarily applied to collaboration with humans. So its design primarily concerns safety, which triggers rigid lower than the industrial 6DOF robotic arm. Thus chatter vibration is usually more serious on collaborative robotic arms than industrial robotic arms. For many years, chatter vibration has been a topic of industrial and academic interest in manufacturing. A great deal of research has been carried out to solve the chatter problem, including identifying, detecting, preventing, and suppressing chatter (Quintana & Ciurana, 2011). Nevertheless, these studies are almost always based on the traditional CNC machine tools, and they are not fully applicable to the robot. Only a few scholars have studied the chatter problem in the robotic machining process. Pan et al. analysed the chatter mechanism in the robotic milling process and found that the chatter type was mode coupling rather than regenerative chatter that always occurred in traditional CNC machine tools (Z. Pan et al., 2005). In the robotic turning process, Ozer et al. (Özer et al., 2013) presented a novel semi-active controller to delay chatter vibrations to improve the cutting performance and the tool life. Currently, Wu et al. (H. Wu et al., 2014) introduced two methods to suppress the robot machining chatter: the passive vibration control method and the active vibration control method. Vibration in assembling electronics was also explored by (Cooper et al., 2019). However, non-planar additive manufacturing by the articulated 6DOF robot arm just emerged quite a recent year. To my knowledge, there has not been relevant research on the chatter vibration effect of 6DOF non-planar additive manufacturing.

Limited by reaching time, the impact of the Covid 19 pandemic and the access to suitable facilities, the present study established a non-planar additive manufacturing platform based on a 6DOF robotic arm and successfully made an initial printing test. However, future work needs to be conducted for the other segment: such as testing various robotic arms for less chatter vibration; printing aesthetic prostheses with a high-performance polymer like PEEK, continuous fibre printing, multi-material printing (switching head during printing depending on requirements of material and extrusion size); conducting a test of mechanical properties; as well as wearing by users and collecting their feedback.

4.6 Conclusion

3D-printed limb prosthetics offer a significant positive change in the lifestyle for thousands of people with a disability worldwide. Fused filament fabrication (FFF) has been one of the most widely applied AM technologies to prosthetics, due to its benefits for customisation low cost and easy accessibility of its facility. However, the weakness in the mechanical strength of 3D printed objects, by FFF hinders its application to the load-bearing parts of limb prosthetics. This weakness is mainly triggered by anisotropy, being strong in the axial directions of the printed filaments but weaker between filaments and layers. Newly emerged non-planar additive manufacturing is a potential solution to the anisotropy issue of FFF as mechanical strength can be increased without increasing weight and compromising geometric freedom. However, relevant research on this technology is still rare, and there is no adequate equipment available in the market. Hence to conduct research in this field, the required hardware and controlling software must first be developed.

In order to promote relevant research in non-planar additive manufacturing and then further expand the application of FFF to limb prosthetics, the present research explored a solution, which is easily accessible and widely applicable to various materials and printing sizes, to non-planar additive manufacturing. (1) It chose the commercial industrial 6DOF robotic arm as the driving system, since its features of long reach, 6DOF, and various payloads bring significant benefits to non-planar additive manufacturing. It also analysed the commonalities of widely used robots in the market e.g. various models from ABB, KUKA and Universal, to guide the development of the non-planar additive manufacturing platform. (2) It developed a multi-head extruder widely compatible with commercial robotic arms in the market, with high flexibility to print different materials, and collision-free (3) It built a controller to control multiple nozzles' temperature and extruding status as well as bridge the extruder controller to the control system of robotic arm by I/O signal. (4) It created an integrated system for the application of non-planar additive manufacturing by a 6DOF robotic arm. Its integrated function consists of slicing 3D models following a non-planar logic, producing a non-planar additive manufacturing toolpath for a commercial 6DOF robotic arm and the developed multi-head extruder and providing an interface for controlling print details and conducting print simulation. (5) It also conducted a practical printing to test the whole system revealing that the non-planar additive manufacturing platform successfully manufactured a sample, although there are still some issues with the printing quality. Futher work may be conducted to keep exploring the balance of aesthetic prosthetics between aesthetics, weight, mechanical strength, by the developed muli-head non-planar addtive manufacturing platform.

Chapter 5

User study

The previous chapters have explored the design and manufacture of personalised aesthetic prostheses. In particular, they have introduced algorithms to generate aesthetic seeds, driven by user interactions such as dancing, applying these to different physical forms, and driving the additive manufacturing process. This chapter considers the perspective of the users, evaluating these various innovations from the point of view of the people who might ultimately use them. It reports a series of workshops conducted with four disabled dancers and dance researchers, in which they tried out the interactive technologies, refected on the resulting designs, and through this revealed insights into the opportunities and challenges of the approach.

5.1 Participants

5.1.1 Background

We have published a paper Beyond Skin Deep: Generative Co-Design for Aesthetic Prosthetics for CHI 2023, demonstrating the generative co-design strategy and user feedback. The study focuses on engaging a small number of participants in depth over an extended time period for two reasons: It is generally difficult in general to gain access to larger numbers of professional disabled dancers as there are not so many of them. The global COVID pandemic slowed the process down greatly and restricted opportunities to recruit and engage a wider cohort. In particular, it was not possible to stage q final more public workshop with a wider selection of dancers as was originally planned

5.1.2 Participants

We recruited two professional disabled dancers and two dance researchers. The dancers, referred to as T and W, were both female with many years of training and professional experience in expressing themselves through improvised bodily movements. Both had high amputations on one leg. They were compensated using industry daily rates recommended by their professional body. The two dance researchers, S and K, were also experienced dance practitioners. They recruited the dancers and contributed insights into dance and disability from their research. K is also a disabled artist researcher with lived experience of disability. The relatively small number of external participants was due to the scarcity of and demand for professional disabled dancers, combined with the effects of the global COVID pandemic which halted our plans for hosting a larger event to gather feedback from the wider dance community. However, engaging even just a few professionals in our design process proved highly illuminating, revealing unanticipated insights as we report below. We had three HCI researchers: SB has been focusing on HCI research for many years; M, whose PhD study is relative to HCI and smart wearable; FZ, the author of the present thesis.

The two dancers were fully informed about the research. They were asked to perform a series of improvision, while wearing the ROKOKO Smart Suit, and interact with the design algorithm by seeing the screen in front. Their movements and produced designs were recorded and analysed. The research was conducted in Centre for Dance Research in Coventry University a safe and supportive environment, with all necessary measures taken to ensure the physical and emotional well-being of the dancers. The data collected was be kept confidential and anonymous, and was only be used for the purpose of the research.

Our decision to collaborate with dancers was influenced by the availability of experienced collaborators from the Centre for Dance Research at Coventry University. The integration of design algorithms with creative human behaviors necessitates expertise in specific creative domains. Throughout the research process, two design researchers from the Centre for Dance Research provided valuable insights on workshop planning, operation, interviews with dancers, and user feedback analysis. They also facilitated the recruitment of disabled dancers, a relatively rare demographic worldwide. Another reason for selecting dance as the focus of our study is its long-standing history as an artistic expression of human movement. Dance has been used for centuries to convey the artist's inner world, establishing a strong connection with their emotional and spiritual experiences.

However, the broader implication here is to seek out equivalent personally expressive skills in other situations. This might be a recognised artistic skill such as music, dance, painting, or sculpting, or perhaps some other somaesthetic skill that involves an aesthetic bodily interaction (various sporting skills spring to mind). In turn, this requires developing interaction techniques that embody a deep knowledge of the chosen skill (as we were able to do by drawing on dancing principles from dance research).

5.2 Process

Our research unfolded over an eighteen-month period, beginning with a period of technical exploration that led to the creation of an interactive generative algorithm called Mogrow. Early experimentation with Mogrow inspired the idea of interacting by dancing, leading us to recruit the dance researchers who in turn recruited the professional dancers. Our first joint workshop occurred in person and explored creative interactions with Mogrow, delivering a set of designs that we came to refer to as aesthetic seeds. A second period of technical development then established further algorithms to apply these seeds to the form of prosthetic greave and to optimise the results for 3D printing, delivering a portfolio of personalised prostheses designs. COVID intervened at this point, introducing some delay while the dancers were unavailable and driving us to collaborate online. Our second joint workshop involved the entire team discussing the final designs and reflecting on the wider process. This was preceded by a planning session with the dance researchers. In the following, Workshop 2a refers to this planning session while Workshop 2b refers to the final workshop involving the whole team. Figure 5.1 summary the workshops. As the process evolved and a tight-knit team emerged, so our roles shifted. The HCI researchers moved from initially being technology designers to becoming co-design facilitators. In turn, both dance researchers and professionals moved from being 'users' to being co-designers, and ultimately co-researchers (with all four appearing as authors of the paper).

The workshop 1 was conducted face-to-face and consisted of two parts: practice and discussion. For the practice, dancers wore a ROKOKO Smart suit (Smartsuit-Pro Tech Specs, n.d.) and then danced so as to interact with the Mogrow to produce aesthetic seeds. It started with making

Summary of Workshops

	Workshop 1	Workshop 2a	Workshop 2b
Date	5th November 2019	2nd March 2022	15th March 2022
Duration	5 hours	60 minutes	90 minutes
Aim	To enable dancers to produce their own aesthetic seeds by interacting with algorithm 01 – Mogrow and collect their feedback on the aesthetic seeds and the experience of "design by dance".	Recall the content of workshop 1 and introduce updates since then to the workshop participants and discuss the questions to discuss with dancers for workshop 2b.	Recall the content of workshop 1 and introduce the updates since then to the dancers, and collect their feedback on the whole study.
Form	Workshop 1 was run on-site, consisting of practice, in which two dancers wore ROKOKO Smart suit danced and interacted with the Mogrow, and discussion, in which the participants' attitudes on aesthetic seed and the interacting experience were discussed.	Workshop 2a was run online. It started with a presentation on the contents of workshop 1 and updates since then by Feng Zhou and then a discussion between spectators.	Workshop 2b was also run online. It consisted of a presentation by the author and a discussion between aimed users and spectators.

Figure 5.1: Summary of workshops.

dancers to get familiar with the Smart suit. Dancers lost one leg, whilst the Smart suit was designed to normal body. In consequence, the extra leg of Smart suit was fold but with sensor of foot swings in air. Then the virtual 3D model simulating dancers' motion showed a virtual leg fold and feet swings in air. This experience appealed to dancers, and they tried to interacted with their virtual leg which has been missing. This viral interaction did not bring discontinuous or clumsy dancing motion, instead, the motions are smooth. Then dancers started to produce aesthetic seed by interacting with Mogrow.

There was a projector showing an animation in that a 3D model of vase gradually generated from a single circle until to a whole vase. Dancers' motion data was linked with the animation of vase generated. Then, dancing motion could affect the vase generation. Dancers firstly interact with Mogrow by functional mode. In the *functional mode*, the movements of specific body parts were directly mapped to key parameters. Moving the left hand increased the rate of particle injection. Moving the right hand faster increased the rate of shrinking. The velocity of the remaining tracking points on the suit was averaged to derive a general rate of bodily movement that was mapped onto friction so that moving one's body faster-reduced friction which led to less compact wrinkling. Dancers seemed clumsy throughout the functional mode. Even they got more familiar after practice, but their motion was still not smooth.

After that, dancers tried to interact with Mogrow by dancing mode, which was inspired by dance theory. The two dance researchers on the team guided us to a conceptual framework that articulates ten underlying principles of expressive dance movement. We chose one of them "axis". Line crossing two shoulders was defined axis one, whilst line crossing hipbone was defined axis two. The angle between two axis and the speed of angle changed were also linked to animation of vase generation. Dancers seemed to get familiar with the dance and interaction behaviours very quick and started enjoyed the process.

After dancers' dance and interaction, we conducted a discussion between dancers, dancer researchers and HCI researchers. The result will be stated later.

Workshop 2a was a planning workshop for workshop 2b. Since there was a more than two years gap between workshop 1 and 2, we ran workshop 2a involving two dancers researcher and two HCI researchers to update the design outcomes during these two years' time and discuss the plan for workshop 2b which involved dancers. In the workshop 2a, I updated the portfolio of prosthetic covers developed from the aesthetic seeds generated from the workshop 1, and discussed the topics we would talk in the workshop 2b. The workshop 2b involved the whole team - two dancers, two dance researchers and two HCI researchers. It started with my presentation showing the portfolio of aesthetic prosthetic cover, visual comparison between the original prosthetics design and the optimised design by the Algorithm 02 - Optimisation of additive manufacturing, as well as various 3D printing materials. And then we had a discussion on the topics summarised from workshp 2b.

5.3 Data capture and analysis

We audio recorded and transcribed the discussions from the three workshops. We followed an inductive approach to coding that proceed in five iterations: (i) the HCI researchers analysed the transcript of the first workshop, generating an initial mindmap of tentative themes, quotes and example interactions; (ii) this was shared and discussed with the two dance researchers in workshop 2.a; (iii) refined themes and examples were then discussed with the two professional dancers in workshop 2.b and the ensuing conversation was transcribed; (iv) the HCI researchers analysed this second transcript, further refining and thickening the themes; (v) the findings and themes were written up in the paper which was read and approved by all parties. Themes concerning visual aesthetics and designing for disabled bodies were evident from the initial workshop, though were greatly expanded throughout subsequent discussions. The insights that aesthetics might extend to other matters such as form, materials and even the optimisation of 3D printing emerged from the later workshops, as did our generalised account of the co-design process.

5.4 Findings

Findings from three workshops are organised by four themes: attitudes to conventional prosthesis, Mogrow, applying aesthetic seeds to the design of prostheses, attitudes to prostheses and disability. The following content will state them separately in detail.

5.4.1 Theme 1 – Attitudes to conventional prosthesis

Frustration with the conventional prostheses

We discussed three frustrations with conventional prostheses: poor physical fit, cumbersome design and manufacturing process, as well as missing agency and autonomy. These are vital to the acceptance of the prosthesis.

Poor physical fit: Personalised prostheses have a better fit to a patient's body, which is crucial to patient satisfaction (Berke et al., 2010; Gailey et al., 2008). However, the traditional method of customised manufacturing prostheses entails plaster casting, which takes much time and human labour. This inefficiency of customisation of the traditional manufacturing approach brought a significant challenge to benefit prosthetic users at scale.

Dancers' feedback indicated that poor physical fit significantly prevents the acceptance of prostheses.

> *T: "We all have different bodies. I had a prosthetic once. But it was also quite based on a normative body and my body was so not normative. So I decided not to use a prosthetic because it doesn't work with my body."*
>
> *K: "That's the same for me. I can't wear a prosthetic because I've got too much arm. There's not enough room to fit the mechanisms in."*

Dancers show a strong desire not only for customised prostheses to fit their own body features, but also for extended prostheses matching their personal requirements exceeding traditional prostheses. They also expressed strong expectation that the additive manufacturing technology is capable to customise their prostheses efficiently.

> *T: "I think 3D printing enables customisation. This could be a real chance to exactly make it work for my body. And it's not just a leg, It's my leg or crutches. And my crutches would have a spring, because they are important to take off the pressure on my shoulders so I can walk and not get pain. And I think this is a really interesting opportunity here and potential to actually get these 3d printed prosthetics rather than from the (hospital)."*
>
> *W: "I wouldn't want a hand, I'd be really interested in something functional, but also really beautiful. (Handclap – T). Because there's no space in-between kind of a hand or a hook."*

The cumbersome design and manufacturing processis another frustration. Frequent modification of prostheses frustrates dancers. They desire a way to simply modify their own prostheses by themselves. 3D printing could be a potential approach.

> *W: "You have to go hundred times to the limb centre, backwards and forwards. People can't feel it (the prosthesis), whereas you could feel it. You cannot do it (modify the prosthesis) yourself and have to rely on somebody taking it away and coming back. That impacted your work and your mental health. (Yeah.- T) Whereas if you can keep doing it yourself and getting it right. (Yeah, exactly – T) Then that's the best way."*

Missing agency and autonomy may trigger negative feelings towards assistive tools. Traditionally, the prosthesis was designed by others and then passed to prosthetic users. There was no initiative of the users in the process of designing their prostheses.

> *W: "I think back ten or twenty years, there's no way we would have been able to get some crutches or prosthetics that we would be able to design ourselves. I think that's really sad."*

The missing of users' involvement in the design process of their prostheses may bring users the feeling that parts of their own body are determined by others, which triggers a poor sense of identity on their prostheses, sometimes even a sense of offence.

> *W:"we've had to have things that have been told. So you've had to have a part of your body (determined by others). I think T, I feel like your crutches are a part of your body in that sense. they are an extension of you. So it's like, they're a part of your body that somebody else is telling you what you have to look like."*

The missing of agency and autonomy has frustrated prosthesis users for a long period. They show strong passion when seeing potential solutions.

> *W:" It is like that people have been able to buy their own glasses for not long. You know, it's been quite new that we've been able to do that. All of those kinds of things that just for 28 years, I haven't been allowed to do that, allowed to touch, or body parts or play with them or do anything because you've got a sticker that says this is property of (others)."*

Aesthetics of the prostheses

Prosthetic users are seeking potentially diverse aesthetics of prostheses over the traditional bare pole model.. Some users make an old "NHS" aesthetic in a new way, for instance, W's friend recently made a prosthetic leg for her, which is based on the traditional bare pole model, but with old-fashioned details and materials, since W prefers organic and natural aesthetic styles, rather than the metal leg.

> *W:"That's designed to be like really old-fashioned. She (my friend) made it like knee bolts that actually wear all the time. It's like the NHS model but a really old prosthetic. Because I don't particularly really like the metal leg. It's not the*

> *fact that I don't want my leg to be seen. I particularly don't like the look of them. And I like organic. Feng is talking about in a way, like an organic, I love words. I love anything that's sort of natural things."*

There is a trend of appreciation of metal-looking, digital, and super technical styles, among younger prosthetic users.

> *K: "I absolutely think there is an emerging generation of young people who use prosthetic limbs, who actively seek out the digital, the manmade, the super technical."*
>
> *W: "I think at the moment, my age group and younger women at the moment quite often like having the metal showing on the leg. I think that's kind of where people's aesthetics is at the moment."*

Some artists who are also prosthetic users have also been exploring the new aesthetic trend of prostheses, e.g. Victoria Modesta (Viktoria Modesta, n.d.) explored cyborg aesthetics on her own prostheses.

> *W: "Victoria Modesta is completely like a cyborg. There's some huge mean, massive following in that way. Because I think people are starting to put bits of different machines in their bodies, I think there are a few sways towards that way."*

5.4.2 Theme 2 – Mogrow

The visual aesthetics of Mogrow

Our dancers showed appreciation for the wrinkled aesthetic design language of the Mogrow.

> *W: "I love the wrinkles because I do think they're really organic and human."*

Moreover, dancers indicated the wrinkled patterns represent disabled people rather than sleek patterns, which are common in conventional prostheses, though interestingly, the forms of Mogrow are inspired by the external nature rather than the human body, which is rejecting a sort of very artificial, digital, completely manmade aesthetics.

> *T: "Because I don't want something sleek, that's also not what I am. That's what I think disabled people are not. (Yeah, we're wrinkling – W). Yeah, we are. So we're so wrinkled."*

Dancers also expressed that the algorithm seems to have a mind of its own and produces wrinkles corresponding to their motions, which brings more meaning to the wrinkle patterns.

> *T: "I quite like the not randomness. Because it seems to have its own brain on how the wrinkles work. And where are they gonna bend or not? I really like that. They reminded me very much of myself in many ways. I still felt very much ownership over what I am."*

Dancing principles and interaction

Dancers showed a strong appreciation for the experience of generative co-design – especially design by dancing motion.

