Embedding perception: how changes in manufacturing can influence visual and tactile preferences

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Abstract

This paper explores how small-but–detectable changes in manufacturing protocol can alter interactive preferences for users. Building on a number of previous studies by the authors, this paper focuses on the manufacture of a set of emotionally attuned pattern-based surface texture designs utilising computer-numerically controlled (CNC) machining. An experiment is subsequently reported that explores how the variations in rastering approach can affect the visual and tactile qualities of the textures in relation to psychological preferences. The implications with respect to human-centred design (HCD) and manufacturing protocol more broadly are subsequently discussed with recommendations for a reconfiguration of computer-aided manufacturing (CAM) approaches.

Introduction

In conventional manufacturing settings, the integration of knowledge pertaining to aspects of perception, human-factors or user experience can be limited (Agost & Vergara, 2014). Culturally, there is a general split between the practises of designers and those of machine technicians who in many cases will implement the vision of a product designer through machining and assembly. This split is characterised by a lack of integration between the two distinct fields of knowledge. On the one hand, user-experience and human-factors knowledge drawn from work in design interaction (see Jordan, 2000; Moggridge, 2007), design semantics (Krippendorff, 2006) and design emotion (Desmet, 2012) to name a few. On the other is the technical knowledge of manufacturing protocol drawn from work in mechanical engineering studies and indeed experience of process use by skilled workers.

The question this work will address is how these worlds can be bridged. Firstly, we will consider the current scholarship concerning the links between manufacturing and perception and explore discourses in material culture studies that have examined the ontic status of making and manufacturing in our contemporary societies. Secondly, by drawing on a number of previous studies carried out by the authors (*blank for review*), we aim to demonstrate how small-but-detectable changes (following Foster, 1984) in conventional manufacturing protocol can have a large impact on aesthetic and tactile preferences. This work uses the development of bespoke pattern-based surface texture designs as a foundation for this, textures that have been designed expressly to elicit certain emotions in the onlooker. By machining these textures into metal surfaces, we create discrete objects that can be examined with respect to the manufacturing strategy. In this example, we focus on CNC machining strategy by exploring through a series of experiments how variances in toolpath can result in dynamic effects in terms of perceptual experience.

Lastly, we explore how the work may challenge the conventional assumptions entrenched within contemporary industrial manufacturing and argue that the experimental results set this scene for an ontological reframing of making and manufacturing at large. This reframing could also allow for the revaluation of key concepts in design emotion and interaction design and how they can link to the critical steps of fabrication.

Manufacturing, Perception And Experience

The questions this work is exploring are complex and must draw on multiple lines of scholarship. Principally, we must consider the relations between manufacturing and perceptual experiences which is the key driver of product enjoyment. Generally, recent scholarship has examined how aspects of material properties and properties derived from particular manufacturing processes affect discrete emotive reactions during particular product interactions. A range of work by Elvin Karana and others has examined some of these phenomena. In a set of studies, Karana et al. (2009, 2010, and 2015) have demonstrated that specific material properties were associated with particular perceptual feelings concluding that the textural basis of the material was a significant factor in the overall assessment. Additionally, Niedderer (2012) has explored novel ways in which manufacturing processes can affect emotional perception and product functionalities.

What is critical here is the embodiment of form and how that articulates with emotional perception and the semantic relationalities between artefact features. There is a range of research that demonstrates how humans perceive form in synesthetic ways i.e. particular geometric arrangements are related to discrete emotive concepts, “joy” or “anger” for instance. This research within experimental aesthetics has usually focused on abstract shapes like lines of isolated geometric elements that have been shown to elicit particular emotive responses to observers. The critical insight from this research is that there is a strong dichotomy between angular forms and curved forms whereby the former is aligned with a negative emotional valence and the latter with a positive valence (see Bertamini et al, 2016; Bar & Neta, 2006; Collier, 1996 for detailed overviews). While there can be interesting contextual effects, the so-called “curvature effect” is quite consistent within most shape interpretation.