> *W:" I think it's a really lovely idea to play with your body and make something, create something from your body, moving. I think it's a bit confusing at first just to get our heads around what it was and how to do it, but I think once you really have it, then you can really start to play with it."*

There was a challenge in interacting with the generative design algorithm for dancers at the beginning, since this was a new way they had never previously experienced. But after spending a short time (like 10 to 20 minutes) on practice, they could understand it and operate very well.

> *M: "Was it hard? Did it take a lot of physical work to move the suit and get it to respond?"*
>
> *W: "Not really. I think it was just the understanding of it. (Yeah – T) In the beginning, you'd be moving and then you wouldn't know what thing had made what happened. I think it just takes time to get used to. But I think when it's really clear, you can then (operate). I think when we started to break it down, then that was clearer and slow it down. It was really clear."*

Two different interaction modes: functional mode and dancing principle mode were explored in the practice in workshop 1. The dancing principle mode showed higher acceptance, since the dancing concepts were explored to fit most of the existing dancing types and obtain a high degree of familiarity with dancers. Whereas the functional mode showed less familiarity to dancers, since it was developed based on basic motions that are not common in dancing practice or even in daily life. Dancers' motions seemed very clumsy in the functional interaction mode.

> *W: "I think the axis one (dancing principle mode) seemed to work better."*
>
> *T: "I think for me, it worked better in the sense of it (dancing principle mode) felt more three-dimensional. The first one (functional mode) felt very functional. But whereas this one (dancing principle mode) where my whole corpus was involved, felt more dancy, organic, and flavour."*

Dancer researchers indicated another potential reason why dancers prefer the dancing principle interaction mode: the dancing principle interaction mode enabled a co-creative interaction way, rather than a direct relationship and response in the functional interaction mode.

SW: "It's getting to the heart of some of your questions, in a sense. I think a dancer's interest is not so much in if I do this, that happens. It's a direct response to me doing this and that's back to the kind of function (functional interaction). Most artists are interested in what's that dialogue that happens and how we work together in that kind of co-creative way, rather than it being a direct relationship. It's a different process; it is not the conductor of the orchestra."

Improvements in interaction

There was some guidance on improving the details of the interaction mode for future studies, such as controlling the algorithm at different velocities and interacting by the motions of raising and lowering.

W: "The speed is the thing that I was struggling with. I think I couldn't control it. So I think maybe playing with the different speeds. Personally, I really like that I could get that (parts of the body e.g. arm or leg) raising and lowering to make the velocity go out in it."

The user study also revealed the potential of an alternative co-creative process. In the workshops, dancers interacted with the algorithm Mogrow by seeing real-time changes in designs responding to their dancing moves on the screen, which is like a process of "real-time interaction". The user study indicated another potential co-creative process – the dancers conduct any dancing moves they like, without seeing the changes in design. Then the design produced by responding to their dancing moves is a substantial record of the dancing experience. This process is like "recording a dancing experience".

K: "It's fascinating to see the difference between ('real-time interaction' and 'recording a dancing experience'). One is about we are looking at the screen and we're liking what we see. The other is about we moved the way we like. (During *the process), we're not really relating to what we're seeing on the screen. But the screen is reflecting our moving."*

T: "I think that is what we start to do later on in the workshop. We were looking at the screen and trying to create these shapes while moving, rather than moving to a specific song we like and ignoring the screen. I think I'd like a combination of both."

Non-normative bodies

The non-normative body features of the disabled dancers raise challenges as well as the potential to the relevant study, in various aspects, such as motion capture, and dancing framework designed based on the normative body.

The motion capture technology proved problematic, since the Rokoko smart suit is designed for the normative body with four limbs, but the dancers actually have three.

K: "SW and I were briefly talking about a kind of suit that's modified absolutely to fit your body. Would you think that would be different?"

T: "Yeah, definitely, It likes costumes. If it fits your body, you look much more different."

However, our dancers also recognised that this introduced a degree of creativity to the process and that it was interesting to have a "virtual limb" they do not actually have on the screen to control algorithm and conduct interaction.

SW: "There's that thing of putting on a normative suit of what that does in your moving. Putting on a suit feels like putting on a not you. You become something else. But when it's not your body as a suit, it kind of feels interesting. I wonder if that made a difference to how you moved."

T: "I don't think it made a difference to how I moved, but certainly how I felt. Seeing these four limbs on screen, where I have three, it's like, what is this? It's an interesting aspect maybe to even play with. When I swing my left side, where I don't have my left leg, the point (trackers) still works. I could create a speed that I couldn't with a leg. So that could be interesting."

SW: " It's almost like a visual prosthetic (yeah – T), you know, it's like a digital prosthetics in a way digital processes (Yeah - T)."

The "virtual limb" also has the potential to be extended more broadly, such as wheelchairs, crutches, and prostheses, which is the potential to obtain a much more sufficient and personalised interaction mode for each dancer.

M: "So it makes me think of extending the body as well (Yeah – T). Like an accelerant (sensor) on the end of an extended piece of costume and actually create a completely different sort of movement like that. That is really interesting."

W: "Or in the chair? Cause I was thinking about that as well in the chair. It'd be interesting to be in the chair and then maybe incorporate the chair within it."

M: "You could put accelerate (sensor) on the chair instead of the suit."

T: "That's the thing. Is it more like the sensor you can add to the joints or to the wheels, or to the crutches? Then, it becomes maybe more me. It's a tricky thing. And also probably depends on how I feel on the base."

The dancing principle interaction mode was developed under the guidance of the dancing concept "axis", specifically the relationship between two axes: the one linking two shoulders and the one crossing the left and right side of the waist, which suits two dancers' body features, even they both have a higher leg amputation. However, other dancing concepts may not fit disabled dancers, due to their body features. There is a requirement to develop dancing concepts, depending on specific features of disabled dancers, so as to guide further HCI study of disabled dancers.

K: "There's also something really interesting within this idea of dancing principles. What I think is worth considering is that actually for the disabled dancer, normative dancing principles often don't relate to or fit the body. Because this notion of access is perhaps really different in a non-conforming body. It just feels like an opportunity (to develop a dancing framework for the non-normative body) rather than adapting to normative dancing principles. There's something really interesting in that."

Aesthetic seed

The aesthetic seed is a unique design produced by a specific interacting experience between dancers and the algorithm Mogrow. It is a tangible design recording an ephemeral dancing experience.

Dancer researchers stated that this" design by dance" approach transformed the dancer's personal ephemeral dancing and interacting experience into something concrete – a personalised design. This whole process improved the feeling of agency.

K: "Because of the so-called ephemeral nature of dance, it is gone (after dancing). I am fascinated by the connection (between dance and design). Any dancer will feel the tangible 3D design that is produced from their dance. As observers of W and T, when I look at these beautiful designs, I can really remember the way were moving. If I am making it up for myself. I can kind of create a narrative around: 'Oh they were doing this kind of movement and I think I am seeing that in this thing."

Naming the design produced by Mogrow and dance was also discussed. Temporarily, these designs were all generally named "aesthetic seeds" by the thesis author. This name was acceptable to participants.

W: "I love the word that Feng has chosen - the aesthetic seeds that you sort of

> *seed something through your own movement. So there is that organic kind of fetal to it."*

However, there is still a requirement of naming specific designs. Dancers suggested naming them based on specific experience or movement.

> *SB: "Would you want to name the designs that you and Mogrow made there?"*
>
> *SW: "Does the name come with familiarity? They find an identity and find naming comes because you have a sort of closeness with it or a friendship with it, maybe."*
>
> *T: "Yeah. I think the name probably could come from that experience or movement, that made me feel a certain way. And I really liked that and I want to give it name, because it reminds me of that (experience or movement). I think for me, would be easier to name it in the process or after the process, or as you said, SW afterwards, when you know, the relationship develops with the prosthetic leg,"*

5.4.3 Theme 3 - Applying aesthetic seeds to the design of prostheses

Connection between users and designs – aesthetic seeds and prostheses

Dancers confirmed their feeling of ownership and agency in the aesthetic seeds, since they saw the real-time reflection of their own dancing motions on the screen. One noteworthy point is that they emphasised the feeling of ownership and agency through the dancing principle interaction mode.

> *T: "I did very much feel that (agency) in the second round (dancing principle mode). Because I could see the result quickly on the screen. When I spiral, it creates (forms). I can see it spiralling. Or when I go up faster, I can see wrinkles growing. I felt very much ownership of what I created."*

However, the dancers did not feel the reflection of their dance on the designs of aesthetic prostheses produced by extending the aesthetic seeds.

> *SB: "In any of the designs (both "aesthetic seeds" and design of aesthetic prosthetic cover), does it feel like they do embed any kind of personal movement or process you went through? Does it draw any memories about actual movements?"*
>
> *W: "Not so much the leg (design of aesthetic prosthetic cover). The designs before (aesthetic seeds) draw back memories."*

One possible reason for losing the feeling of agency in the prosthesis design is that, due to the effect of the Covid pandemic, the process of extending these aesthetic seeds to the prosthetic cover design was conducted without the involvement of dancers, so dancers could not reflect their interacting experience on the prosthetic designs.

> *W: "I think because we were seeing that (real-time procedure of producing aesthetic seeds by dancing-interaction) when we were doing it. When we were seeing that image (aesthetic seeds were shown to dancers in the third workshop, which is three years later after producing these aesthetic seeds) coming up on the screen, we could see what we were doing. So I feel more of a connection there."*
>
> *SB: "Yeah. So you generated it ("aesthetic seed"), you saw that image and then there's that recognition, that was me dancing, but not when it's been transformed again."*

Fortunately, dancers also indicated the potential to re-establish the missing emotional connections.

> *T: "I can't recognize which of the seeds (aesthetic seeds) has been taken (to produce a particular prosthetic cover design). For example, if I know that was the "aesthetic seed" number one of Tanya in that prosthetic leg. And then I can make that connection again probably. Just like we decided on which vase we like best and things like that (after the dancing workshop, W and T chose their favourite aesthetic seed (vase shape). There's much more emotional connection to it."*

Thus, the aesthetic seeds produced through the dancing principle mode strongly reflected the dancers' interacting experiences and brought feelings of agency and personalisation. However, the design of the aesthetic prosthetic cover extended from the aesthetic seed failed to reflect the dancing–interaction experience, which has the potential to be improved by building emotional connections.

Materials and personal aesthetic taste

Material is important for designs since different materials usually invoke various additional feelings. There are plenty of 3D printing materials in the market. Figrue 5.3 illustrates some examples of 3D printing materials, which have been shown to dancers in workshop 2b. Prosthetic designs with different materials and various 3D printing materials were presented to users in workshop 2b. And the discussion was conducted on the topic of materials after the presentation.

The discussion on materials with users started with transparent material, through which the metal bar and mechanical components are visible. Dancers showed a strong appreciation for this.

> *T: "I was very intrigued by the see-through or the glass one (prosthetic cover produced by the present design approach) (Figure: 5.2)."*

One reason for dancers' appreciation for the transparent prosthesis is that the transparent cover consists of wrinkled geometry, through which the inner structure is visible, but reshaped by the wrinkled transparent cover. This phenomenon not only brings a daedal visual of the inner structure and sufficient potential to be applied to the stage interacting with light.

Figure 5.2: Prosthesis with see-through material.

> *T: "The glass one (Figure: 5.2) breaks up the sleek line of the red metal. I really liked that, It seems to be moving differently in itself. Then I can imagine when the light breaks in, you can play so much with that, especially in a performance or a setting or something like that."*

Another reason is that the transparent prosthesis mixes the function of the prosthesis and art. It emphasises simultaneously function and aesthetics, rather than simply pretend human limb.

> *K: "Does it feel important that you can sense the workings, the functionality of the prosthesis, and what's happening in the prosthetic leg? So it's not pretending to be a normal leg, but you also have a sense of the functionality because you can see the workings. Does that feel important or even a thing?"*
>
> *W: "I think it's nice to have that extra side to add an art piece on top of the function. So it's like a mix of two. So it's really nice to have that mix."*

Then the discussion transferred to various 3D printing materials, which was conducted after I showed images of various possibilities in workshop

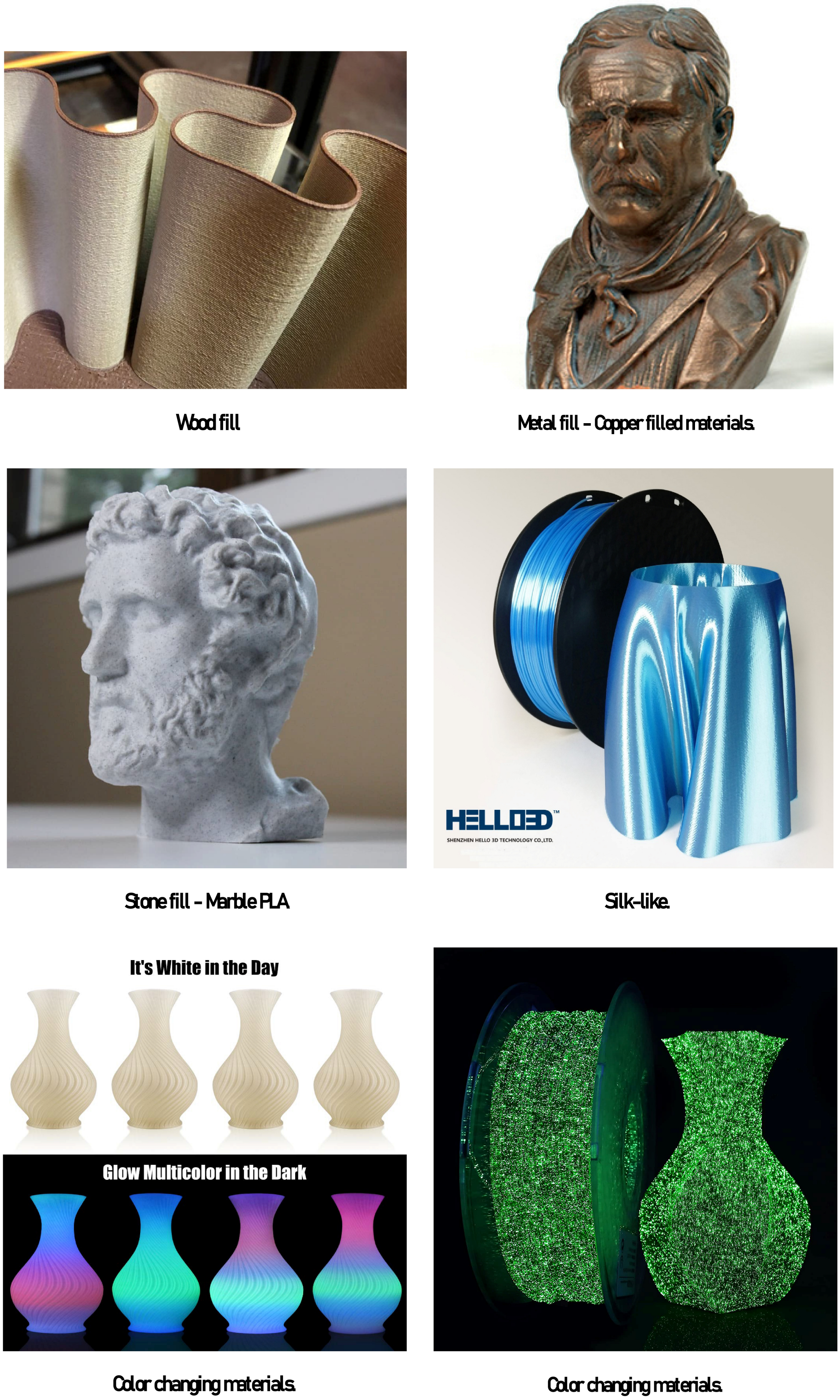


Figure 5.3: Other 3D printing materials.

2b. W showed appreciation for most of the organic materials from nature, rather than the materials similar to the human body.

> *W:" I think everybody's so different on what they like, aren't they? But for me personally, it will be organic ones. I love silk, wood, stone, all of those kinds of ones. I love all of them."*
>
> *SB: "Yeah, natural organic materials, which come up in the conversation a few times, seemed to me about organic materials in the natural world, beyond the human body. If I got that right, is there a particular reason why is that attractive, as kind of an area to find materials?"*
>
> *W: I may personally think Because the body is an organic thing, that (natural organic materials)'s what I just sort of like. I've actually worn prostheses with pretend skin. But I'm not so interested in wearing that.*

W also showed interest in replacing prostheses made of different materials for different occasions, e.g. one that can be lighted up for clubbing and one showing normal materials for daily work.

> *W: "I do like the one that changes colour. In the sense that you can have two different (prosthetics). It can give a different life. If you're going to go out clubbing, then you can go (with the luminous one). And you can wear a prosthesis made from normal-looking material for daily work."*

The perception of materials appears to be subjective. K showed strong interest in glazer materials but rejected materials appear comedic.

> *K: "I think this is really interesting that we don't have the exact same perception, the same experience of it. I really like all that glitter ones (Figure: 5.3). And there's something just ringing a bell for me, this is perceptual and it's also totally subjective. I'm aware of something in me that slightly avoids anything that might appears comedic. I'm saying I do not want to go against things and stand out. Cause I'd be contradicting myself, (if do so). I actually think it's about one's own perception."*

The feedback on more 3D printing materials showed the preference for the materials for building prostheses is subjective. W showed primarily interest in organic materials, rather than mechanical-looking materials,whereas, K showed interest in both glazer and organic materials. However, K was concerned more about the agency of the design and materials of the prosthesis, but tried to avoid "against anything".

Feedback on the design modified by the algorithm 03: optimisation of additive manufacturing

The algorithm 03 – optimisation of additive manufacturing was developed to modify the prosthetic cover design extended from the aesthetic seed, to improve the manufacturing efficiency. Specifically, it eliminates overhanging parts that require printing supporting structures during additive manufacturing, which took much time and materials. However, simultaneously, the appearance of the modified design needs to be as same as possible as the original design. The result of the experiment stated in Chapter 3 has demonstrated that algorithm 03 efficiently reduced the material and time consumption of manufacturing. To evaluate whether the algorithm keeps the original pattern, participant's feedback was collected as follows:

> *Feng: "Can you tell difference between these two designs?" (prosthetic cover designs with and without revision by the algorithm 03 - efficiency of additive manufacturing.)*
>
> *W: (shook her head).*

Thus, algorithm 3 improved the additive manufacturing efficiency, and simultaneously saved the aesthetic details.

5.4.4 Theme 4 – Attitudes to prostheses and disability

Compared with traditional prostheses, the generative co-design and manufacturing approaches of the present study are distinct in the following aspects. The design approach enables customising aesthetics of prostheses with users' involvement in the design process, which brings the feeling of personalisation, agency, and ownership to the designed prosthesis. Moreover, the additive manufacturing approach enables the customisation of the prosthesis, based on an individual's body features or specific requirements for augmented prostheses. These features expand participants' attitudes toward the prosthesis and even disability.

Form and function

Unusual forms of augmented prostheses bring new constraints and opportunities for movement. The augmented prostheses explored by the present study do not have to be the leg shape. Its shape could be flexible based on specific requirements. This randomness in the geometry of augmented prostheses brings new constraints and opportunities. It requires consideration of specific shapes, characteristics and feelings. This phenomenon also triggers reconsideration of the relationship between the prosthesis and its user – does the prosthesis move the user, or does the user move the prosthesis?

> *T: "When we talk about dance and movement, this is a movement investigation: how does that prosthetic leg or whatever I've created now, move me rather than how I can move it? It's based on shape, based on characteristics and how it feels. I think it's beautiful. And with that, massively long stage, it makes you want to move a certain way and its choreography. And for me, that crib choreography is*

> *beautiful."*

Prostheses with unusual forms are potential to be applied as an element of performing disability. K introduced a relevant social activity.