How this connects to design though, is another more complex question. As design interplays with the complexities of aesthetics, functionality, culture and society, form takes on what has been described as a “semantic” status. In notable work from Krippendorff (2006), the semantic layering of artefacts and interfaces is examined and showing through the application of affordance theory (see Gibson 1979 and Norman 1999) that designed artefacts have complex layers of meaning that convey different meanings to different groups. In a large study by Forty (1986), the status of products are viewed through the lens of a psychology of “desire” arguing that product personalisation and ornamentation efforts are functions of psychological and social needs, the differentiation between “masculine” and “feminine” archetypes for example.

Ashby and Johnson’s studies (2002) in material experience also present significant insights into the perceptual factors that relate to intrinsic material properties. Furthermore, Miodownik (2007) has examined these relationships and their applications in a range of design contexts.

Manufacturing and making offers a unique way in which to examine the perceptual properties of artefacts. As Ingold has argued (ibid), the inherent material properties and the traces of manufacturing processes offer us a kind of “map” into the artefact and the motions and energy transferences that created it. This relates to what Alexander et al. (1977) and other scholars of material culture have referred to as “patterning” – a structured process in which form has a becoming or an emergence. It is to patterning that we will turn next.

Pattern and texturing

Pattern is perhaps the most powerful meta-concept within design. Patterns – tessellating geometric shapes organised by symmetry operations or repeated structures or motions – have been a feature of art, architecture and made artefacts for millennia. Decorative pattern work is for example seen in ancient Celtic stonework and in the ornamentation of ancient Egyptian, Greek and Babylonian architecture (see Wade, 1982 for a comprehensive graphical summary). Analysis of pattern and aesthetic culture of pattern making has revealed the epistemic links between the application of pattern-forming symmetry operations and mathematical knowledge. Washburn and Crowe 1988 for instance in their seminal analysis “Symmetries of Culture” explore how pattern designs may relate to a kind of primitive form of set-theory where the actual aesthetic embodiment relayed abstract mathematical knowledge. Hann (2012, 2013) has also conducted considerable analysis showing that pattern is a powerful design tool utilised throughout practically every world culture. In essence, pattern and pattern-based activities form an integral part to any design process. Indeed, as Ingold (2008, 2012, 2013, 2015) has explored, patterning work that is implicit within the creation of textiles brings-forth the artefact. The object emergence from a complex exchange of patterning motions, flows of energy and flows of material. Furthermore, pattern engages directly with a nexus of psychological and cultural drivers. As the authors have demonstrated in

The next question is how do we explore these concepts practically? To consider these things, we required some kind of artefact to work with; an artefact that could provide a medium by which to carry out experimental work and explore these questions at multiple levels. A set of previous studies by the authors (see *blank for review*) was used as the foundation for the creation of a set of pattern-based surface texture designs. These artefacts are an ideal type of object to explore the difference in manufacturing approach as their designs were drawn from an analysis of the symbolic status of geometric shapes, notably the dichotomy between curvature and angularity corresponding strongly to positive or negative emotive valences respectively (see *blank for review*). Each of the designs shown at Figure 1 is configured to embody an emotive concept as derived from Plutchik’s (1980) model of emotion categories: A) “Trust” B) “Joy” C) “Fear” D) “Surprise”. A study cataloguing their development by the authors showed that the pattern designs corresponded strongly to the intended emotive response.

The patterns were then built into a CAD programme, allowing them to be “translated” into three-dimensional objects that could subsequently be fabricated. Through a phase of iteration and refinement, the CAD models were developed to be machinable, which meant the removal of hard-edged exterior corners which would be impossible to machine. Machining was selected as a viable choice for exploring perceptual properties of process for a range of reasons. Principally, there is a wealth of computer-aided manufacturing (CAM) resources that allow for control over aspects of the process. Additionally, machining processes are highly standardised, meaning that an unorthodox approach or the introduction of new knowledge into machining practices would have more impact and widespread value.

In order to get a feel for how a surface texture could be CNC machined whilst retaining features of its process trace that may affect perceptual properties, the CAM software EdgeCAM was utilised. EdgeCAM can simulate specific operations on specific machines, hence we were able to explore specifics of manufacturing workflow in some detail. Figure 2 highlights some of the simulation work that was carried out. As the designed textures were quite intricately detailed, a small 1 mm ball nose cutter was used in the simulations.

Critically, toolpath was identified as the most viable variable to explore. As the tool cuts through the material, it forms small ridges known as scallops. This is the trace of the machining process, what Ingold (ibid) has described as an exchange between a “field of forces” and Simondon (2005) called the link between two “transformational half-chains” – as the tools works to cut the material, the material also works against the tool, forming a distinct structure, exterior to the fundamental control of the designer. These trace lines left as the tool cuts the material made a good candidate in which to explore perceptual changes caused by manufacturing variations. Thus, in our setup, we deliberately left these traces very prominent, obviously visible and distinguishable to touch. Each design was simulated with seven toolpath variations. These variations focused on the raster angle of a zigzag tool motion pattern (a pattern on a pattern!) in which 15° changes were applied from 0 ° to 75 °.

With the intention of exploring this to the fullest extent, aluminium plates were sourced in which the textures could be machined. Metal offered both a technical forming challenge and also an interesting aesthetic quality. Figure 2 additionally shows the final manufacturing setup which utilised a Denford Microengraver Pro machine. The metal plate is held in place directly on a vacuum suction bed with metal chip periodically removed and lubrication applied. While this machine was not state-of-the-art, it represents a widely available kind of CNC machining tool. Thus using it for manufacturing seemed appropriate and provides a wider opportunity for recreation of the presented methods. Below in Figure 3 is an outline of the raster approach variations against an abstract representation of the “surprise” pattern. As shown, the “datum” angle is set parallel to the work piece in the vertical plane.

Though the final surface texture artefacts had a range of small defects, the end surface quality was strong in the main. Crucially, the process trace remained prominent and hence could be tangibly analysed. A total of 28 textured plates were created, with seven raster angle variations for each. Figure 4 below shows a sample of the finished artefacts.

Experimental Protocol

The experiment involved a visual and tactile preference examination of the seven toolpath strategies for each of the four designs, examining how this may affect the perceptual experience of these objects. The experimentation was grounded within the philosophy and approaches of Kansei Engineering and HCD whereby experiential preferences are established based on reviewing design variations against known perceptual effects (Lévy, 2013). The stage was split into two key stages, one visual and one tactile, corresponding to two fundamental senses, sight and touch. Based on the comparison tests that are widely used in optometry, these tests used the datum plates mentioned in the previous paragraph against the “comparison plates” (the remaining six plates) as a means of establishing if the differences in toolpath strategy related to any preferences in the visual or tactile domains. If some preferences could clearly be established, this has implications for machining protocol and manufacturing ontologies more generally.

Experimental setup

Visual and tactile preferences were the focus of this experimental stage where the six design variations were each compare against a datum. Each set of six comparison plates were presented to the participants in a randomized order to minimise automatic responses. Each participant was presented with a worksheet that contained three response options for each test, for the visual preference phase*; “visually prefer”, “visually don’t prefer”, “no visual preference”*. Each of these responses could be suffixed with “when compared to the datum plate” to establish the direction of the preferences. This was made sufficiently clear by both the researcher and the provided information sheets. For the tactile preference test that followed, the terminology was aligned around tactile comfort; “*more comfortable”, “less comfortable”, “no preference”* (which again could be suffixed with “when compared to the datum plate”). The plates were presented one by one in a randomized order and arranged next to the datum plate for visual comparison. All the plates included, each participant was required to assess 28 plates in total in both the visual and tactile domains equalling and total of 56 preference comparisons. Tactile comparison involved a short, guided interaction with the two plates, first the datum then the comparison using the participants index and middle fingers. While a maximum of two minutes was allotted to each task, most people were able to decide on their preferences in 10 or 20 seconds, making the experiment very quick overall.