> *K: "There's an amazing Canadian visually impaired artist. He does a live-work - social interactive piece. He has a cane, which is meters and meters long. When he walks around the streets, wherever he gets, people are pushed out of the way. It is real amplification of what people look at. He gets assistive aid is so big that people can't ignore it."*

There is a fine line between an art piece and a functional piece of prosthesis. It firstly shows in design. The prosthesis for performance does not have strict requirements of functional consideration. So, its geometry could be random for performance. But the design of the prosthesis having functional requirements has a limitation on geometry.

> *W: "If we were thinking down the performance way, we don't need to consider functional and disfunctional. So you could completely make something that's really funny to play with. There are lots of different tangents that you could go down in that way. But for functional, I think if it was for a crutch or a leg, it has to stop at some point to be functional. Because if it goes with bits pointing out and going all over the place, then you wouldn't be able to walk at all with it. So it has to have a limit."*

A fine line between an art piece and functional piece of prosthesis is also shown in physical features such as weight. User feedback indicates the weight makes a significant difference on prostheses, when considered functional or dysfunctional. For instance, some material is too heavy to be appropriate for functional prostheses, e.g. wood, for which the application of alternative 3D printing materials show similar texture may be the alternative solution for a functional prosthesis. Correspondently, an artistic prosthesis has randomness in material choice.

> *W: "Weight makes quite a big difference with prostheses, especially with the artificial leg, The wooden leg (from the project of alternative limbs) is really heavy to wear. So it's very much an art piece rather than a functioning piece. I think there's such a fine line between an art piece and a functioning piece. you curb things that you'd really want to have, like I would love to have a wooden leg. But I just wouldn't be able to walk with it. Cause it's just too heavy. But, as you said, you could make different materials that look like wood, so that's really great."*

Expanded roles of the prosthesis

The present study brings many innovative factors to the prosthesis by applying the generative co-design approach and additive manufacturing technology to the process of prosthesis customisation, which triggers prosthesis users to reconsider the role of the prosthesis, like jewellery and costume. The shifting of the role of the prosthesis also means shifting attitudes toward disability.

Jewellery: Dancers showed high appreciation for the role of jewellery. One reason is that they thought dance goes well with jewellery.

> *W: "I feel like jewellery and dancing really go well. I do not know if there's something. (Yeah, Why is that? That is so interesting – K). That is really lovely together. (Is it about fluidity or person? I don't know, it is fascinating! - K) . I mean, creating jewellery with your body would be amazing. (Yeah, really I think. – K). Actually, everybody would love to do it. (Yeah.- K, Yeah, - T)."*
>
> *K: "I've said to you (W) for ages, that I'd really like to get a brace, something that's there, but that it's very difficult to find such a thing. So it'd be really interesting to make it."*

The other deeper reason might be that creating designs of the prosthesis with their own body and motion brought feelings of personal identity, just like the feeling that jewellery brings to humans.

> *K: "I think that's fascinating. It goes back to ownership and autonomy. There's something about identity, about creating something, and particularly about a disabled identity. So recently, I just bought a solid silver hand. That I sometimes wear on a necklace, and actually, it's got so much meaning for me."*

Costume: Another potential role of the designed prosthesis is costume. The designs produced by the present design approach brought a feeling of autonomy, which is vital for disabled dancers but has been overlooked by the conventional costume.

> *K: "Are our voices included in the design? I think there's a really distinct difference (between users' voices are included and not). I'm interested in the question of, is it a costume? It's really great to have those conversations about how a particular costume works for your body, versus someone just layering stuff on."*

Augmented prosthesis beyond the body: Our dancers showed interest in the topic of the visibility or invisibility of prostheses. The form of the prosthesis does not have to look like parts of the human body. It could be either merged together with the environment e.g. installations on stage to be invisible or enlarged to emphasise the disability. The visible and ivisibility of the prosthesis might vary for different roles, such as users and spectators. Thus, playing with its visible and invisible is the potential to enrich the innovative and artistic expression of the prostheses.

> *T: "I'm not wearing a prosthetic, but I have my mobility aids and assistive tools e.g. my crutches. I'm really interested in the way, how I walk with my crutches and make the mobility aids invisible. It lets the body appear in a different way. If*

you would like to let prosthesis disappear in a way, on stage and in a performance setting, I think you could do amazing things with that and play with this idea of making things visible or invisible. For instance, for the one having that visible disability, it's very visible and visceral, It's very there for me. But for someone who is not having it, it's not visible."

The politics of the body

A third strand of the prosthesis more than function and aesthetics is proposed by the user study as politics, which concerns how disability is perceived.

K: "There seems to be something about politics. I was imagining there's something that could attach to my left hand and be massive, like really long and curl around my body. I could push it across the stage. It takes up space and there's something fundamentally political about that. It just feels like a little extra thing than aesthetics and function. So it's not a function of how is this limb enabling me to do something nor an aesthetic thing of how it's conforming to a human limb. But this third strand, this political strand is actually this kind of resisting, not being seen. There's something very specific about the experience of having a missing limb. But for me, there's something about how that's perceived. I love this idea of just decorating my left hand in a way that invites looks."

The autonomy of the prostheses also reflects the politics of the body. The feeling of autonomy and ownership of the prostheses is vital, since missing autonomy of prostheses triggers users to feel having part of their own body given and determined by others, which might be a primary reason why many disabled people reject using prostheses. However, this phenomenon has been overlooked in a long term in designing and manufacturing prostheses.

K: "I'm finding it so interesting. W and T, you're both nodding towards a situa-

tion of (ownership & autonomy). That autonomy in the (present designs) seems to make a really big difference to how you relate to them. And that made me think that it feels so important, vital even, for this relationship with one's own assistive tools or prosthetics. It's neither something basically medical models of disability, nor something that's being handed to you. It's kind of you're in control of it."

The personalised prosthesis embedded with a specific interacting experience brought users' feelings of autonomy and ownership, which gained an appreciation of dancers.

T: "I think to have this option of putting a layer on it, makes it (prosthesis) even more (interesting). It's a bit more of my taste, just like that part is connected to the experience I had. We had these shapes we created, that had been already attached to a specific experience. How amazing they are!"

Another politics of the body and prosthesis raised in the user study is appropriation. Dancers proposed the question of who has the ownership of the prosthesis, which is vital.

T: "I do hear a discussion on appropriation: who is allowed to wear a prosthetic; who creates a prosthetic and then use it in art; and who makes lots of money out of it. I think it's a very important question. It also gets political, isn't it? Is it (prosthesis) part of the disability culture that we create here? Or is it an art piece? To whom does it belong?"

Conventionally, the ownership of the prosthesis design usually belongs to designers or creators, rather than the users. This phenomenon may trigger problems for the prosthesis users since the disabled sometimes see the prosthesis as part of their own body. Then it would be strange that part of their own body is owned by others. It opens up all relevant ethical questions.

> *SW: "It gets a bit complicated. W, I think you were saying earlier that the prosthetic is never yours. It's always owned elsewhere. We're not used to the idea that we don't own our bodies and performance. But the prosthesis has a different relationship to our body, since who made it claims its ownership. It's a tangles situation in a way. It's quite interesting though. I think it opens up all sorts of ethical questions as well,"*

To summarise, this chapter demonstrates the user study. User feedback plays a significant role in the evaluation of outcomes of the design and manufacturing phases. The next chapter will synthesise all research outcomes consisting of the design and manufacturing phases with results of user feedback and conduct analysis.

Chapter 6

Framework

The previous chapters have explored the generative co-design and non-planar additive manufacture of personalised aesthetic prostheses. In particular, they have introduced algorithms to generate aesthetic seeds, driven by user interactions such as dancing, applying these to different physical forms, optimising these forms for efficiency of additive manufacturing; developed a non-planar additive manufacturing platform for manufacturing aesthetic prostheses, enabling mechanical performance without concession to aesthetics and weight; as well as reported a series of workshops, through which dancers tried out the interactive technologies, reflected on the resulting designs and evaluated the various innovations on design and additive manufacturing approaches. This chapter aims to bring all outcomes together through a framework.

Figure: 6.1 summarises the framework, which integrates design, manufacturing and user evaluation perspectives into a workflow for creating personalised aesthetic prostheses. It consists of three main phases: a design phase, a manufacturing phase and a user evaluation. This section will summarise the outcomes for each phase in five subsections, illustrated in

Figure: 6.1. The user evaluation was conducted to evaluate the innovations in the design and manufacture of aesthetic prostheses. Thus, the outcomes of user evaluation will be separately stated in the corresponding design and manufacturing subsections.

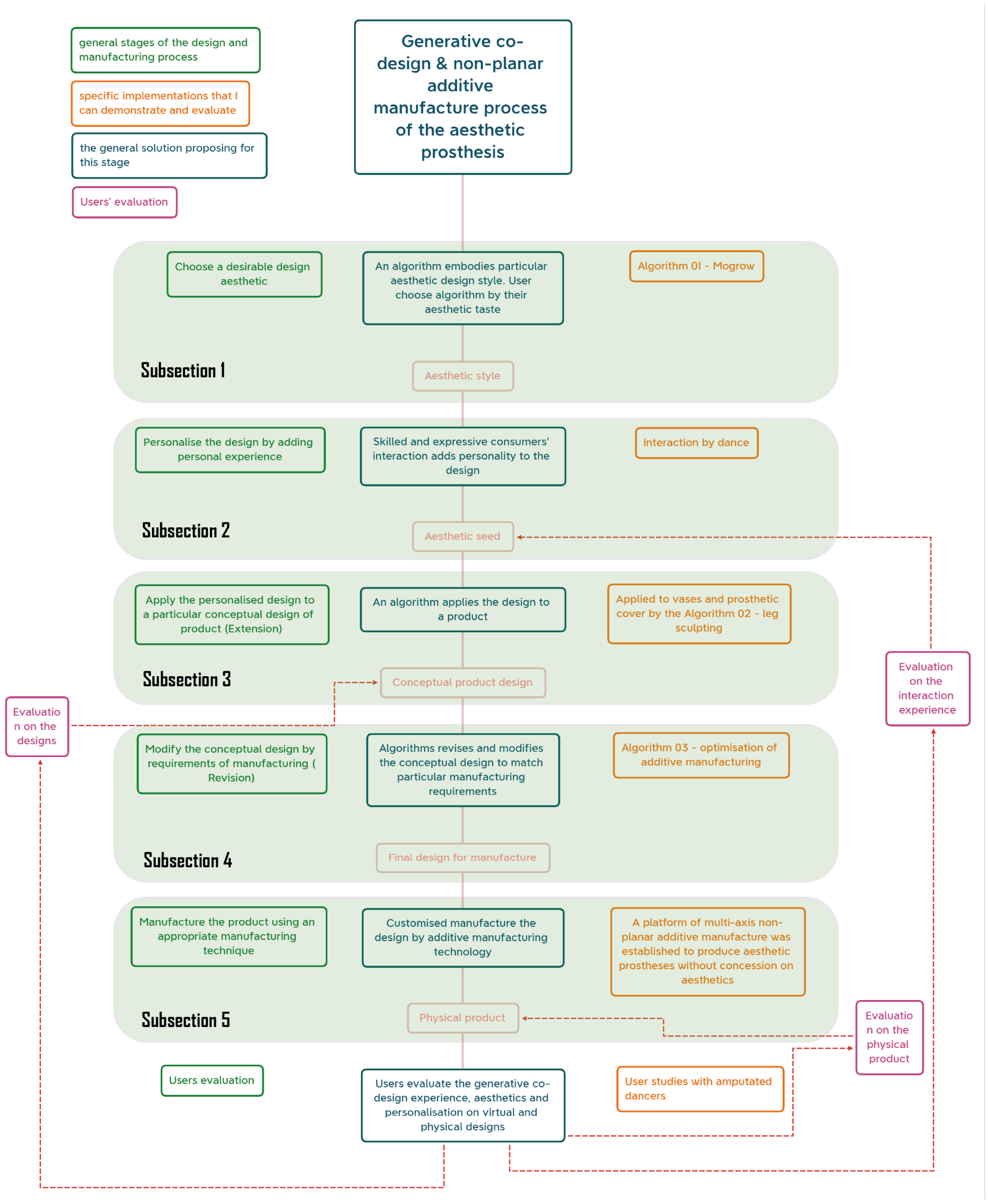


Figure 6.1: Generative co-design & non-planar additive manufacturing process of the aesthetic prosthesis.

6.1 Choose a desirable design aesthetic

Outcomes

The framework starts with “Choose a desirable design aesthetic” by selecting the corresponding algorithm, which is also the first step of the design phase. In the present research, one example generative co-design algorithm - Mogrow - has been developed to be the chosen algorithm. It produces designs with curved and organic aesthetic styles inspired by the beauty of nature (Franke, 1997) and Birkhoff (1933)’s aesthetic formula. It can produce massively various aesthetic designs without the involvement of professional designers.

Evaluation

Aesthetics of Mogrow: Mogrow is capable to produce aesthetics with high acceptance by dancers. The user study indicated that both the two dancers showed appreciation for the organic and wrinkled designs produced by the algorithm Mogrow. They also stated that the aesthetics of other generative design algorithms are also interesting, when designs produced by other generative algorithms are shown to them.

Aesthetics of generative design: This phenomenon further indicates that the application of generative design is potential to produce acceptable personalised aesthetic designs.

Expand the application of generative design: Most conventional studies of generative design focused on the improvement of design efficiency and shape optimisation (Chase, 2005; Cleveland, 2010; Gu & Behbahani, 2018; Kielarova et al., 2013; Krish, 2011; Lin & Lee, 2013; Rodrigues et al., 2015; Shea et al., 2005; Singh & Gu, 2012; Troiano & Birtolo, 2014). There is a significant gap in applying the generative design approach in the practice of producing aesthetic designs. This thesis fills this gap by establishing the generative design algorithm Mogrow and applying the produced aesthetic designs to specific products.

Massive customisation of aesthetic designs: Rather than customised manufacture, customisation of aesthetic design is another significant challenge of customisation, which was usually overlooked. It took too many resources of professional designers to benefit users at scale. This phenomenon is significant in designing aesthetic prostheses. The generative design has been seen as an efficient solution for customised product development, since the application of the power of computers enables to perform creative tasks more efficiently than the conventional approaches (Gabriel et al., 2016; McKnight, 2017). Moreover, the present study demonstrates generative design is potential to produce acceptable aesthetic designs by dancers. Thus, it is feasible to produce massive customised aesthetic designs for every prosthetic user, which bridges the gap between the limited resource of professional designers and the massive requirements of aesthetic customisation in the process of designing prostheses.

Expansion

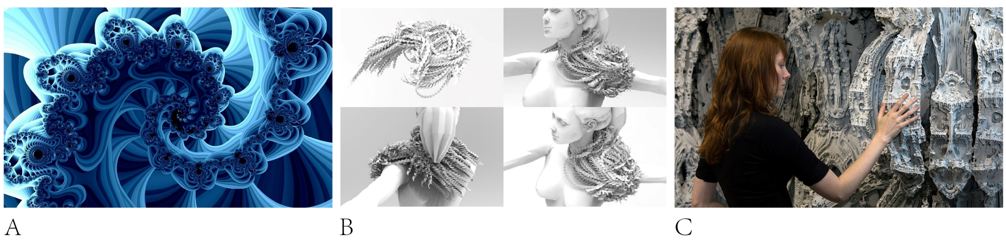


Figure 6.2: Designs by generative design approach (Fractal Wallpaper, n.d.; Hansmeyer & Dillenburger, 2017)

Each generative design algorithm usually carries a particular aesthetic style (Fractal Wallpaper, n.d.; Hansmeyer & Dillenburger, 2017; Schumacher, 2017). Figure: 6.2 illustrates designs from various algorithms. The design by the algorithm based on Fractal shows regular, repetitive, but simultaneously high complexity by multiple iterations of a similar pattern (Figure: 6.2a). Figure: 6.2b demonstrates a design by the algorithm developed from flocking. It carries a flowing aesthetic. The design shown in Figure: 6.2c takes a high-resolution aesthetic that human designers could hardly achieve. It is produced by a single volume that spans millions of branches, growing and folding repeatedly. It should be noted, that the overall integrated design and manufacture workflow illustrated in Figure: 6.1 would be equally applicable to any other design aesthetic selected.

6.2 Personalise the design by adding personal experience

Outcomes

After selecting the algorithm, the next step is to "personalise the design by adding personal experience", in which skilled and expressive consumers interact with the selected design algorithm to add personality to their designs. As stated in the literature, Blom (2018), personal experience can significantly increase the feeling of self-identity with a design.

How to embed a user's personal experience into their prostheses design is the aim of this step in the design process. The co-designer is the dancer, who can expressively interact with the environment and algorithms through dance. In the algorithmic approach used in this research, motion capture technology is used to generate data that represents the users' dancing. This data is used as input to Mogrow which then produces the corresponding aesthetic design. Thus, a co-design approach combining the users' personal interaction experience with the Mo-grow algorithm enables their dance to be embedded into a unique aesthetic design. This unique aesthetic design at this stage is best termed an aesthetic seed as it has not yet been applied to a particular object. i.e. Rather than create a specific design, Mogrow creates an aesthetic seed which is an aesthetic archetype. The dancer's involvement in the early stage of the design process represents how co-design theory was applied to this study. A workshop was conducted with two female lower-limber amputated dancers to produce the aesthetic seeds. The first rows of Figure: 6.3 & 6.4 illustrate these aesthetic seeds by two dancers: T and W They consist of multiple closed curves and show a continuous transformation from bottom to top. These aesthetic seeds will vary with different dancers and with different interactive experiences with the same dancer. Thus each aesthetic seed represents a dancer's particular personalised interactive experience with Mo-grow.

Evaluation

The artistic expression of dance: Researchers have explored the dance as an instrument for artistic expression, which exploits the aesthetic, expressive and creative qualities of the body (L. A. Blom & Chaplin, 1988; Loke & Robertson, 2011; Schiphorst, 2011; Zhou et al., 2021). This artistic expression has been expanded to accompaniment to human dancers such as visualisation, costumes, or mechanical bodies which respond to the performance's human dancer (Karpashevich et al., 2018). The present study firstly further expands the artistic expression of dance as the form of product designs, which indicates a new field of dance artistic expression.

Motion capture: The technology of motion capture technology has been applied to research of dance, for instance, "kinaesthetic creativity", which explores the emergent and dynamic relations between the moving body and interactive technology during creative processes such as movement ideation (Hsueh et al., 2019; Svanæs, 2013). This study reveals there is a significant research gap in the application of motion capture technology to dance research for the non-normative body. It also indicates the potential of applying extended motion capture technology, which not only tracks the human body but also extended body parts like wheelchairs, crutches, prostheses or anything else users see as their body extension, showing strong potential to rich and personalise the interaction mode, in the HCI study of disabled dancers.

Dancing principle: Raheb, Whatley and Camurri (2018) proposed dancing principles broadly suitable to various dance genres, such as contemporary dance, ballet, Greek folk, flamenco and so on. This study applies the dancing principles as guidance of interactive manner for dancers to interact with design algorithm and indicates that the application of the dancing principle improves the efficiency and pleasure of the dancers' interacting experience. On the other hand, these dancing principles were designed based on the normative human body. The present study expands the application of the dancing principles to the dance study on the non-normative body and indicates it is essential to tailor the dancing principles to fit the non-normative body.

Co-design: This is also a co-design process enabling users' involvement in the early stage of the design process, which enriches the research of the topic – co-design & prosthesis, like Blom (2018)'s study indicated that co-design embodied a deeper, richer expression of the individual identity of the amputees beautifully and intricately. Moreover, the conventional approach to enabling the prosthetic users' involvement in the co-design process primarily relies on conversation through which, users and designers directly discuss feelings and aesthetic preferences. This process requires the deep involvement of professional designers, which brings significant challenges to massive benefits, due to the limited resource of professional designers. The present study enables the users' involvement in the co-design process through the interaction between dance and generative co-design algorithm, which is capable to produce aesthetic designs automatically, without the involvement of professional designers.