Results And Discussion

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Machining strategies for visual preferences

Considering the visual preference results first, Table 1 shows the comparison plate preference results against the distinct designs and toolpaths with the datum plate preference results. These results exclude "no preference" choices, the colour coding indicating the relative differences in the values (green-high, red-low, white-mid);

Table 1 – Participant preferences for visual comparison of plates

	Comparison plate preference results ("visually prefer")					
	0 °	15 °	30 °	45 °	60 °	75 °
Surprise	38	23	33	19	13	8
Joy	21	23	14	24	13	6
Fear	9	28	18	22	9	23
Trust	20	8	19	26	37	36

	Datum plate preference results ("visually don't prefer")					
	0 °	15 °	30 °	45 °	60 °	75 °
Surprise	13	22	16	26	33	47
Joy	32	30	35	31	39	50
Fear	43	27	38	31	47	33
Trust	27	48	37	24	16	18

On analysis, there is a statistically significant difference between the comparison plate preferences and the datum preferences indicating that most people are drawn to some making approaches over others. The two graphs presented below are essentially inversions of each other but allow us to understand the data more effectively and identify trends (Figure 7). The graphs include the results for all four designs and are colour coded for the benefit of the reader.

As the toolpath variations have been explored against a set of four different pattern-based texture designs, the structural basis of these designs must be closely considered in any analysis, and each can be looked at in turn. The results for *Surprise* show that preferences are more aligned towards the datum as the raster angle moves away from 0° where the highest visual preferences are seen for the comparison plates. The lowest visual preference is seen for the 75° plate. The trend is not strictly linear but the trend towards preference for the datum is clear where the relative graph lines would intersect on their respective upwards and downwards trends. One notable deviation are the results for 15 ° and 30 °, which show a sharp decline and then a sharp increase in preference respectively. It is not clear why this is the case, but it is most likely due to subtle aesthetic differences leading to a subconscious judgement as the surface quality of both was very good.

A similar relationship is seen for *Joy* though it is not quite as pronounced and is subject to more variation against the different toolpath strategies. Generally, the datum plate was visually preferred but there were notable results for 0, 15 and 45° variations that recorded nearly half of the participants preferring. 30° recorded an unusually high number of "no preference" results leaving that relationship inconclusive. As the toolpath moves towards 75°, recorded preferences fall steeply, and the datum plate records its highest preference ratings. Why there is such a sharp drop in visual preference after a 45° raster angle is not entirely clear. The surface finish between the parts was consistent overall so is more probably connected to how the toolpath pattern interacts with the texture design. 45° and 15° respectively recorded 24/62 and 23/62 participant preferences. It can be speculated that the visual dynamics of the making process provide better visual energy, in turn enhancing the impact of the aesthetic symbolism that is evidenced the increased levels of perceived emotive intensity noted for *love*, *joy* and *optimism*.

Fear was built upon a cubic structural basis and the design was driven by a dynamic angularity. Considering the investigation results, there are several points of interest. Overall, the participants were drawn to the datum approach more than any other in terms of visual preference. The results for the 15° variation noted a tiny majority of one and the 75° variation recorded a just below half indicating a preference. In terms of preference trends, any relationships remain elusive and may only be established with further study. It appears that most participants aligned to a linear cutting approach as it visually compliments the cubic structure of the design. Examples such as the 60° variation, which recorded a notably low preference distribution, could be explained by a relatively poor surface quality, although this cannot account for all such examples.

On analysis of the visual preference results for Trust shows a more linear trend line with visual preference increasing as the raster angle becomes more extreme. Some of these results will have to be discussed against surface finish inadequacies, but this cannot account for the observed trends in this case. Visual preference at the 15° variation remains low, possibly owing to chatter-based machining errors, but increases steadily with the 60° and 75° variations recording majority preferences of 37/62 and 36/62 respectively. The subtle visual dynamics of the toolpath against the texture design may make these offset rastering angles more pleasing visually.

Machining strategies for tactile preferences

As the experiment was repeated is the same way and the “no preference” choices are similarly not included. Table 2 below provides the data for both the comparison plate preferences against the datum plates.

Table 2 - Participant preferences for tactile comparison of plates

	Comparison plate preference results ("more comfortable")					
	0 °	15 °	30 °	45 °	60 °	75 °
Surprise	13	12	7	3	12	6
Joy	7	15	11	4	3	3
Fear	6	11	8	11	5	18
Trust	10	9	7	10	16	12

	Datum plate preference results ("less comfortable")					
	0 °	15 °	30 °	45 °	60 °	75 °
Surprise	28	23	46	43	28	41
Joy	37	39	41	45	45	49
Fear	41	33	47	38	46	24
Trust	32	45	45	39	26	24

Two graphs can again be generated from this data that can help in the identification of trends. The graphs are presented as follows and represent inversions of one another as before (Figure 8).