Expansion

The present study only applied one of the ten dancing concepts based on the normative body. The exploration of the modified dancing concepts considering special body features of disabled dancers and application of more dancing concepts will be potential to enable the personalised interacting mode (interacting motion package) in the HCI research based on dancers' personal body features and dancing habits.

Moreover, the extended motion capture technology is potential to bring more flexibility to this interacting motion package.

6.3 Extension – apply the personalised aesthetic seed to a particular conceptual design of the product

Outcomes

The next step of the design phase is to apply the aesthetic seed to a specific product, which is defined as "extension". In this study, the objects selected to illustrate this design step were a vase and an aesthetic prosthesis

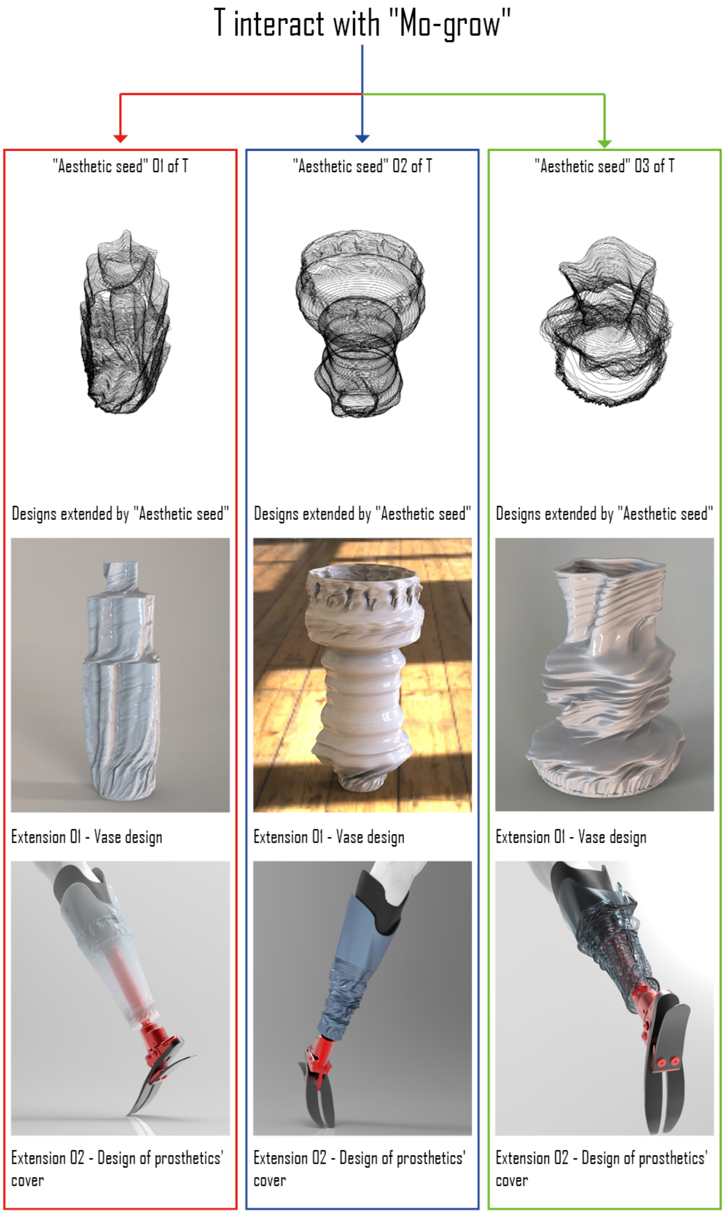


Figure 6.3: aesthetic seeds, vase designs and designs of aesthetic prosthesis cover by the dancer T.

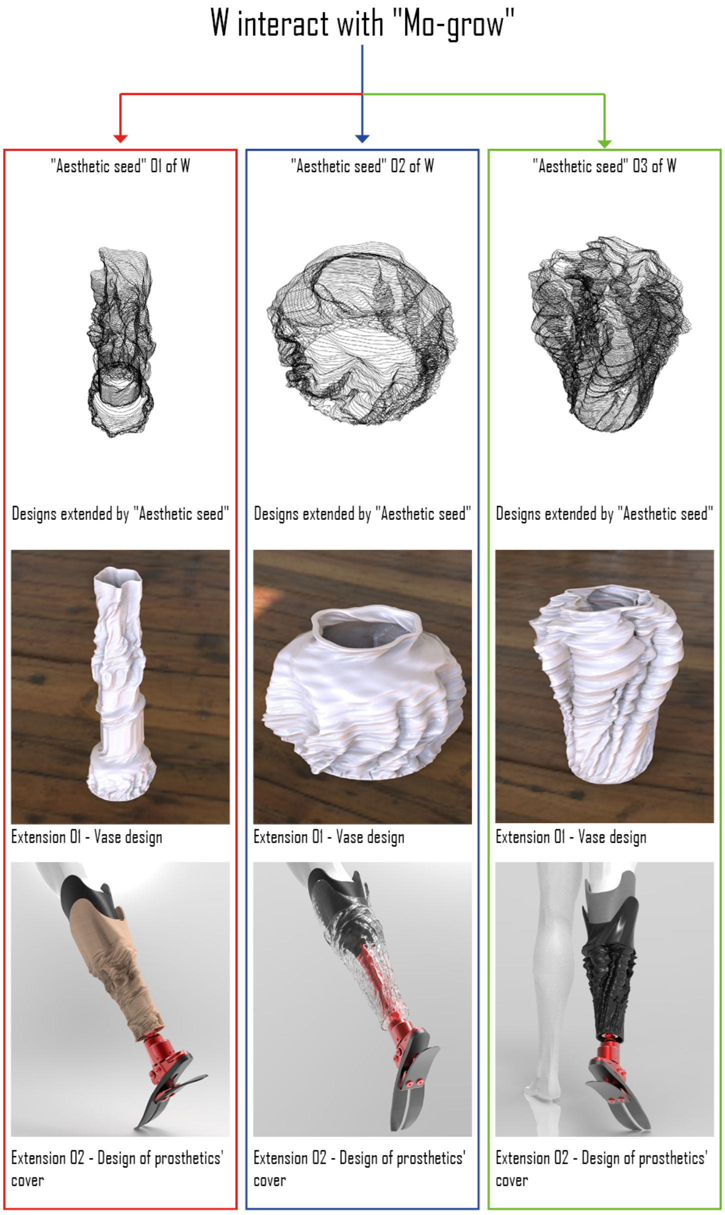


Figure 6.4: aesthetic seeds, vase designs and designs of aesthetic prosthesis cover by the dancer W.

cover. The vase was generated by simply joining lofted curves consisting of aesthetic seed. The aim of this exercise was to quickly show how the aesthetic seed can be extended to a specific product design. The second rows of Figure: 6.3 & 6.4 illustrate vase designs extended from dancers T and W's aesthetic seed. The next development of this design step focused on the aesthetic prosthesis cover design. Algorithm 02: leg sculpting was developed for this purpose. It applies a personalised aesthetic seed to a prosthesis cover design and simultaneously customises the design functionally based on the user's personal features. The bottom rows of Figure: 6.3 & 6.4 demonstrate these prosthesis covers' design.

Evaluation

Functional customisation: Enabled by 3D scanning of the sound limb and generative design algorithm, this step achieves automatic customisation of the prosthesis design fitting personal body features, without the involvement of the professional designers. As demonstrated above, the customised design has been overlooked but is quite essential to the process of prosthesis customisation, since the relevant study of prosthesis customisation primarily focused on the manufacture, but the fact is that the process of customised design usually requires many resources of professional designers triggering it fails to benefit prosthesis users at scale. This study developed an approach to automatically customising the prosthesis based on personal body features, which significantly improves the efficiency of this customising process and potentially benefits prosthesis users at scale.

Aesthetical customisation: At the same time as functionally customising prosthesis design based on personal body features, the unique aesthetic style embedding the personal experience on the aesthetic seed produced at the previous step is transferred to the design of the prosthesis. This embedded personal experience enables a deeper, richer expression of the individual identity of the amputees beautifully and intricately. Thus the prosthesis is both functional and aesthetic customisation for its users, which both functionally and psychologically benefits prosthesis users.

Refreshed attitude to the prosthesis: Due to the significant changes compared with the conventional design process of prostheses, the design approach of the present study triggered dancers to shift their attitude toward disability and reconsider the role of their prostheses by bringing the feeling of personalisation, agency, ownership and autonomy to the design and enabling customisation based on their body features and specific requirements. The shifting of the role of the prosthesis also means shifting attitudes toward disability, which is potential to improve the psychological feeling of prosthesis users and open a broader scope to the relevant study.

Expansion The aesthetic seeds are also potential to be extended to other designs by developing corresponding algorithms based on specific requirements, like souvenirs produced by a meaningful dancing show on the stage, crutches or wheelchairs, or any other designs, on which dancers would like to implant their marks, particular experience or personality.

6.4 Revision – modify the conceptual design to the requirements of the manufacturing

Outcomes

Modifying the conceptual design to produce the final design for manufacture is the final step of the design phase. Specifically, the optimisation of additive manufacturing efficiency (from a design perspective) is the aim of this step. Algorithm 03 – optimisation of additive manufacturing was developed to reduce material consumption and manufacturing time by eliminating overhanging parts, thus removing the need for a supporting structure in the additive manufacturing process.

Evaluation

Improving the efficiency of additive manufacturing without compromising aesthetics: Most of the conventional research on the improvement of additive manufacturing by optimisation of supporting structure, has a prerequisite – reversing the original design (Jin et al., 2015; Masood, 1996; Mohan Pandey et al., 2003; Thrimurthulu et al., 2004; Z. Zhao & Laperrière, 2010), which may be triggered by the separation of the design and manufacturing processes. For that, most designers or engineers normally search solutions in their own field. The application of generative design and additive manufacturing bridge the design and manufacturing into an integration process. The produced design could be directly applied to produce data for additive manufacturing, which drove me to consider breaking the prerequisite reversing the original design, and exploring the question: is that feasible to eliminate supporting structure for time and material consumption during the process of additive manufacture by slight changes to the design, especially when the design details primarily relate to aesthetics? The printing experiment in Chapter 3 and the user evaluation of the aesthetics of the designs revised by algorithm 03 optimisation of additive manufacture demonstrate that algorithm 03 efficiently improves the printing time and consumption of materials and simultaneously keeps the original aesthetics of the conceptual designs.

Expansion

This algorithm is applicable to more 3D geometries by slicing the 3D model into equidistant contours, scanning and modifying the overhanging parts and creating the new 3D model, for which all overhanging parts have been eliminated by these revised contours. It is also applicable to various additive manufacturing technologies more than FFF, such as Selective Laser Sintering (SLS), Stereolithography (SLA), Direct Metal Laser Sintering (DMLS) and so on, since most additive manufacturing technology has the requirement of printing supports in the overhanging parts.

6.5 Manufacturing

Outcomes

After the design phase, it comes the manufacturing phase. Beyond improving manufacturing efficiency through design optimisation explored in the design phase, this phase primarily focuses on improvements within the manufacturing scope. It explores an additive manufacturing approach capable to balance the requirements of mechanical properties, weight, and aesthetics for prostheses, as well as users' attitudes towards common materials in the market for FFF.

Aesthetic designs usually require a high degree of geometric freedom than functional designs, which easily conflicts with the requirements of physical factors of a prosthesis, e.g. mechanical properties and weight. Thus, an important aspect of this project is to investigate manufacturing methods that are suitable for both the structural and aesthetic demands of the designs. Following a study of potential manufacturing methods, a commercial 6DOF robot arm was selected as the most appropriate platform for the non-planar additive manufacturing of aesthetic prostheses, enabling the required mechanical performance without concession to aesthetics and weight. Based on the 6DOF robot arm, the present research developed a non-planar additive manufacturing platform consisting of a slicing and controlling system and a multi-head extruder. The platform can broadly work with the various 6DOF commercial robot in the market and potential to adapt various applications of non-planar additive manufacturing.

Moreover, users' attitude towards common materials in the market for FFF has also been explored. It indicates that users show subjective on materials building their prosthesis, and various 3D printing materials show potential to suit different users. For instance, one participant was fond of most of the organic materials from nature, rather than materials similar to the human body or shiny-looking materials like metal. Correspondingly, another participant was interested in glazer materials but rejected materials appear comedic. The application of transparent material even inspired deeper consideration of the expressions of prostheses. Rather than simply mimicking a human limb, transparent material emphasising simultaneously function and aesthetics attracted all participants.

Evaluation

Establishing a non-planar additive manufacturing platform: non-planar additive manufacturing has been demonstrated broad improvements for the conventional additive manufacturing technology, such as supporting-free printing (Lin & Lee, 2013; Wu et al., 2017; Xu et al., 2019; H. ming Zhao et al., 2018), improving printing efficiency (Huang et al., 2016), significantly increasing the strength of prints (Allum et al., 2021; Fang et al., 2020a; Pelzer & Hopmann, 2021), improving the printing quality by eliminating the staircase effect (Etienne et al., 2019; Llewellyn-Jones et al., 2016). However, there are still significant challenges to conducting multi-axis non-planar additive manufacturing, such as a lack of standard hardware and a corresponding control system. The present study fills this research gap by establishing a non-planar additive manufacturing platform broadly suitable for various non-planar additive manufacturing applications.

Improving strength by eliminating anisotropy: The Anisotropy of mechanical property – strong along with the axial directions of filaments but weak in other directions – can be observed in all models fabricated by FFF (Ahn et al., 2002). It is also a significant challenge for additively manufacturing prostheses. Maroti et al. (2019) explored anisotropic mechanical properties in additive manufacturing of upper limb prosthetics and indicated special care should be taken in designing the printing processes, because the mechanical properties of the manufactured objects are significantly influenced by the orientation of printing. However, there is quite rare relevant research on improving the mechanical property by eliminating the effect of anisotropy. Fang et al. (2020) presented an algorithm for non-planar volumetric slicing and showed that printing non-planar layers oriented along stress lines without increment of the material could increase the strength of prints by more than 6x. The present study enriches the relevant research by establishing the non-planar additive manufacturing platform as well as slicing software to produce printing paths following sinusoidal geometry, which is also theoretically potential to improve mechanical properties of prints by eliminating the effect of anisotropy and without increment of material and weight.

Mitigating contradictions of mechanical properties, weight, and aesthetics, in manufacturing aesthetic prostheses: As analysed in the literature review, mechanical strength, weight and freedom of morphology for aesthetics are three primary factors for manufacturing prostheses. Prostheses usually require high mechanical strength to support the human body, especially for the lower artificial limbs, and light weight to minimise the muscular effort for locomotion (Gailey et al., 1994; Lewallen et al., 1986; Macfarlane et al., 1991; Martin & Morgan, 1992; Winter & Sienko, 1988). Meantime, higher freedom of morphology enables broader space for the aesthetic consideration of design. However, balancing them faces significant challenges. The often-used conventional approaches to strengthen 3D printed objects without changing the materials are modifying the geometry of the design (Stava et al., 2012) (Zhou et al., 2013), which easily leads addition of weight and limitation to the freedom of morphology relating to aesthetics; and optimising infill patterns or increasing infill rate (Lu et al., 2014; Wang et al., 2013; Zhang et al., 2015), although which will not affect the morphology of the prints, it easily increases the weight of the prostheses. As stated in the last paragraph, the non-planar additive manufacturing platform enables the improvement of mechanical properties only by changing printing orientation without morphological changing of the prostheses and addition of the infill rate. Thus it is therictically a potential solution to balance the prosthesis requirements on mechanical strength, weight and freedom of morphology for aesthetics.

Attitudes towards additive manufacturing materials: Material is a significant manufacturing factor that influences users' feelings about physical products. However, prosthesis users' psychological feeling has been overlooked in the research on manufacturing prostheses by additive manufacturing technology. This study explores the feeling and preferences of disabled dancers specifically on various commercial 3D printing materials of FFF, and demonstrates that dancers show a general interest in various commercial 3D printing materials, and simultaneously subjectivity in the preference of materials. It also indicates that the feelings on additive manufacturing material also reflect the deeper consideration of function, aesthetics of prostheses and even attitudes on disability and self-identity.

Expansion

The developed non-planar additive manufacturing platform requires experiments of printing practice and mechanical evaluation of the manufactured samples. There are several potential expansions as follows: the whole system works with most of the commercial 6DOF robotics, which enables flexibility of upgrade based on various applications; the multi-head extruder was designed with three heads and compatibility with various FFF additive manufacturing facilities which enables additive manufacturing with multiple materials and resolutions; the mechanical parts of the platform are designed as to be potential to work with additive manufacturing of fibre reinforced polymers, which is the potential to further improve the weight-strength ratio that enables lighter prostheses with enough mechanical properties.

On the other hand, the user study on additive manufacturing materials was conducted by presenting images of various materials and discussing participants' feelings. The physical products with various materials enable users to feel them physically, which may bring deeper and broader feelings to various materials.

Conclusion

Having introduced our process, we now offer two more general reflections on it. First, our process shows how customisation and personalisation can be combined in co-designing physical projects. Previous research within marketing and business studies has argued that customisation typically involves consumers making explicit choices when tailoring a product, whereas personalisation is more algorithmic and data-driven (Arora et al., 2008; Sundar & Marathe, 2010). Customisation is typically applied to tailor physical products, even if it is delivered through digital means such as websites, whereas algorithmic personalisation dominates the world of digitally native products such as search engines and social media. Previous HCI research introduced the idea of customisation maps to explain how different stakeholders in a product (manufacturers, distributors, prosumers and consumers) might customise both its physical and digital aspects, though did not discuss algorithmic personalisation (Benford et al., 2018). Our co-design process complements this by showing how people may employ both explicit choices and algorithms to tailor a physical product. This might potentially also involve multiple stakeholders.

While we have presented our process as being broadly linear, we recognise that there are likely to be aspects of circularity in practice. Design processes are often iterative, co-design involves dialogue, and aspects of visual appearance, materiality and form are often hard to separate cleanly in practice, all of which suggest feedback loops between the different stages of the process. There is also likely to be back pressure from later stages to earlier ones, for example, some generative algorithms may be easier to optimise for particular kinds of manufacturing than others which will make them better initial choices as design partners. We have also not considered the possibility of 'closing the loop' by gathering data from actual product use that might then be fed back into further design cycles. Aesthetic seeds might be generated from everyday use rather than specific design sessions.

Chapter 7

Conclusion

This thesis explored the personalisation of aesthetic prostheses from both perspectives of design and manufacture. From the design perspective, it explored the generative co-design approach, which combines the advantages of generative design – enabling the efficient exploration of many designs, with collaborative design – enabling users' involvement in the design process so as to embody a deep expression of individual identity within the designed prostheses. Three algorithms were established for design perspective. Mogrow is a generative co-design algorithm driven by motion capture technology so that dancing can generate personalised aesthetic seeds. Leg sculpting is a generative design algorithm that applies an aesthetic seed to a specific product, a prosthesis cover that is personalised to fit users' unique body features. A final algorithm optimises the design of the prosthesis produced by leg sculpting to be manufactured without printing supports, significantly improving the efficiency of additive manufacturing without compromising aesthetic details. From the manufacturing perspective, additive manufacturing was selected as the basic strategy due to its advantage in customisation. The personalised design of the aesthetic prosthesis requires a high degree of geometric freedom, which challenges the requirements of mechanical properties such as strength, degree of stiffness, and weight. Thus, this thesis also established a non-planar additive manufacturing platform based on the 6DOF robotic arm as a manufacturing approach that can accommodate tradeoffs between visual aesthetic, form, weight, material and the mechanical properties of aesthetic prostheses. Evaluation on design and manufacture was collected by three workshops from disabled dancers.

7.1 Answer the research questions

This thesis has answered six research questions:

Is generative co-design a feasible approach to efficiently producing aesthetic designs that are acceptable by dancers and applicable to prosthetic designs?

Conventionally, generative design has been primarily applied to the improvement of design efficiency and shape optimization (Chase, 2005; Cleveland, 2010; Gu & Behbahani, 2018; Kielarova et al., 2013; Krish, 2011; Lin & Lee, 2013; Rodrigues et al., 2015; Shea et al., 2005; Singh & Gu, 2012; Troiano & Birtolo, 2014). There is quite limited research on applying the generative design approach to aesthetic designs as part of product design. This thesis explored the application of the generative design approach to produce designs of aesthetic prostheses, which enriched the relevant research that applies generative design to product designs with aesthetic concerns.

Co-design enables the involvement of non-designer users in the design process. It has been also applied to investigate the design of prostheses, and demonstrated that the application of the co-design approach to the prosthetic design embodied a deep and rich expression of the individual identity (Blom, 2018). This thesis extended prior research by applying the strategy of co-design to embody personal identity with personalised prosthetic design by applying generative design toolkits, which enables the production of massive various designs through interaction between dancers and generative design algorithm.

The present research established a generative co-design strategy by combining generative design and co-design approaches. It achieved personalised aesthetic designs without the involvement of professional designers, which brings the potential to address the challenge that limited resources of professional designers hinder the massive benefit of personalised aesthetic designs. The user evaluation has demonstrated that both the final design and the design experience of the established generative co-design strategy gained positive feedback from users.

How can dancers effectively interact with generative co-design to produce personalised designs?

Co-design enables non-designers' involvement in the design process by toolkits to enable users' interaction through non-designing activity. More than that, the present study considered dancers' most highly trained and attuned mode of personal expression as being dance. Therefore, I explored collecting the dancing data by motion capture technology to interact with generative co-design algorithms. In this process, non-normative bodies also need to be considered. While employing motion capture to interact with Mogrow by dancing was generally well received, we immediately encountered challenges arising from the assumptions inherent in the ROKOKO suit that users have four limbs and move in conventional ways, assumptions which permeate both the physical design of the suit and its underlying software model and virtual representation of the moving body.

The other challenge we faced was how to achieve interaction by dance. Motion capture can only capture basic motion data e.g. relative position, velocity, acceleration, on multiple tracking points (17 trackers in this case). But they are not directly applicable as dancing motion input. Then we applied one of the dancing concepts by Raheb, Whatley and Camurri (2018) – axis. The user evaluation suggested that the dancing principle mode might achieve higher acceptance since the dancing concepts were explored to fit most of the existing dancing types and obtain a high degree of familiarity with dancers.

How can the resulting designs then be applied to diverse forms of prostheses?

Different from the conventional design strategy – facing single and specific design, the design strategy of the present study aimed to establish a personal design system, which focuses on applying the generative co-design strategy to abstract a personally aesthetic archetype (aesthetic seed) and expand it to various specific designs, while retaining the aesthetic details of this aesthetic archetype. For instance, an aesthetic seed is might produced by capturing a dancer's performance in a significant stage show. This aesthetic seed then becomes a tangible record of this dancing experience that otherwise passes in a flash. Then this aesthetic seed is extendable to various specific designs e,g, prostheses, vases, jewellery, or souvenirs for gifting. All of these specific designs will keep the aesthetic details of the original aesthetic seed, which can reflect the dancers' memory of that important stage show. Rather than a single specific design by conventional design strategy, this personal design system can produce massive various personalised aesthetic designs without the involvement of professional designers, which is potential to achieve massive benefits.

The process of extending the aesthetic seed to various specific designs is achieved by a generative design approach which needs to be customised by specific requirements for a particular design, specifically a prosthetic cover in this research. In this process, customisation based on personal ergonomic data is quite important, since the prosthesis usually needs to be customised based on specific personal body features. Thus, the present study developed a generative design algorithm – leg sculpting with the interface of inputs of personal data, e.g. shape and size. Simultaneously, leg sculpting also kept the original aesthetic details of the aesthetic seed, by slicing both the aesthetic seed and the aimed reference leg shape with equidistant contours and scaling the size of the contours consisting of the aesthetic seed to match the corresponding contours on the reference leg model.

How can the resulting prosthetic designs be made viable for additive manufacture without compromising their aesthetics?

For a long time now, aesthetic design has been affected or limited by manufacturing technology. For instance, the design language of most buildings is linear, due to the limitations of construction technology. Although there are some nonlinear architectural designs e.g. designs from Zaha Hadid Architects, their cost is too high to be expanded broadly, due to the low efficiency of manufacturing non-linear architectural designs by conventional construction technology. Thus, to obtain the massive benefit of a new design strategy, efficiency and limitation of manufacturing technology also need to be considered.

Additive manufacturing has been seen as an ideal manufacturing approach for geometrically complex design, due to its advantage that manufacturing complex geometry does not take significantly longer time or materials than a simple one. However, it has its own limitations, notably requiring printing supporting structure for the overhanging parts, which usually results in a significant increment of manufacturing time and material consumption and also significantly affects manufacturing efficiency. One of the aims of the present research is to enable mass-scale personalised aesthetic design. Thus exploration of improving manufacturing efficiency is essential. My strategy was to slightly modify the details of aesthetic design to remove the overhanging parts which require supports, and simultaneously keep the original aesthetic details. This was attained by a generative design algorithm – optimisation of additive manufacturing. The process starts by slicing the conceptual design of the prosthetic cover into contours at 1.5 mm intervals (the layer height of our target additive manufacturing machine). We determined a maximum overhang angle limit of 55 degrees, above which a supporting structure would need to be introduced. Our algorithm then iteratively traverses the 3D model in both top-down and bottom-up directions, incrementally adjusting overhanging contours to be less than the 55-degree threshold. The experience was conducted to compare the time taken and material consumption for the modified design and the original design. It demonstrated that The printed version of the optimised designrequires 63.5% of the printing time and 67.6% materials of the original. The user evaluation indicated that there is no noticeable aesthetically difference between the optimized and the original design.

How can additive manufacture accommodate tradeoffs between visual aesthetic, form, weight, material and mechanical properties of aesthetic prostheses?

Mechanical property is a primary factor for prostheses. In order to strengthen

3D printed objects without changing the material, most of the conventionally existing methods in the literature on additive manufacturing are based on two approaches: modifying the geometry of design (Stava et al., 2012) (Zhou et al., 2013), as well as optimising infill patterns and rate (Lu et al., 2014) (W. Wang et al., 2013) (Zhang et al., 2015). However, in manufacturing aesthetic prostheses, these two approaches have significant limitations. Modification of design geometry can conflict with the requirements of aesthetics, since aesthetic design usually requires a high degree of geometric freedom. In turn, increasing infill patterns and rates may bring extra weight, which is another sensitive factor for prostheses. It is agreed by most prosthetists that the weight of prosthetic devices should be as light as possible, once the requirements of the safest, efficient and most functional componentry possible are matched (R. S. Gailey et al., 1994; Lewallen et al., 1986; Macfarlane et al., 1991; Martin & Morgan, 1992; Winter & Sienko, 1988). Thus, three factors: mechanical property, weight and aesthetics are all significantly important for manufacturing prostheses, but to some extent are contradictory to each other.

The existence of anisotropy in mechanical properties – with greatest strength in the filament direction and weakest strength between layers in the build direction (Maroti et al., 2019) on the manufactured objects by Fused Filament Fabrication (FFF), which is wildly applied in manufacturing prosthesis, brings more challenge but also opportunities to accommodate the tradeoffs between the prementioned three factors. A new research trend of additive manufacturing – non-planar additive manufacturing has been developed to address anisotropy, which also has the potential to accommodate the tradeoffs between mechanical properties, weight, and aesthetics by arranging printing orientation based on the force undertaken by the printed objects to increase its mechanical properties without changing geometry nor increase of infill.

In order to achieve manufacturing prostheses by non-planar additive manufacturing, the platform for non-planar additive manufacturing practice is essential. However, the relevant research is still in its infancy. There is no existing platform in the market for non-planar additive manufacturing. In order to bridge this gap, the present research established an integrated non-planar additive manufacturing platform based on an industrial 6DOF robotic arm, consisting of a multi-head extruder and controlling system. The reason to choose the commercial 6DOF industrial robotic arm has been analysed by previous contents: easy accessibility, reliability, flexibility with working range and payload, and affordability. The established non-planar platform had broad applicability to most models of the commercial 6DOF robotic arm from brands of ABB, KUKA, and Universal, as well as to the various materials, both of which will benefit others' future relevant work. Limited by time and accessibility to the proper facilities, the manufactured sample by the non-planar additive manufacturing platform was not suitable for the test of mechanical properties. However, this thesis explored the non-planar additive manufacturing platform through the whole flow from theoretical research, hardware and software development, and manufacturing practice, and demonstrated that the platform had theoretical support and was fully functional. The remaining task of the mechanical property test of the manufactured sample can be conducted by switching to the right facility quickly.

How does the integrated flow of design and manufacturing prosthetic prostheses incorporate aesthetics?

The aesthetics of prosthetics runs more than skin deep, reaching beyond decorative appearance to include form, function, impact on embodied experience, and statements about body image. 'Beyond skin deep' can be considered literally in terms of prosthetics which have skin but also internals, and metaphorically in terms of meaning more than just a focus on visual beauty. This provides a concrete instantiation of the principles considered by the wider HCI literature on aesthetics.

Figure 7.1 also shows how various aesthetics are embedded throughout this design process:

1, Choose a generative design algorithm: The established algorithm by this research – Mogorw was inspired by the aesthetic theories of the beauty of nature (Franke, 1997) and Birkhoff (1933)'s aesthetic formula to explore the aesthetics produced by generative design. The outcomes indicate that the aesthetics produced by generative design obtain high acceptance by dancers. While we have only described one such algorithm, Mogrow, it would be entirely feasible and sensible to create a suite of such algorithms, each with its own distinctive design style. There are, for example, examples of algorithms that paint or post-process images with various recognised visual styles style (Fractal Wallpaper, n.d.; Hansmeyer & Dillenburger, 2017; Schumacher, 2017). Choosing an algorithm is like choosing to work with a particular designer whose style one appreciates.

2, Choice of expressive skilled interaction: Deciding how to interact expressively with the algorithm is an important aesthetic choice. Our dancers appreciated being able to interact through a highly tuned, hard-earned skill that enabled them to express themselves aesthetically. In response, we developed an interaction technique that was attuned to this skill, in this case by drawing on deeper knowledge of dance principles. In terms of Hsueh et al.'s (2019) taxonomy for kinaesthetic creativity reviewed above, our approach falls under the category of 'control' where

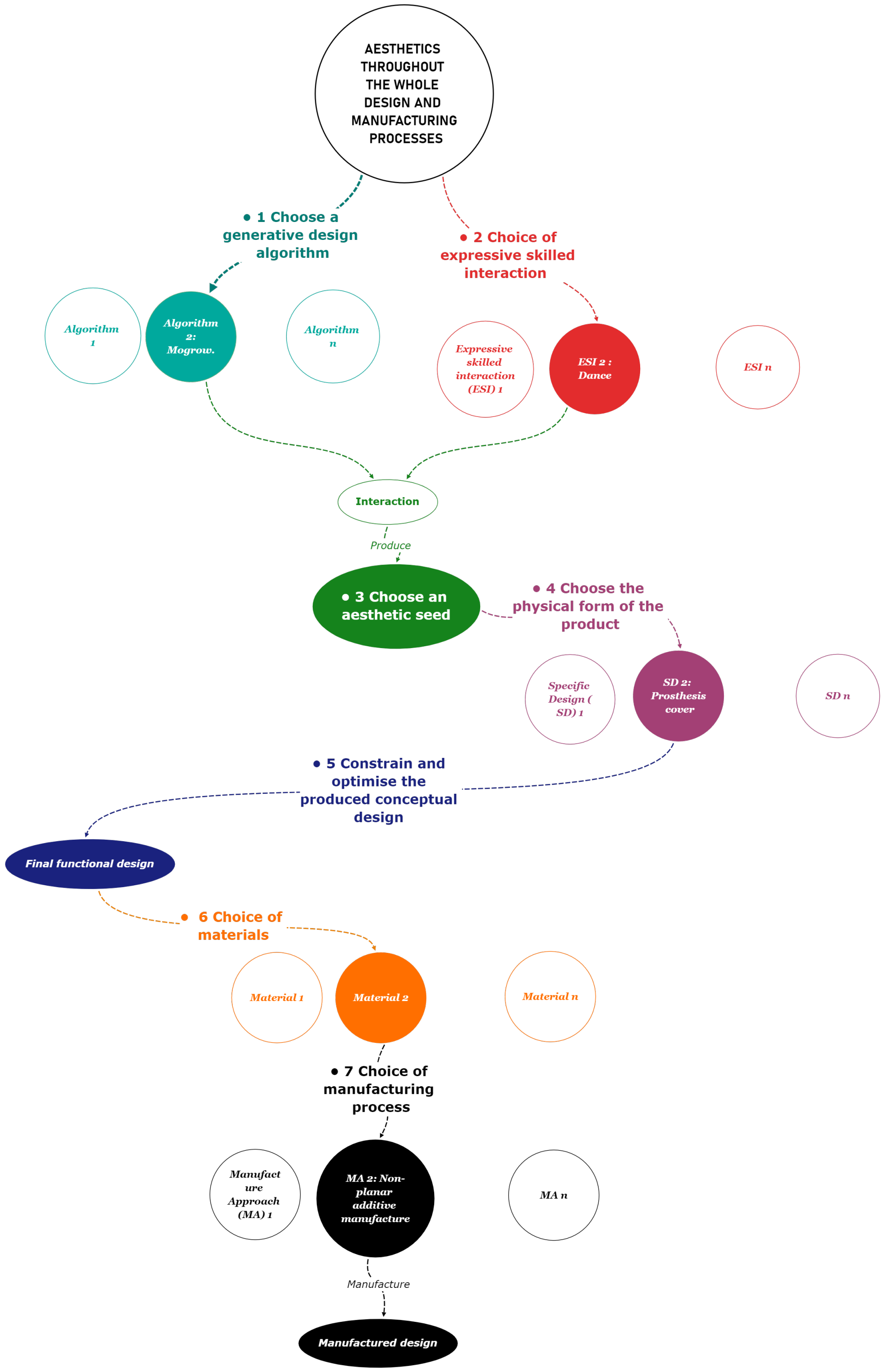


Figure 7.1: Aesthetics throughout the whole design and manufacture process.

dancing is used to control a system, though arguably also includes aspects of ‘co-creating’, though in this case between human and algorithm, rather than between two humans mediated via the algorithm as they discuss. The broader implication is to seek out equivalent personally expressive skills in other situations involving other kinds of human co-designers. This might be a recognised artistic skill (e.g., music, dance, painting, sculpting, poetry) or more broadly any kind of somaesthetic skill that involves a finely tuned bodily interaction (e.g., sports). Our example involved the interactive control of a generative algorithm to sculpt its output in real-time. However, we acknowledge the potential to feed algorithms with examples of existing images, pre-recorded music and other creative outputs in an offline mode. Whatever the skill chosen and interaction technique supported, we argue that harnessing people’s own aesthetic skills can empower them as co-designers alongside the algorithm, rather than requiring them to adapt to its creative process as would be the case if they use some kind of direct manipulation interface to control its various parameters.

3, Choose an aesthetic seed: The idea of capturing particular moments of expressive interaction as abstract representations called aesthetic seeds was one of the key ideas to emerge during our process. Our dancers appreciated being able to interpret the seeds even after some considerable time had passed, re-interpreting them in terms of their movements. Indeed, this appeared to be easier with the abstract form of the seeds rather than cases where they had been applied to the form of a prosthetic cover. Choosing an aesthetic seed extends beyond the visual beauty or otherwise of the design to encompass memory, sense-making and personal connections. Aesthetic seeds might then be best generated from meaningful interactions, but also readily associated, for example being presented alongside photos, videos and so forth that help make these meaningful connections.

4, Choose the physical form of the product: Our dancers highlighted various aesthetic choices when choosing the physical form of the product, in this case, the shapes of the prosthetic covers onto which the aesthetic seeds were mapped. Shape, size and weight all affected the aesthetics of their bodily movement with the product, in this case, dancing, both in terms of constraining movement, but also opening up new possibilities. For example, the idea of wearing an unusually shaped prosthetic such as a spike to enable a new kind of expressive movement becomes feasible when such products can be rapidly co-designed and manufactured.

5, Constrain and optimise the produced conceptual design: A key aspect of our approach is that the resulting products can be rapidly and cheaply manufactured using automated manufacturing techniques such as additive manufacturing. However, this may require optimising the design to the particular requirements of the chosen manufacturing technique, in our case by reducing overhanging elements in the design so as to reduce the time and materials required. Such changes might potentially significantly affect the resulting design and so should be open to scrutiny and perhaps control by human co-designers.

6, Choice of materials: Choosing a material for the product also involved aesthetic choices in terms of its look and feel, in our case with our dancers preferring organic materials, but also further highlighted the matter of visibility through the use of transparent materials that both partially cover and partially reveal the inner workings of the product.

7, Choice of the manufacturing process: As demonstrated above, personalisation goes throughout the design process, which correspondingly requires customisation in the manufacturing process. As stated in the literature review, additive manufacturing technology has been demonstrated to be an efficient solution for customised manufacturing. Therefore, additive manufacturing is the primary manufacturing approach here. Since various additive manufacturing technologies suit different requirements, this step requires a choice of suitable additive manufacturing technology. Specifically, aesthetic prostheses usually have requirements simultaneously in a high degree of geometric freedom for aesthetics, strong mechanical properties to support human body weight, and lightweight for easy movement, three of which are usually contradictory. In order to accommodate trade-offs between visual aesthetic, weight, and mechanical properties of aesthetic prosthetics, the present study established a non-planar additive manufacturing platform

All of the above jointly answer research question 6: How does the integrated flow of design and manufacturing prosthetic prostheses incorporate aesthetics?

7.2 Limitations of the research

There are some limitations in the present research:

- Limited by time, only one generative design algorithm – Mogrow was developed for this stage. Thus, users did not have a chance to choose generative design algorithms based on their aesthetic preferences.
- The Covid pandemic prevented on-site workshops, which triggered poor involvement of dancers in the following design process by applying aesthetic seeds produced by the first workshop to the prosthesis designs. This situation reduced the dancers' feeling of agency in the prosthesis designs.

• Significant research gap, limited time and resources of facilities triggered an uncompleted manufacturing loop. This research on the manufacturing part initially aimed to manufacture the aesthetic prosthesis with the non-planar additive manufacturing approach to achieve proper mechanical properties without compromising aesthetics. However, the significant research gap that there is no existing system for non-planar additive manufacturing, limited time and access to proper facilities obstructed the research progress. As a result, the aim of the manufacturing part was compromised to developing a non-planar additive manufacturing system, which is potential to support relevant future research broadly.

• Due to the limited number of dancers with amputation, there were only two participants for this user study. Both of them are female and have the same lower limb's amputations. This small number of users of the same gender and amputation may limit the representativeness of the collected user feedback. The study search conducted in-depth engagement with users within three years to reduce the negative impact.

• Due to the limiting factors on manufacturing, no physical prostheses or prosthesis covers were manufactured. Thus the users' feedback was limited to designs. Future work is required to manufacture the physical prosthesis, test its mechanical properties and collect users' feedback.

7.3 Future work

More work needs to be conducted in future:

More algorithms: Since each generative design algorithm usually carries a particular aesthetic style, and the present research only demonstrated a single algorithm Mogrow, it is essential to develop more algorithms for users' various aesthetic tastes.