The variations in tactile preference present a bigger challenge to unpack given firstly the subtleties of the tactile changes and secondly the visual references that the participants also had had. The extent of the subtleties may account for the lower rate of preference variation that is seen across the two graphs above. Upon analysis, a statistically significant difference between the datum and comparison results was indicated, suggesting that most of the participants did prefer one kind of tactile interaction over another. However, the "no preference" responses were significantly higher than that of the visual preference examination indicating that tactile differences as a results of machining strategies of this scale are less detectable than visual differences. The "no preference" results are listed as follows: Surprise 73 / 372, Joy 83 / 372, Fear 97 / 372 and Trust 110 / 372.

While these results are skewed towards a preference for the datum or a "no preference" response, the most extreme toolpath preference are seen at the lower and higher ends of the raster angle spectrum. *Surprise* shows the highest preference ratings for 0, 15 and 60°. *Joy* shows a similar relationship with the highest preferences given for 15 and 30° with the preferences dropping sharply with the other variations. A relatively large number of participants (18) recorded a preference for *fear* at 75° and *trust* at 60° (16). Considering Table 2, the concentration of positive datum preferences is focused upon the central area from 15-60°. As these preferences significantly decrease around this area (indicated by red), this provides evidence that some proportion of people prefer the tactile experience of cutting angles that deviate slightly from a toolpath parallel to the workpiece edge. Interestingly, this result is echoed somewhat in the visual responses suggesting there may be an alignment between the visual and tactile preference choices although this is probably a weak relationship. Aesthetic uniformity may be another factor that influenced the responses. The *trust* pattern was created to be very uniform and structured, but *surprise* and *joy* less so. A tactile sense of uniformity may affect the "no preference" responses; if the pattern has a more uniform construction, tactile differences are less detectable.

Implications for design practice and manufacturing engineering

The work concluded that variances in process parameters had measurable impact on user preferences in terms of the visual and tactile domains. As this aspect of the work is of a subjective disposition and reliant on the interpretation of participants, any conclusions drawn are open to question and scrutiny. The accumulation of more data may produce clearer relationships but what can be concluded is that there are consistently a proportion of people who have aesthetic and tactile preferences with respect to toolpath. If the datum approaches represent a kind of "normality" or an orthodox technical approach and the comparison plates represent unorthodox approaches, it is clear that an orthodox approach is not always favoured with significant numbers of participants having preferences for an experiential space out with a kind of designated material-manufacture "normality".

In essence, this points to the presence of an individuation that exists *prior* to the completion of the artefact as it is sold to the user. The evidence presented in this work suggests that the free modification of targeted process parameters can achieve specific experience factors. With respect to the patterning and texturing features explored in the previous sections, such features could for instance be used on housings of consumer products. Apple Mac laptops and Linn hi-fi systems utilise CNC metal machining in the construction of their products. A kind of patterning and texturing could be used to enhance the aesthetics of these artefacts and "guide" users (following affordance theory) in some ways by drawing them visually and emotively towards points of interest that may perform function or enhance product identity.

This raises the question of creating a generalizable tool; how can these new concepts of perception and experience be integrated with current production practices to achieve novel outcomes? To do this, the function and architecture of CAM systems can be re-examined. Standard CAM systems and systems of process control more generally have in-built biases towards particular kinds of manufacturing outcomes – efficient and free of "imperfections" (adhering to a Taylorist manufacturing philosophy). This bias to what Pallasma (2005/2012) called the "flatness" in modern production has led the architecture of CAM systems to limit the exploration capacity of processes and removing what can be broadly described as user-experience concepts. The diagram below shows the as-is status of CAM systems where the process has an in-built linearity with the cultural assumptions of hylomorphism (see Ainsworth, 2016). The designer wants to create something; accordingly, the processes are tailored to achieve this exact goal.

This presupposes that the in-process dynamics cannot offer anything in themselves of value out with the bounds of perfected object fabrication. As we have seen however, the intrinsic qualities of a process can introduce new and interesting properties into fabricated objects at both the level of form and perception. EdgeCAM for instance has a sophisticated rendering engine and allows the user to “see” how the part would look utilising a defined set of parameters (similar systems for additive manufacturing such as Fusion 360). As the process is simulated, interesting effects appear in the render as the simulation creates patterns. The problem is that these interesting possibilities are not highlighted by the software at all. Furthermore, CAM software does not offer any insight into UX or human factors; properties of perception and experience and not considered in reference to a simulated process (Wang, 2019). With respect to this observed short coming, a new CAM architecture is proposed and mapped out in the diagram below (Figure 10).

The new hypothetical architecture integrates human-factors options into a CAM software system and also unorthodox possibilities relating to the ductus of process. This could include perceptual information such as emotions, semantic meaning, and affordances. For example, a CAM simulation mapping the fabrication of a part through additive manufacturing could offer the user options with respect to the visual interest factors of the build. Additionally, a build could be tailored for comfort utilising texturing options. Handheld objects such as gaming controllers could be attuned for specific experiential outcomes within the CAM system, drawing on the dynamics of process ductus. This essentially reframes the CAM philosophies seen earlier as not just processes of material transformation control, but processes linked to potential perceptual experiences.

Conclusions

This work has presented an experiment to explore how small variations in manufacturing protocol can influence the perceptual properties of artefacts. By drawing on several previous studies by the authors, a number of pattern-based textured surface designs were fabricated using CNC machining. To explore how adjustments in approach can alter perceptual qualities, we focused on the rastering approach that is taken when CNC milling machines finish a part. Because rastering leaves an identifiable trace, it offered an opportunity to examine how raster angle variation may influence visual and tactile preferences.

Subsequently, an experiment was devised in which participants would select their preferred rastering approach in terms of visual and tactile interaction. The results clearly showed that a large range of preferences were present indicating strongly that the “default” protocols that are presented by current CAM systems are not necessarily well attuned to human-centred preferences. Consequently, we propose a reframing of CAM architecture that integrates qualitative user experience factors into the manufacturing rationale. This may not only broaden the scope of modern manufacturing practices but introduce useful human-centred concepts into technical disciplines that previously neglected their value.