More creative activities applied to interact with the generative design algorithms: The present study applied to dance as an interactive activity in the co-design process. The broader creative activities include recognized artistic skill (e.g., music, dance, painting, sculpting, poetry), more broadly any kind of somaesthetic skill that involves a finely tuned bodily interaction (e.g., sports), as well as other creative outputs in an offline mode (e.g., existing images, pre-recorded music) are potential to be explored for future study.

Wider application to designs: More than prostheses and vases in the present research, the aesthetic seeds have the potential to be extended to other designs by developing corresponding algorithms based on specific requirements, like souvenirs produced by a meaningful dancing show on the stage, crutches or wheelchairs, or any other designs, on which users would like to implant their marks, particular experience or personality.

Broaden the application of the algorithm - Optimisation of additive manufacturing: Time and material consumption hinder the efficiency of additive manufacturing more than FFF, which was demonstrated in the present thesis. It also affects the efficiency of most other additive manufacturing technology such as SLS, SLA, DMLS and so on. It is potential to be applied to accommodate tradeoff between manufacturing efficiency and aesthetics in the practice of manufacturing aesthetic designs by various additive manufacturing technology.

Continue the manufacturing experiment with high precision 6DOF

robot: Manufacturing high-quality samples by the established non-planar additive manufacturing platform with high precision 6DOF robotic arm are essential to evaluate whether the non-planar additive manufacturing technology can accommodate tradeoffs between three primary contradictory factors of manufacturing prostheses – mechanical property, weight and aesthetics.

Bibliography

Viktoria Modesta.

ABB (2018). Operating manual RobotStudio. page 588.

ABB (2019). IRC5 Datasheet. page 4.

ABB Robotics (2015). Technical reference manual, RAPID Instructions, Functions and Data types. page 1546.

Adamatzky, A. (2019). *Slime mould in arts, crafts and architecture.* River Publishers.

Ahlers, D., Wasserfall, F., Hendrich, N., and Zhang, J. (2019). 3D printing of nonplanar layers for smooth surface generation. *IEEE International Conference on Automation Science and Engineering*, 2019-Augus:1737–1743.

Ahn, S. H., Montero, M., Odell, D., Roundy, S., and Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*, 8(4):248–257.

Alaoui, S. F., Carlson, K., Cuykendall, S., Bradley, K., Studd, K., and Schiphorst, T. (2015). How do experts observe movement? In *ACM International Conference Proceeding Series*, volume 14-15-August-2015.

Alaoui, S. F., Franoise, J., Schiphorst, T., Studd, K., and Bevilacqua, F. (2017). Seeing, sensing and recognizing laban movement qualities. In *Conference on Human Factors in Computing Systems - Proceedings*, volume 2017-May.

Alcaide-Marzal, J., Diego-Mas, J. A., and Acosta-Zazueta, G. (2020). A 3D shape generative method for aesthetic product design. *Design Studies*, 66:144–176.

Allen, R. J. and Trask, R. S. (2015). An experimental demonstration of effective Curved Layer Fused Filament Fabrication utilising a parallel deposition robot. *Additive Manufacturing*, 8:78–87.

Alley, R. D., Williams, T. W., Albuquerque, M. J., and Altobelli, D. E. (2011). Prosthetic sockets stabilized by alternating areas of tissue compression and release. *Journal of Rehabilitation Research and Development*, 48(6):679–696.

Allum, J., Kitzinger, J., Li, Y., Silberschmidt, V. V., and Gleadall, A. (2021). ZigZagZ: Improving mechanical performance in extrusion additive manufacturing by nonplanar toolpaths. *Additive Manufacturing*, 38(August 2020):101715.

an Jin, Y., He, Y., and zhong Fu, J. (2015). Support generation for additive manufacturing based on sliced data. *The International Journal of Advanced Manufacturing Technology 2015 80:9*, 80(9):2041–2052.

Ando, T. Hill of buddha.

Ando, T. (1988). The most spectacular artworks by Tadao Ando — Vogue Paris.

Ando, T. (1989). Shaping the light. Church of Light by Tadao Ando — The Strength of Architecture — From 1998.

Arora, N., Dreze, X., Ghose, A., Hess, J. D., Iyengar, R., Jing, B., Joshi, Y., Kumar, V., Lurie, N., Neslin, S., Sajeesh, S., Su, M., Syam, N., Thomas, J., and Zhang, Z. J. (2008). Putting one-to-one marketing to work: Personalization, customization, and choice. *Marketing Letters*, 19(3-4).

B-N Sanders, E. and Jan Stappers, P. (2008). Co-Design Co-creation and the new landscapes of design Co-creation and the new landscapes of design.

Bae, H. J., Bae, S., Yoon, J., Park, C., Kim, K., Kwon, S., and Park, W. (2017). Self-organization of maze-like structures via guided wrinkling. *Science advances*, 3(6):e1700071.

Baljko, M. and Tenhaaf, N. (2008). The aesthetics of emergence. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 15.

Barata, S. d. O. Limbs - The Alternative Limb Project.

Barnsley, M. F. (1988). *Fractals Everywhere*. Academic Press.

Bassoli, E., Gatto, A., Iuliano, L., and Violante, M. G. (2007). 3D printing technique applied to rapid casting. *Rapid Prototyping Journal*, 13(3):148–155.

Benford, S., Koleva, B., Preston, W. W., Angus, A., Thorn, E. C., and Glover, K. (2018). Customizing hybrid products. In *Conference on Human Factors in Computing Systems - Proceedings*, volume 2018-April.

Bentley, P. (1999a). Aspects of Evolutionary Design by Computers. In *Advances in Soft Computing*.

Bentley, P. J. (1999b). *Evolutionary Design by Computers*. Morgan Kaufmann.

Berke, G. M., Fergason, J., Milani, J. R., Hattingh, J., Mcdowell, M., Nguyen, V., and Reiber, G. E. (2010). Comparison of satisfaction with current prosthetic care in veterans and servicemembers from vietnam and OIF/OEF conflicts with major traumatic limb loss. *Journal of Rehabilitation Research and Development*, 47(4).

Bermudez, B. and Ziegler, C. (2014). Pre-choreographic movement kit. In *ACM International Conference Proceeding Series*.

Bhuvaneswar, C. G., Epstein, L. A., and Stern, T. A. (2007). Reactions to amputation: Recognition and treatment. *Primary Care Companion to the Journal of Clinical Psychiatry*, 9(4):303–308.

Biddiss, E. and Chau, T. (2007). Upper limb prosthesis use and abandonment: A survey of the last 25 years. *Prosthetics and Orthotics International*, 31(3):236–257.

BIRKHOFF G. D. (1933). *Aesthetic Measure*. Harvard University Press, Cambridge,Massachusetts.

Bisig, D. and Palacio, P. (2016). Neural narratives - Dance with virtual body extensions. In *ACM International Conference Proceeding Series*, volume 05-06-July-2016.

Blom, J. (2018). The Aesthetics of Prosthetic Greaves: Co-Design for Expressing Personal Identity. *Making Futures*, 5(2):2042–1664.

Blom, L. A. and Chaplin, L. T. No Title.

Bødker, S. (2006). When second wave HCI meets third wave challenges. In *Proceedings of the 4th Nordic conference on Human-computer interaction: changing roles*, pages 1–8.

Bonabeau, E., Dorigo, M., and Theraulaz, G. (1999). *Swarm Intelligence: From Natural to Artificial Systems*. Oxford University Press.

Bosmans, J. C., Suurmeijer, T. P., Hulsink, M., Van Der Schans, C. P., Geertzen, J. H., and Dijkstra, P. U. (2007). Amputation, phantom pain and subjective well-being: A qualitative study. *International Journal of Rehabilitation Research*, 30(1):1–8.

Boutwell, E., Stine, R., and Hansen, A. (2012). Socket fabrication for an above-knee prosthesis. *Journal of Prosthetics and Orthotics*, 24(1):2–10.

Brandt, E., Binder, T., and Sanders, E. B. (2012). Tools and techniques: Ways to engage telling, making and enacting. *Routledge International Handbook of Participatory Design*, (February 2019):145–181.

Brecher, C., Müller, S., Kuz, S., and Lohse, W. (2013). Towards anthropomorphic movements for industrial robots. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 8026 LNCS(PART 2):10–19.

Brenton, H., Kleinsmith, A., and Gillies, M. (2014). Embodied design of dance visualisations. In *ACM International Conference Proceeding Series*, pages 124–129. Association for Computing Machinery.

Brinck, I. (2017). Empathy, engagement, entrainment: the interaction dynamics of aesthetic experience. *Cognitive Processing 2017 19:2*, 19:201–213.

Brinck, I. (2018). Empathy, engagement, entrainment: the interaction dynamics of aesthetic experience. *Cognitive Processing*, 19(2).

Buswell, R. A., Soar, R. C., Gibb, A. G., and Thorpe, A. (2007). Freeform Construction: Mega-scale Rapid Manufacturing for construction. *Automation in Construction*, 16(2):224–231.

Cairns, N., Murray, K., Corney, J., and McFadyen, A. (2014). Satisfaction with cosmesis and priorities for cosmesis design reported by lower limb amputees in the United Kingdom: Instrument development and results. *Prosthetics and Orthotics International*, 38(6):467–473.

Carolo, L. (2020). 5-Axis 3D Printer: The Latest Advancements — All3DP.

Carrick, J. (2017). Flocking algorithms for generative design. *Architectural Science Review*, 60(4):287–296.

Carroll, Á. M. and Fyfe, N. (2004). A comparison of the effect of the aesthetics of digital cosmetic prostheses on body image and well-being. *Journal of Prosthetics and Orthotics*, 16(2):66–68.

Carroll, E. A., Lottridge, D., Latulipe, C., Singh, V., and Word, M. (2012). Bodies in critique: a technological intervention in the dance production process. In *Proceedings of the ACM 2012 conference on Computer Supported Cooperative Work*, pages 705–714.

Casas Niccolo (2021). Plasticity by Niccolo Casas with Parley for the Oceans and Nagami, Venice Biennale Architecture 2021 - YouTube.

Cen, L. and Melkote, S. N. (2017). Effect of Robot Dynamics on the Machining Forces in Robotic Milling. *Procedia Manufacturing*, 10:486–496.

Chakraborty, D., Aneesh Reddy, B., and Roy Choudhury, A. (2008). Extruder path generation for Curved Layer Fused Deposition Modeling. *CAD Computer Aided Design*, 40(2):235–243.

Chase, S. C. (2005). Generative design tools for novice designers: Issues for selection. In *Automation in Construction*, volume 14.

Chau, H. H., Chen, X., McKAY, A., and de Pennington, A. (2004). Evaluation of a 3d shape grammar implementation. In *Design computing and cognition'04*, pages 357–376. Springer.

Cheetham, M. (2011). The human likeness dimension of the "uncanny valley hypothesis": behavioral and functional MRI findings. *Frontiers in Human Neuroscience*, 5.

Chen, R. K., an Jin, Y., Wensman, J., and Shih, A. (2016). Additive manufacturing of custom orthoses and prostheses-A review.

Chen, Y. and Dong, F. (2013). Robot machining: Recent development and future research issues. *International Journal of Advanced Manufacturing Technology*, 66(9-12):1489–1497.

Chen, Z., Zhao, Y., and Liu, Y. (2020). High-speed sintering in multi-material additive manufacturing: A review. *Journal of Manufacturing Processes*, 57:123–136.

Ciolfi Felice, M., Fdili Alaoui, S., and Mackay, W. E. (2018). Knotation: exploring and documenting choreographic processes. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–12.

Cleveland, P. (2010). Style based automated graphic layouts. *Design Studies*, 31(1).

Cooper, M. P., Griffiths, C. A., Andrzejewski, K. T., and Giannetti, C. (2019). Motion optimisation for improved cycle time and reduced vibration in robotic assembly of electronic components. *AIMS Electronics and Electrical Engineering*, 3(3):274–289.

Correia, N. N., Masu, R., Pham, A. H. D., and Feitsch, J. (2021). Connected Layers: Evaluating Visualizations of Embodiment in Contemporary Dance Performances. In *TEI 2021 - Proceedings of the 15th International Conference on Tangible, Embedded, and Embodied Interaction*. Association for Computing Machinery, Inc.

Dai, C., Wang, C. C., Wu, C., Lefebvre, S., Fang, G., and Liu, Y. J. (2018). Support-free volume printing by multi-axis motion. *ACM Transactions on Graphics*, 37(4).

Dalsgaard, P. and Hansen, L. K. (2008). Performing perceptionstaging aesthetics of interaction. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 15.

Davies, E. J., Friz, B. R., and Clippinger, F. W. (1970). Amputees and their prostheses. *Artificial limbs*, 14(2):19–48.

de Macedo, R. Q., Ferreira, R. T. L., Gleadall, A., and Ashcroft, I. (2021). VOLCO-X: Numerical simulation of material distribution and voids in extrusion additive manufacturing. *Additive Manufacturing*, 40.

Desmet, P. M. A. and Pohlmeyer, A. E. (2013). Positive design: An introduction to design for subjective well-being. *International journal of design*, 7(3).

Dewey, J. (1929). Nature, communication and meaning.

Dierichs, K. and Menges, A. (2015). ICD Aggregate Pavilion 2015 on Vimeo.

Donovan, J. (2020). ROBOT FABRICATION — USING RHINO GRASSHOPPER - Design Robotics.

Donovan-Hall, M. K., Yardley, L., and Watts, R. J. (2002). Engagement in activities revealing the body and psychosocial adjustment in adults with a trans-tibial prosthesis. *Prosthetics and orthotics international*, 26(1):15–22.

Dourish, P. (2001). *Where the action is.* MIT press Cambridge.

Dunn, D. S. (1996). Well-being following amputation: Salutary effects of positive meaning, optimism, and control. *Rehabilitation Psychology*, 41(4):285–302.

Dursun, M. (2021). *THE CHILDREN'S PROSTHESIS CO-DESIGN TOOLKIT: ELICITING CHILDREN'S NEEDS FOR HAND PROSTHESES USING GENERATIVE DESIGN TOOLS A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES OF MIDDLE EAST TECHNICAL UNIVERSITY.* PhD thesis.

Duty, C., Failla, J., Kim, S., Smith, T., Lindahl, J., and Kunc, V. (2019). Z-Pinning approach for 3D printing mechanically isotropic materials. *Additive Manufacturing*, 27(March):175–184.

Eichenhofer, M., Wong, J. C., and Ermanni, P. (2017). Continuous lattice fabrication of ultra-lightweight composite structures. *Additive Manufacturing*, 18:48–57.

El Raheb, K., Tsampounaris, G., Katifori, A., and Ioannidis, Y. (2018a). Choreomorphy: A whole-body interaction experience for dance improvisation and visual experimentation. In *Proceedings of the Workshop on Advanced Visual Interfaces AVI*. Association for Computing Machinery.

El Raheb, K., Whatley, S., and Camurri, A. (2018b). A conceptual framework for creating and analyzing dance learning digital content. In *ACM International Conference Proceeding Series*. Association for Computing Machinery.

Esquenazi, A. (2004). Amputation rehabilitation and prosthetic restoration: From surgery to community reintegration. *Disability and Rehabilitation*, 26(14-15):831–836.

Etienne, J., Ray, N., Panozzo, D., Hornus, S., Wang, C. C., Martínez, J., McMains, S., Alexa, M., Wyvill, B., and Lefebvre, S. (2019). Curvislicer: Slightly curved slicing for 3-axis printers. *ACM Transactions on Graphics*, 38(4).

EyeQue Corporation (2000). Product Manual. 40(15):1–5.

Ezair, B., Fuhrmann, S., and Elber, G. (2018). Volumetric covering printpaths for additive manufacturing of 3D models. *CAD Computer Aided Design*, 100:1–13.

Fang, G., Zhang, T., Zhong, S., Chen, X., Zhong, Z., and Wang, C. C. (2020). Reinforced FDM: Multi-axis filament alignment with controlled anisotropic strength. *ACM Transactions on Graphics*, 39(6).

Ferguson-Pell, M., Busby, G., and Colborne, B. (2013). The future of custom prosthetic socket fabrication: A perspective. *Journal of Prosthetics and Orthotics*, 25(4):181–184.

Fern'andez, J., Miguelez, J. M., and Alvarez, D. (2016). A review of socket materials in lower limb prosthetics. *Journal of Materials Science: Materials in Medicine*, 27(3):49.

Ferreira, R. T. L., Ashcroft, I. A., Li, S., and Zhuo, P. (2019). Optimisation of Fibre-Paths in Composites Produced by Additive Manufacturing. *EngOpt 2018 Proceedings of the 6th International Conference on Engineering Optimization*, pages 1083–1094.

Flake, G. W. (2000). *The computational beauty of nature: Computer explorations of fractals, chaos, complex systems, and adaptation.*

Fortenberry, D. (1991). Single Greaves in the Late Helladic Period. *American Journal of Archaeology*, 95(4).

Frank, H. G. and Franke, H. W. (1997). *Aesthetische Information.*

Fry, N. R., Richardson, R. C., and Boyle, J. H. (2020). Robotic additive manufacturing system for dynamic build orientations. *Rapid Prototyping Journal*, 26(4):659–667.

Gabriel, A., Monticolo, D., Camargo, M., and Bourgault, M. (2016). Creativity support systems: A systematic mapping study. *Thinking Skills and Creativity*, 21.

Gailey, R., Allen, K., Castles, J., Kucharik, J., and Roeder, M. (2008). Review of secondary physical conditions associated with lower-limb amputation and long-term prosthesis use.

Gailey, R. S., Wenger, M. A., Raya, M., Kirk, N., Erbs, K., Spyropoulos, P., and Nash, M. S. (1994). Energy expenditure of trans-tibial amputees during ambulation at self-selected pace. *Prosthetics and Orthotics International*, 18(2):84–91.

Gao, Q., He, Y., zhong Fu, J., Liu, A., and Ma, L. (2015a). Coaxial nozzle-assisted 3D bioprinting with built-in microchannels for nutrients delivery. *Biomaterials*, 61:203–215.

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C., Shin, Y. C., Zhang, S., and Zavattieri, P. D. (2015b). The status, challenges, and future of additive manufacturing in engineering. *CAD Computer Aided Design*, 69:65–89.

Gardner, M. (1970). Mathematical games: The fantastic combinations of john conway's new solitaire game "life". *Scientific American*, 223(4):120–123.

Gaver, W. (2012). What should we expect from research through design? In *Proceedings of the SIGCHI conference on human factors in computing systems*, pages 937–946.

Gero, J. S. (1996). Creativity, emergence and evolution in design. *Knowledge-Based Systems*, 9(7).

Gholizadeh, H., Abu Osman, N. A., Eshraghi, A., Ali, S., and Sævarsd'ottir, G. (2014). Transtibial prosthesis suspension systems: Systematic review of literature. *Clinical Biomechanics*, 29(1):87–97.

Gholizadeh, H., Lemaire, E. D., and Eshraghi, A. (2016). Prosthetic suspension: Less daily prosthesis use and greater perceived problems. *Prosthetics and Orthotics International*, 40(5):583–588.

Gibson, I., Rosen, D., and Stucker, B. (2015). *Directed Energy Deposition Processes. In: Additive Manufacturing Technologies.*

Gienke, O., Pan, Z., Yuan, L., Lepper, T., and Van Duin, S. (2019). Mode coupling chatter prediction and avoidance in robotic machining process. *International Journal of Advanced Manufacturing Technology*, 104(5-8):2103–2116.

Gleadall, A., Ashcroft, I., and Segal, J. (2018). VOLCO: A predictive model for 3D printed microarchitecture. *Additive Manufacturing*, 21(November 2017):605–618.