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Figures

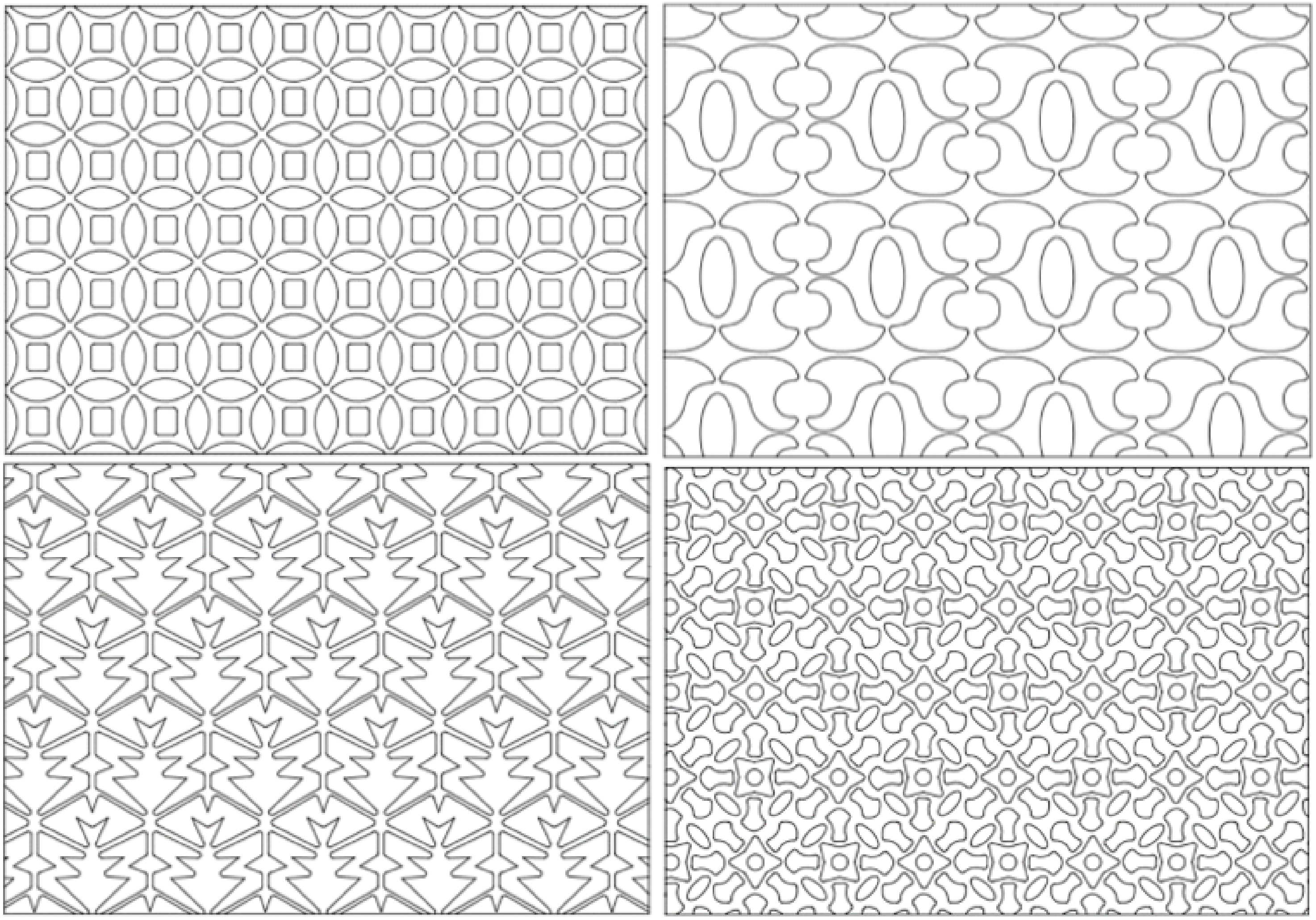

Figure 1

Four pattern design variations developed by the authors (see *blank for review*)