Godwyll, R. (2021). GitHub - robin-gdwl/Robots-in-Grasshopper: A repository of plugins and software that can be used to control industrial robots with Grasshopper in Rhino3D.

Gonzalez, B., Carroll, E., and Latulipe, C. (2012). Dance-inspired technology, technology-inspired dance. In *NordiCHI 2012: Making Sense*

Through Design - Proceedings of the 7th Nordic Conference on Human-Computer Interaction.

Goodfellow, I., Pouget-Abadie, J., Mirza, M., Xu, B., Warde-Farley, D., Ozair, S., Courville, A., and Bengio, Y. (2014). Generative adversarial nets. In *Advances in Neural Information Processing Systems*, volume 27, pages 2672–2680.

Goodwin, D. (2020). How to Define the Tool Center Point (TCP) on a Robot - Technical Articles.

Gould, J. D. and Lewis, C. (1985). Designing for usability: Key principles and what designers think. *Communications of the ACM*, 28(3).

Greenfield, G. (2005). On the Origins of the Term "Computational Aesthetics". Girona, Spain. Computational Aesthetics 2005.

Gretsch, K. F., Lather, H. D., Peddada, K. V., Deeken, C. R., Wall, L. B., and Goldfarb, C. A. (2016). Development of novel 3D-printed robotic prosthetic for transradial amputees. *Prosthetics and orthotics international*, 40(3):400–403.

Gu, N. and Behbahani, P. A. (2018). Shape Grammars: A Key Generative Design Algorithm. In *Handbook of the Mathematics of the Arts and Sciences.*

Guo, Y., Dong, H., Wang, G., and Ke, Y. (2016). Vibration analysis and suppression in robotic boring process. *International Journal of Machine Tools and Manufacture*, 101:102–110.

Gurit Holding AG (2000). Guide to Composites. *Available in URL: http://www. netcomposites. com/ . . .*, page 74.

Hadid, Z. (2007). Abu Dhabi Performing Arts Centre – Zaha Hadid Architects.

Hadid, Z. (2008). Celeste Necklace Cuff – Zaha Hadid Architects.

Hadid, Z. (2013). Stuart Weitzman Flagship Store – Zaha Hadid Architects.

Hafner, B. J., Sanders, J. E., Czerniecki, J. M., and Fergason, J. (2002). Energy storage and return prostheses: Does patient perception correlate with biomechanical analysis? *Clinical Biomechanics*, 17(5):325–344.

Hahl, J., Taya, M., and Saito, M. (2000). Optimization of mass-produced trans-tibial prosthesis made of pultruded fiber reinforced plastic. *Materials Science and Engineering: A*, 285(1-2):91–98.

Hall, M. L. and Orzada, B. T. (2013). Expressive Prostheses: Meaning and Significance. *Fashion Practice*, 5(1):9–32.

Hallnäs, L. and Redström, J. (2002). From use to presence. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 9:106–124.

Halskov, K. and Hansen, N. B. (2015). The diversity of participatory design research practice at PDC 2002-2012. *International Journal of Human Computer Studies*, 74.

Hamilton, R. A. (1997). *Big Steps Forward for Amputees.*

Han, P. (2017). Additive Design and Manufacturing of Jet Engine Parts. *Engineering*, 3(5).

Handling, M. R O B OT I C S IRB 6700 The 7th generation of large industrial robots ABB . This 7th generation of large.

Hansmeyer, M. and Dillenburger, B. (2017). Digital Grotesque.

Hart, M. (2021). These Prosthetic Limbs Are Literal Artistic Masterpieces - Nerdist.

He, S., Yan, C., Deng, Y., Lee, C. H., and Zhou, X. (2020). A tolerance constrained G2 continuous path smoothing and interpolation method for industrial SCARA robots. *Robotics and Computer-Integrated Manufacturing*, 63:101907.

He, Y., Wu, W. B., and Fu, J. Z. (2014). Rapid fabrication of paper-based microfluidic analytical devices with desktop stereolithography 3D printer. *RSC Advances*, 5(4):2694–2701.

Heidegger, M., Macquarrie, J., and Robinson, E. (1962). Being and time.

Hilhorst, M. (2005). 'Prosthetic fit': On personal identity and the value of bodily difference. *Medicine, Health Care and Philosophy 2004 7:3*, 7(3):303–310.

Hoenig, F. (2005). Defining computational aesthetics. *Computational Aesthetics'05 Proceedings of the First Eurographics conference on Computational Aesthetics in Graphics, Visualization and Imaging*, pages 13–18.

Höök, K. (2018). Designing with the body : Somaesthetic interaction design.

Höök, K., Jonsson, M. P., Ståhl, A., and Mercurio, J. (2016). Somaesthetic appreciation design. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 3131–3142.

Höök, K., Stahl, A., Jonsson, M., Mercurio, J., Karlsson, A., and Johnson, E.-C. B. (2015). COVER STORY¡br¿¡br¿Somaesthetic Design. *Interactions*, 22(4):26–33.

House, P., Avenue, N. S., Details, A., Whatley, S., Information, R., Date, R. D., and Details, C. (2016). Peer review Peer review. *Global Health Promotion*, 10(1):2–3.

Hsueh, S., Alaoui, S. F., and Mackay, W. E. (2019). Understanding kinaesthetic creativity in dance. *Conference on Human Factors in Computing Systems - Proceedings*, pages 1–12.

Huang, Y., Zhang, J., Hu, X., Song, G., Liu, Z., Yu, L., and Liu, L. (2016). FrameFab: Robotic Fabrication of Frame Shapes. *ACM Trans. Graph. Article*, 3516(1112):978–1.

Hussain, S. and Sanders, E. B. (2012). Fusion of horizons: Co-designing with Cambodian children who have prosthetic legs, using generative design tools. *CoDesign*, 8(1):43–79.

Hybs, I. and Gero, J. S. (1992). An evolutionary process model of design. *Design Studies*, 13(3).

Irrlitz, G. (2015). Kritik der Urteilskraft (1790). *Kant-Handbuch*, pages 331–368.

Jost, B., Ketterl, M., Budde, R., and Leimbach, T. (2015). Graphical programming environments for educational Robots: Open Roberta - Yet another one? *Proceedings - 2014 IEEE International Symposium on Multimedia, ISM 2014*, pages 381–386.

Kaiser, S. B. (1997). *The social psychology of clothing : symbolic appearances in context.* Fairchild Publications, New York, 2nd ed. rev. edition.

Kanis, M., Brinkman, W.-P., and Perry, M. (2009). Designing for positive disclosure: What do you like today? *International Journal of Industrial Ergonomics*, 39(3):564–572.

Karpashevich, P., Hornecker, E., Honauer, M., and Sanches, P. (2018). Reinterpreting schlemmer's Triadic Ballet: Interactive costume for unthinkable movements. In *Conference on Human Factors in Computing Systems - Proceedings*, volume 2018-April.

Karras, T., Laine, S., and Aila, T. (2018). A style-based generator architecture for generative adversarial networks. *arXiv preprint arXiv:1812.04948*.

Karunakaran, K. P., Bernard, A., Suryakumar, S., Dembinski, L., and Taillandier, G. (2012). Rapid manufacturing of metallic objects. *Rapid Prototyping Journal*, 18(4):264–280.

Ke Sun, C., Wei, T.-S., Yeop Ahn, B., Yoon Seo, J., Dillon, S. J., Lewis, J. A., Sun, K., Dillon, S. J., Wei, T. S., Ahn, B. Y., Lewis, J. A., and Seo, J. Y. (2013). 3D Printing of Interdigitated Li-Ion Microbattery Architectures. *Advanced Materials*, 25(33):4539–4543.

Keating, S. and Oxman, N. (2013). Compound fabrication: A multi-functional robotic platform for digital design and fabrication. *Robotics and Computer-Integrated Manufacturing*, 29(6):439–448.

Kelsey, M. (2018). *Non-Technical Canyon Hiking Guide to the Colorado Plateau, 7th Edition*. Brigham Distributing.

Khurana, J. B., Dinda, S., and Simpson, T. (2020). Active - Z printing: A new approach to increasing3D printed part strength. *undefined*.

Kielarova, S. W., Pradujphongphet, P., and Bohez, I. L. J. (2013). An approach of generative design system: Jewelry design application. In *2013 IEEE International Conference on Industrial Engineering and Engineering Management*, pages 1329–1333. IEEE.

Kilian, A. and Ochsendorf, J. (2018). PARTICLE-SPRING SYSTEMS FOR STRUCTURAL. (June).

Kim, Y. H. (2013). BIOLOGICAL GROWTH (3-Dimensional Garden) on Vimeo.

Klute, G. K., Kallfelz, C. F., and Czerniecki, J. M. (2001). Mechanical properties of prosthetic limbs: Adapting to the patient. *Journal of Rehabilitation Research and Development*, 38(3):299–307.

Kr, M. (2021). Comparison of multi-axis printing strategies effects on large-scale 3D printed surface quality.

Krish, S. (2011). A practical generative design method. *CAD Computer Aided Design*, 43(1):88–100.

Kubalak, J. R., Wicks, A. L., and Williams, C. B. (2019). Exploring multi-axis material extrusion additive manufacturing for improving mechanical properties of printed parts. *Rapid Prototyping Journal*, 25(2):356–362.

Kujala, S. (2003). User involvement: A review of the benefits and challenges. *Behaviour and Information Technology*, 22(1).

KUKA Roboter GmbH (2016). KUKA Sunrise OS 1.11 KUKA Sunrise Workbench 1.11. pages 1–557.

Labarre, S. (2010). Almost Genius: Women's Prosthetic Limbs as Fashion Accessories.

Ladd, C., So, J.-H., Muth, J., Dickey, M. D., Ladd, C., So, J.-h., Dickey, M. D., and Muth, J. (2013). 3D Printing of Free Standing Liquid Metal Microstructures. *Advanced Materials*, 25(36):5081–5085.

Lamb, J. M. and Kallal, M. J. (1992). A Conceptual Framework for Apparel Design. *Clothing and Textiles Research Journal*, 10(2):42–47.

Law, D., Cheung, M. C., Yip, J., Yick, K. L., and Wong, C. (2016). Scoliosis brace design: influence of visual aesthetics on user acceptance and compliance. *http://dx.doi.org/10.1080/00140139.2016.1227093*, 60(6):876–886.

Lee, H. C., Herawan, T., and Noraziah, A. (2012). Evolutionary grammars based design framework for product innovation. *Procedia Technology*, 1:132–136.

Lewallen, R., Dyck, G., Quanbury, A., Ross, K., and Letts, M. (1986). Gait kinematics in below-knee child amputees: a force plate analysis. *Journal of pediatric orthopedics*, 6(3):291–298.

Leyton, M. (2003). *A generative theory of shape*, volume 2145. Springer.

Li, B., Zhang, H., Ye, P., and Wang, J. (2020). Trajectory smoothing method using reinforcement learning for computer numerical control machine tools. *Robotics and Computer-Integrated Manufacturing*, 61:101847.

Lin, M.-H. and Lee, L.-C. (2013). An experimental study for applying generative design to electronic consumer products. In *International Conference of Design, User Experience, and Usability*, pages 392–401. Springer.

Lipson, H. and Kurman, M. (2013). *Fabricated: The new world of 3D printing.* Wiley.

Liu, H., Tang, M., and Frazer, J. H. (2004). Supporting creative design in a visual evolutionary computing environment. *Advances in Engineering Software*, 35(5):261–271.

Liu, Z., Chua, C., Leong, K., and Lim, C. (2019). Functionally graded material: An overview. In *Proceedings of the 2nd International Con-*

ference on Progress in Additive Manufacturing (Pro-AM 2018), pages 413–418. Springer.

Llewellyn-Jones, T., Allen, R., and Trask, R. (2016). Curved Layer Fused Filament Fabrication Using Automated Toolpath Generation. *3D Printing and Additive Manufacturing*, 3(4):236–243.

Lohfeld, S., McHugh, P., Serban, D., Boyle, D., O'Donnell, G., and Peckitt, N. (2007). Engineering Assisted Surgery™: A route for digital design and manufacturing of customised maxillofacial implants. *Journal of Materials Processing Technology*, 183(2-3):333–338.

Loke, L. and Robertson, T. (2011). The lived body in design: Mapping the terrain. In *Proceedings of the 23rd Australian Computer-Human Interaction Conference*, pages 181–184.

Loomis, M. (2010). About Generative Design platforms by Mark Loomis - Designplaygrounds.

Loomis, M. (2011). Rhino Grasshopper VS Generative Components - Designplaygrounds.

Lu, L., Sharf, A., Zhao, H., Wei, Y., Fan, Q., Chen, X., Savoye, Y., Tu, C., Cohen-Or, D., and Chen, B. (2014). Build-to-last: Strength to weight 3D printed objects. *ACM Transactions on Graphics*, 33(4).

Lura, D. J., Wernke, M. M., Carey, S. L., Kahle, J. T., Miro, R. M., and Highsmith, M. J. (2015). Differences in knee flexion between the genium and c-leg microprocessor knees while walking on level ground and ramps. *Clinical Biomechanics*, 30(2):175–181.

Macfarlane, P. A., Nielsen, D. H., Shurr, D. G., and Meier, K. (1991). Gait Comparisons for Below-Knee Amputees Using a Flex-Foot™ Versus a Conventional Prosthetic Foot. *undefined*, 3(4):150–161.

Machado, P. and Cardoso, A. (1998). Computing Aesthetics. In *Advances in Artificial Intelligence*, pages 219–228.

Mak, A. F. T., Zhang, M., and Boone, D. A. (2001). State-of-the-art research in lower-limb prosthetic biomechanics- socket interface : A review. (October 2020).

Maroti, P., Varga, P., Abraham, H., Falk, G., Zsebe, T., Meiszterics, Z., Mano, S., Csernatony, Z., Rendeki, S., and Nyitrai, M. (2019). Printing orientation defines anisotropic mechanical properties in additive manufacturing of upper limb prosthetics. *Materials Research Express*, 6(3).

Marsh, G. (2011). Automating aerospace composites production with fibre placement. *Reinforced Plastics*, 55(3):32–37.

Martin, P. E. and Morgan, D. W. (1992). Biomechanical considerations for economical walking and running. *Medicine and Science in Sports and Exercise*, 24(4):467–474.

Masood, S. H. (1996). Intelligent rapid prototyping with fused deposition modelling. *Rapid Prototyping Journal*, 2(1):24–33.

Mazzone, E. (2012a). *Designing with children: reflections on effective involvement of children in the interaction design process*. PhD thesis, University of Central Lancashire.

Mazzone, E. (2012b). Designing with Children: Reflections on Effective Involvement of Children in the Interaction Design Process.

McKnight, M. (2017). Generative Design: What it is? How is it being used? Why it's a game changer. *KnE Engineering*, 2(2):176.

Mentis, H. M. and Johansson, C. (2013). Seeing movement qualities. In *Proceedings of the sigchi conference on human factors in computing systems*, pages 3375–3384.

Merleau-Ponty, M. (1996). *Phenomenology of perception*. Motilal Banarsidass Publishe.

Millstein, S. G., Heger, H., and Hunter, G. A. (1986). Prosthetic use in adult upper limb amputees: A comparison of the body powered and electrically powered prostheses. *Prosthetics and Orthotics International*, 10(1):27–34.

ming Zhao, H., He, Y., zhong Fu, J., and jiang Qiu, J. (2018). Inclined layer printing for fused deposition modeling without assisted supporting structure. *Robotics and Computer-Integrated Manufacturing*, 51(May 2016):1–13.

Mital, M. A., Pierce, D. S., and WARREN, R. (1971). *Amputees and their prostheses*, volume 102. American Medical Association.

Mitchell, W. J. (2005). Constructing Complexity. *In Computer aided architectural design futures 2005 - proceedings ofthe 11th international CAAD futures conference (pp. 41e50).*, pages 41–50.

Mohan Pandey, P., Venkata Reddy, N., and Dhande, S. G. (2003). Slicing procedures in layered manufacturing: A review. *Rapid Prototyping Journal*, 9(5):274–288.

MOLES, A. (1958). *THÉORIE DE L INFORMATION ET PERCEPTION ESTHÉTIQUE*. Flammarion, Paris.

Molitch-Hou, M. (2020). No Title.

Mueller, B. (2012). Additive Manufacturing Technologies – Rapid Prototyping to Direct Digital Manufacturing. *Assembly Automation*, 32(2):151–154.

Mullins, A. (2009). Is Choosing a Prosthesis So Different than Picking a Pair of Glasses?

Murray, C. D. (2005). The Social Meanings of Prosthesis Use. *Journal of Health Psychology*, 10(3):425–441.

Murray, C. D. (2009). Being like everybody else: the personal meanings of being a prosthesis user. *https://doi.org/10.1080/09638280802240290*, 31(7):573–581.

Narmontas, W. (2016). Limit degrees of freedom in development.

Nejur, A. (2019). Generative Urban Design using Physical Form-Finding on Vimeo.

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T., and Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, 143(December 2017):172–196.

Nguyen, D. (2013). The beauty of prostheses : designing for female amputees. *undefined*.

Olabi, A., Bearee, R., Nyiri, E., and Gibaru, O. (2010). Enhanced trajectory planning for machining with industrial six-axis robots. *Proceedings of the IEEE International Conference on Industrial Technology*, pages 500–506.

O'Neill, M., McDermott, J., Swafford, J. M., Byrne, J., Hemberg, E., Brabazon, A., Shotton, E., McNally, C., and Hemberg, M. (2010).

Evolutionary design using grammatical evolution and shape grammars: Designing a shelter. *International Journal of Design Engineering*, 3(1):4–24.

Özer, A., Eren Semercigil, S., Prasanth Kumar, R., and Yowat, P. (2013). Delaying tool chatter in turning with a two-link robotic arm. *Journal of Sound and Vibration*, 332(6):1405–1417.

Palanisamy, C., Raman, R., and kumar Dhanraj, P. (2021). Additive manufacturing: a review on mechanical properties of polyjet and FDM printed parts.

Pan, W. (2006). Incorporating gene functional annotations in detecting differential gene expression. *Journal of the Royal Statistical Society. Series C: Applied Statistics*, 55(3):301–316.

Pan, Y., Zhou, C., Chen, Y., and Partanen, J. (2014). Multitool and multi-axis computer numerically controlled accumulation for fabricating conformal features on curved surfaces. *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, 136(3).

Pan, Z., Zhang, H., Zhu, Z., and Wang, J. (2005). Chatter analysis of robotic machining process. *Journal of Materials Processing Technology*, 55(3):301–309.

Paul, R. P. (1981). *Robot manipulators: mathematics, programming, and control: the computer control of robot manipulators.*

Pearson, J. E. (1993). Complex patterns in a simple system. *Science*, 261(5118):189–192.

Pelzer, L. and Hopmann, C. (2021). Additive manufacturing of non-planar layers with variable layer height. *Additive Manufacturing*, 37(November):101697.

Peter, B. (1999). *An Introduction to Evolutionary Design by Computers*. Number January 1999.

Petersen, M. G., Hallnäs, L., and Jacob, R. J. (2008). Introduction to special issue on the aesthetics of interaction. *ACM Transactions on Computer-Human Interaction*, 15.

Phon-Amnuaisuk, S. and Panjapornpon, J. (2012). Controlling generative processes of generative art. *Procedia Computer Science*, 13:43–52.

Pieper, D. L. (1968). *The kinematics of manipulators under computer control*. PhD thesis.

Pitkin, M. (2009). Design features of prosthetic covers from a manufacturer's perspective. *Journal of Prosthetics and Orthotics*, 21(3):134–137.

Pohjolainen, T., Alaranta, H., and Kärkäinen, M. (1990). Prosthetic use and functional and social outcome following major lower limb amputation. *Prosthetics and Orthotics International*, 14(2):75–79.

Preston, W., Benford, S., Thorn, E.-C. C., Koleva, B., Rennick-Egglestone, S., Mortier, R., Quinn, A., Stell, J., and Worboys, M. (2017). Enabling hand-crafted visual markers at scale. In *DIS 2017 - Proceedings of the 2017 ACM Conference on Designing Interactive Systems*, pages 1227–1237. Association for Computing Machinery, Inc.

Profita, H. P., Stangl, A., Matuszewska, L., Sky, S., and Kane, S. K. (2016). Nothing to hide: Aesthetic customization of hearing AIDS and cochlear implants in an online community. *ASSETS 2016 - Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility*, pages 219–227.

Prusinkiewicz, P. and Lindenmayer, A. (1990). *The Algorithmic Beauty of Plants*. Springer-Verlag.

Pullin, G. (2009). *Design Meets Disability*. MIT Press., Boston.

Pullin, G. and Higginbotham, J. (2010). Design Meets Disability. *http://dx.doi.org/10.3109/07434618.2010.532926*, 26(4):226–229.

Quintana, G. and Ciurana, J. (2011). Chatter in machining processes: A review. *International Journal of Machine Tools and Manufacture*, 51(5):363–376.

Ramot, Y., Haim-Zada, M., Domb, A. J., and Nyska, A. (2016). Biocompatibility and safety of PLA and its copolymers.

Raz, O. (2020). Cost reduction in additive manufacturing: An approach for integrated energy and material flow optimization. *Journal of Cleaner Production*, 245:118830.

Redström, J. (2008). Tangled interaction: On the expressiveness of tangible user interfaces. *ACM Trans. Comput.-Hum. Interact*, 15.

Renner, G. and Ekárt, A. (2003). Genetic algorithms in computer aided design. *CAD Computer Aided Design*, 35(8 SPEC.).

Resnik, L., Meucci, M. R., Lieberman-Klinger, S., Fantini, C., Kelty, D. L., Disla, R., and Sasson, N. (2012). Advanced Upper Limb Prosthetic Devices: Implications for Upper Limb Prosthetic Rehabilitation. *Archives of Physical Medicine and Rehabilitation*, 93(4):710–717.

Reynolds, C. W. (1987a). *ACM SIGGRAPH Computer Graphics*.

Reynolds, C. W. (1987b). Flocks, herds and schools: A distributed behavioral model. *ACM SIGGRAPH Computer Graphics*, 21(4):25–34.

Riddick, J. C., Haile, M. A., Wahlde, R. V., Cole, D. P., Bamiduro, O., and Johnson, T. E. (2016). Fractographic analysis of tensile failure of acrylonitrile-butadiene-styrene fabricated by fused deposition modeling. *Additive Manufacturing*, 11:49–59.

Rochus, P., Plesseria, J. Y., Van Elsen, M., Kruth, J. P., Carrus, R., and Dormal, T. (2007). New applications of rapid prototyping and rapid manufacturing (RP/RM) technologies for space instrumentation. *Acta Astronautica*, 61(1-6):352–359.

Rodricks, R. Grasshopper Addons and Plugins — Grasshopper Docs.

Rodrigues, E., Amaral, A. R., Gaspar, A. R., and Gomes, Á. (2015). An approach to urban quarter design using building generative design and thermal performance optimization. *Energy Procedia*, 78:2899–2904.

Rutten, D. (2021). David Rutten.

Rybarczyk, B. and Behel, J. (2008). Limb loss and body image. *Psychoprosthetics*, pages 23–31.

s, D. S. (2013). Interaction design for and with the lived body: Some implications of merleau-ponty's phenomenology. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 20:1–30.

Sahu, S., Choudhury, B. B., and Biswal, B. B. (2017). A Vibration Analysis of a 6 Axis Industrial Robot Using FEA. *Materials Today: Proceedings*, 4(2):2403–2410.

Sanders, E. B. (1999a). Postdesign and participatory culture. *Proceedings of useful and critical: The position of research in design*, 11.

Sanders, E. B., Brandt, E., and Binder, T. (2010). A framework for organizing the tools and techniques of Participatory Design. In *ACM International Conference Proceeding Series*.

Sanders, E. B. and Stappers, P. J. (2014). Probes, toolkits and prototypes: Three approaches to making in codesigning. *CoDesign*, 10(1):5–14.

Sanders, E. B.-N. (1999b). Postdesign and participatory culture. In *Useful Critical: The Position of Research in Design.*, number September.

Sanders, E. B.-N. (2000). Generative Tools for Co-designing. In *Collaborative Design*, pages 3–12. Springer London.

Sanders, E. B. N. (2006). Nurse and patient participatory workshops for the NBBJ project. *Inpatient tower expansion for H. Lee Moffitt Cancer Center and Research Institute, Tampa, FL, USA*.

Sanders, E. B.-N. and Stappers, P. J. (2008). Co-creation and the new landscapes of design. *CoDesign*.

Sandusky, R. J. (1997). Bringing design to software. *Journal of the American Society for Information Science*, 48(12).

Sanoff, H. (2007). Special issue on participatory design.

Sansoni, S. (2014). Psychological distress and well-being in prosthetic users the role of realism in below-knee prostheses. *9th International Conference on Design and Emotion 2014: The Colors of Care*, pages 552–561.

Sansoni, S., Speer, L., Wodehouse, A., and Buis, A. (2016). Aesthetic of Prosthetic Devices: From Medical Equipment to a Work of Design. *Emotional Engineering Volume 4*, pages 73–92.

Sansoni, S., Wodehouse, A., and Buis, A. (2015). A new design system of below-Limb prostheses-the role of a visual prosthetic designer. *Proceedings of the International Conference on Engineering Design, ICED*, 1(DS 80-01):1–10.

Saradjian, A., Thompson, A. R., and Datta, D. (2008). The experience of men using an upper limb prosthesis following amputation: positive coping and minimizing feeling different. *Disability and rehabilitation*, 30(11):871–883.

Scaife, M., Rogers, Y., Aldrich, F., and Davies, M. (1997). Designing for or designing with? Informant design for interactive learning environments. In *Conference on Human Factors in Computing Systems - Proceedings*.

Schaffalitzky, E., Gallagher, P., MacLachlan, M., and Ryall, N. (2011). Understanding the benefits of prosthetic prescription: exploring the experiences of practitioners and lower limb prosthetic users. *https://doi.org/10.3109/09638288.2010.529234*, 33(15-16):1314–1323.

Schiphorst, T. (2011). Self-evidence: applying somatic connoisseurship to experience design. In *CHI'11 extended abstracts on human factors in computing systems*, pages 145–160.

Schuh, G., Bergweiler, G., Lukas, G., Hohenstein, S., and Schenk, J. (2020). Feature-based print method for multi-axis material extrusion in additive manufacturing. *Procedia CIRP*, 93:885–890.

Schuler, D. and Namioka, A. (2017). *Participatory design: Principles and practices*.

Schumacher, P. (2017). Thallus Installation – Zaha Hadid Architects.

Shackleton, D. (2010). Co-Creation and Co-Design in a Post Design Era. *Current-Design Research Journal*.

Shang, J., Tian, X., Luo, M., Zhu, W., Li, D., Qin, Y., and Shan, Z. (2020). Controllable inter-line bonding performance and fracture patterns of continuous fiber reinforced composites by sinusoidal-path 3D printing. *Composites Science and Technology*, 192(January):108096.

Shea, K., Aish, R., and Gourtovaia, M. (2005). Towards integrated performance-driven generative design tools. In *Automation in Construction*, volume 14.

Shieh, M.-D., Li, Y., and Yang, C.-C. (2018). Comparison of multi-objective evolutionary algorithms in hybrid Kansei engineering system for product form design. *Advanced Engineering Informatics*, 36:31–42.

Shusterman, R. (2012). *Thinking through the body: Essays in somaesthetics*. Cambridge University Press.

Siebers, T. (2010). *Disability aesthetics*. University of Michigan Press Ann Arbor.

Singh, V. and Gu, N. (2012). Towards an integrated generative design framework. *Design Studies*, 33(2).

Singh, V., Latulipe, C., Carroll, E., and Lottridge, D. (2011). The choreographer's notebook: a video annotation system for dancers and choreographers. In *Proceedings of the 8th ACM Conference on Creativity and Cognition*, pages 197–206.

Smurr, L. M., Gulick, K., Yancosek, K., and Ganz, O. (2008). Managing the Upper Extremity Amputee: A Protocol for Success. *Journal of Hand Therapy*, 21(2).

Sousa, A. I., Corredeira, R., and Pereira, A. L. (2009). The body in persons with an amputation. *Adapted physical activity quarterly : APAQ*, 26(3):236–258.

Spehar, B., Clifford, C. W., Newell, B. R., and Taylor, R. P. (2003). Universal aesthetic of fractals. *Computers and Graphics (Pergamon)*, 27(5):813–820.

Spiel, K., Kayali, F., Horvath, L., Penkler, M., Harrer, S., Sicart, M., and Hammer, J. (2018). Fitter, happier, more productive? the normative ontology of fitness trackers. In *Extended abstracts of the 2018 CHI conference on human factors in computing systems*, pages 1–10.

Staker, M., Ryan, K., and LaBat, K. (2009). Medicine and design investigate residual limb volume fluctuations: Three case studies. *Australasian Medical Journal*, 1(12):156–161.

Stava, O., Vanek, J., Benes, B., Carr, N., and Měch, R. (2012). Stress relief: improving structural strength of 3D printable objects. *ACM Transactions on Graphics (TOG)*, 31(4).

Stephanidis, C. (2013). HCI International 2014. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 8006 LNCS(PART 3).

Stiny, G. and Gips, J. (1971). Shape grammars and the generative specification of painting and sculpture. In *IFIP congress (2)*, volume 2, pages 125–135. Citeseer.

Stones, C. and Cassidy, T. (2010). Seeing and discovering: how do student designers reinterpret sketches and digital marks during graphic design ideation? *Design Studies 31(5):439-460.*

Su, J. and Zhang, S. (2010). Research on product shape innovation design method with human-computer interaction through genetic algorithm. In *2010 IEEE 11th International Conference on Computer-Aided Industrial Design Conceptual Design 1*, volume 1, pages 301–305. IEEE.

Summit, S. (2013). These People May Have Lost a Limb, but Not Their Sense of Style TwistedSifter.

Summit, S. (2016). Beautiful Prosthetics by Bespoke Innovations — Brave the Woods.

Sun, J., Frazer, J. H., and Mingxi, T. (2007). Shape optimisation using evolutionary techniques in product design. *Computers Industrial Engineering*, 53(2):200–205.

Sundar, S. S. and Marathe, S. S. (2010). Personalization versus customization: The importance of agency, privacy, and power usage. *Human Communication Research*, 36(3).

Svanæs, D. (2013). No Title. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 20(1):1–30.

Tajima, S. and Sencer, B. (2017). Global tool-path smoothing for CNC machine tools with uninterrupted acceleration. *International Journal of Machine Tools and Manufacture*, 121:81–95.

Tam, K. M. M. and Mueller, C. T. (2017). Additive Manufacturing Along Principal Stress Lines. *3D Printing and Additive Manufacturing*, 4(2):63–81.

Tamari, T. (2017). Body image and prosthetic aesthetics: Disability, technology and paralympic culture. *Body and Society*, 23:25–56.

Telfer, S., Pallari, J., Munguia, J., Dalgarno, K., McGeough, M., and Woodburn, J. (2012). Embracing additive manufacture: implications for foot and ankle orthosis design. *BMC Musculoskeletal Disorders*, 13(1):84.

Tero, A., Takagi, S., Saigusa, T., Ito, K., Bebber, D. P., Fricker, M. D., Yumiki, K., Kobayashi, R., and Nakagaki, T. (2010). Rules for biologically inspired adaptive network design. *Science*, 327(5964):439–442.

Thrimurthulu, K., Pandey, P. M., and Reddy, N. V. (2004). Optimum part deposition orientation in fused deposition modeling. *International Journal of Machine Tools and Manufacture*, 44(6):585–594.

Tofail, S. A., Koumoulos, E. P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., and Charitidis, C. (2018). Additive manufacturing: scientific and technological challenges, market uptake and opportunities.

Troiano, L. and Birtolo, C. (2014). Genetic algorithms supporting generative design of user interfaces: Examples. *Information Sciences*, 259:433–451.

Umetani, N. and Schmidt, R. (2013). Cross-sectional structural analysis for 3D printing optimization. *SIGGRAPH Asia 2013 Technical Briefs, SA 2013*.

Vainshtein, O. (2011). I have a suitcase just full of legs because I need options for different clothing: Accessorizing Bodyscapes. *Fashion Theory - Journal of Dress Body and Culture*, 16(2):139–170.

Van Nort, D. (2015). [radical] signals from life: from muscle sensing to embodied machine listening/learning within a large-scale performance piece. In *Proceedings of the 2nd International Workshop on Movement and Computing*, pages 124–127.

van Rijn, H., Stappers, P., Scheuer, C., Boot, E., Carse, N., Clardy, A., Gallagher, J., Heck, S., Marron, S., Martinez-Alvarez, L., Masarykova, D., Mcmillan, P., Murphy, F., Steel, E., Ekdom, H. V., and Vecchione,

H. (2007). Getting the shy to talk: scripts and staging for contextmapping. *Physical Education and Sport for Children and Youth with Special Needs Researches – Best Practices – Situation*, pages 1–5.

Visser, F. S., Stappers, P. J., van der Lugt, R., and Sanders, E. B.-N. (2005). Contextmapping: experiences from practice. *CoDesign*, 1(2).

Vlachaki, A., Paterson, A. M. J., Porter, S. C., and Bibb, R. J. (2020). Exploring users' attitudes towards prosthesis aesthetics in the UK and Greece. *https://doi.org/10.1080/24735132.2020.1727699*, 4(1):4–23.

Wang, W., Wang, T. Y., Yang, Z., Liu, L., Tong, X., Tong, W., Deng, J., Chen, F., and Liu, X. (2013). Cost-effective printing of 3D objects with skin-frame structures. *ACM Transactions on Graphics (TOG)*, 32(6).

Wang, Y., Tan, Q., Pu, F., Boone, D., and Zhang, M. (2020). A Review of the Application of Additive Manufacturing in Prosthetic and Orthotic Clinics from a Biomechanical Perspective. *Engineering*, 6(11):1258–1266.

Wasserfall, F., Hendrich, N., Ahlers, D., and Zhang, J. (2020). Topology-aware routing of 3D-printed circuits. *Additive Manufacturing*, 36(August):101523.

W.C.A.F.A (2021). 12 Best Insect-Inspired Fashion and Floral Designs -Article onThursd.

Wickramasinghe, S., Do, T., and Tran, P. (2020). FDM-Based 3D printing of polymer and associated composite: A review on mechanical properties, defects and treatments. *Polymers*, 12(7):1–42.

Winter, D. A. and Sienko, S. E. (1988). Biomechanics of below-knee amputee gait. *Journal of biomechanics*, 21(5):361–367.

Witkin, A. and Kass, M. (1991). Reaction-diffusion textures. *ACM SIGGRAPH Computer Graphics*, 25(4):299–308.

Wolfram, S. (2002). *A New Kind of Science*. Wolfram Media.

Wright, P., Wallace, J., and McCarthy, J. (2008). Aesthetics and experience-centered design. *ACM Transactions on Computer-Human Interaction*, 15(4).

Wu, C., Dai, C., Fang, G., Liu, Y. J., and Wang, C. C. (2017). RoboFDM: A robotic system for support-free fabrication using FDM. *Proceedings - IEEE International Conference on Robotics and Automation*, pages 1175–1180.

Wu, H., Wang, Y., Li, M., Al-Saedi, M., and Handroos, H. (2014). Chatter suppression methods of a robot machine for ITER vacuum vessel assembly and maintenance. *Fusion Engineering and Design*, 89(9-10):2357–2362.

Wu, R., Peng, H., Guimbretière, F., and Marschner, S. (2016). Printing arbitrary meshes with a 5DOF wireframe printer. *ACM Transactions on Graphics*, 35(4):1–9.

Xenakis, I. and Arnellos, A. (2015). Aesthetics as an Emotional Activity That Facilitates Sense-Making: Towards an Enactive Approach to Aesthetic Experience. In *Contributions To Phenomenology*, volume 73.

Xie, F., Chen, L., Li, Z., and Tang, K. (2020). Path smoothing and feed rate planning for robotic curved layer additive manufacturing. *Robotics and Computer-Integrated Manufacturing*, 65(February):101967.

Xu, K., Li, Y., Chen, L., and Tang, K. (2019). Curved layer based process planning for multi-axis volume printing of freeform parts. *CAD Computer Aided Design*, 114:51–63.

Yang, Y., Fuh, J. Y., Loh, H. T., and Wong, Y. S. (2003). Multi-orientational deposition to minimize support in the layered manufacturing process. *Journal of Manufacturing Systems*, 22(2):116–129.

Yaraghi, N. A., Guarín-Zapata, N., Grunenfelder, L. K., Hintsala, E., Bhowmick, S., Hiller, J. M., Betts, M., Principe, E. L., Jung, J. Y., Sheppard, L., Wuhrer, R., McKittrick, J., Zavattieri, P. D., and Kisailus, D. (2016). A Sinusoidally Architected Helicoidal Biocomposite. *Advanced Materials*, 28(32):6835–6844.

Yoon, J. S., Kim, K., and Seo, H. S. (2019). Computational modeling for cure process of carbon epoxy composite block. *Composites Part B: Engineering*, 164(August 2018):693–702.

Zafra, D. (2019). Antelope Canyon is Shutting Down Its Photo Tours Due to Overcrowding and Negative Reviews.

Zhang, C., Anzalone, N. C., Faria, R. P., and Pearce, J. M. (2013). Open-Source 3D-Printable Optics Equipment. *PLOS ONE*, 8(3):e59840.

Zhang, X., Xia, Y., Wang, J., Yang, Z., Tu, C., and Wang, W. (2015). Medial axis tree—an internal supporting structure for 3D printing. *Computer Aided Geometric Design*, 35-36:149–162.

Zhao, G., Ma, G., Feng, J., and Xiao, W. (2018). Nonplanar slicing and path generation methods for robotic additive manufacturing. *International Journal of Advanced Manufacturing Technology*, 96(9-12):3149–3159.

Zhao, Z. and Laperrière, L. (2010). Adaptive direct slicing of the solid model for rapid prototyping. *http://dx.doi.org/10.1080/002075400189581*, 38(1):69–83.

Zhou, Q., Chua, C. C., Knibbe, J., Goncalves, J., and Velloso, E. (2021). Dance and choreography in hci: A two-decade retrospective. In *Conference on Human Factors in Computing Systems - Proceedings*. Association for Computing Machinery.

Zhou, Q., Panetta, J., and Zorin, D. (2013). Worst-case structural analysis. *ACM Transactions on Graphics*, 32(4).

Zimmerman, J., Forlizzi, J., and Evenson, S. (2007). Research through design as a method for interaction design research in hci. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 493–502.

Zuniga, J., Katsavelis, D., Peck, J., Stollberg, J., Petrykowski, M., Carson, A., and Fernandez, C. (2015). Cyborg beast: A low-cost 3d-printed prosthetic hand for children with upper-limb differences. *BMC Research Notes*, 8(1).

Zuniga, J., Katsavelis, D., Peck, J. L., Stollberg, J., Petrykowski, M., Carson, A., and Fernández, C. (2016). Cyborg beast: a low-cost 3d-printed prosthetic hand for children with upper-limb differences. *BMC Research Notes*, 9(1):1–6.

Zwierzchowski, J. (2017). a Device for Automatic Robot Tool Center Point (Tcp) Calibration Adjustment for the Abb Industrial Robots. *Engineering Mechanics 2017*, (May):1138–1141.