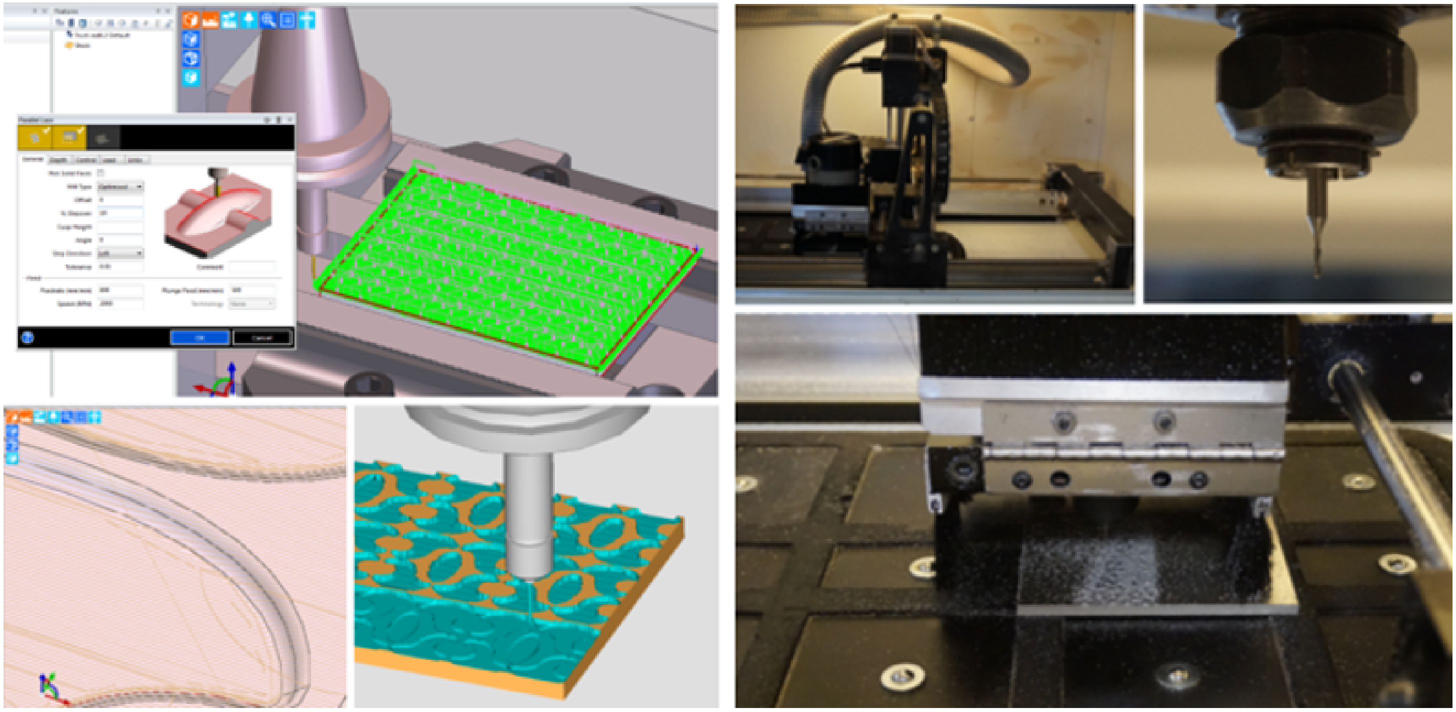

Figure 2

EdgeCAM simulation processes and setup for Denford Microengraver Pro with detail of cutting process and 1 mm ball nose cutting tool

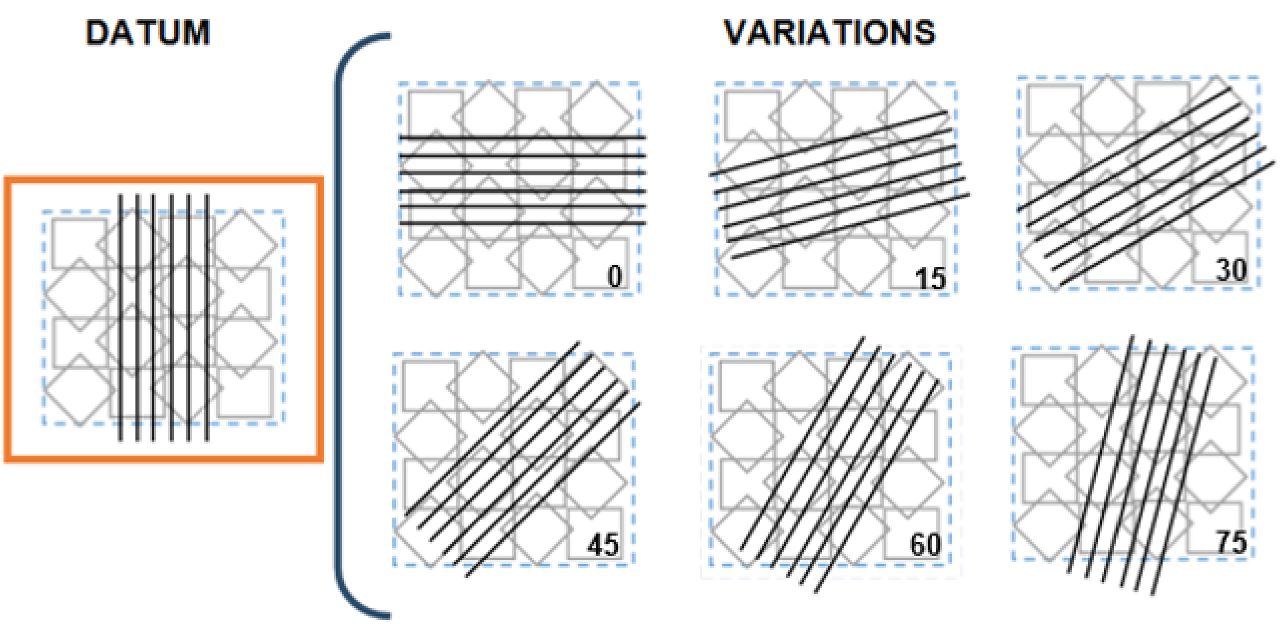

Figure 3

Parallel lace rastering angle variations

Figure 4

Machined aluminium plates for “fear”, “surprise”, “trust” and “joy” designs with perspective view

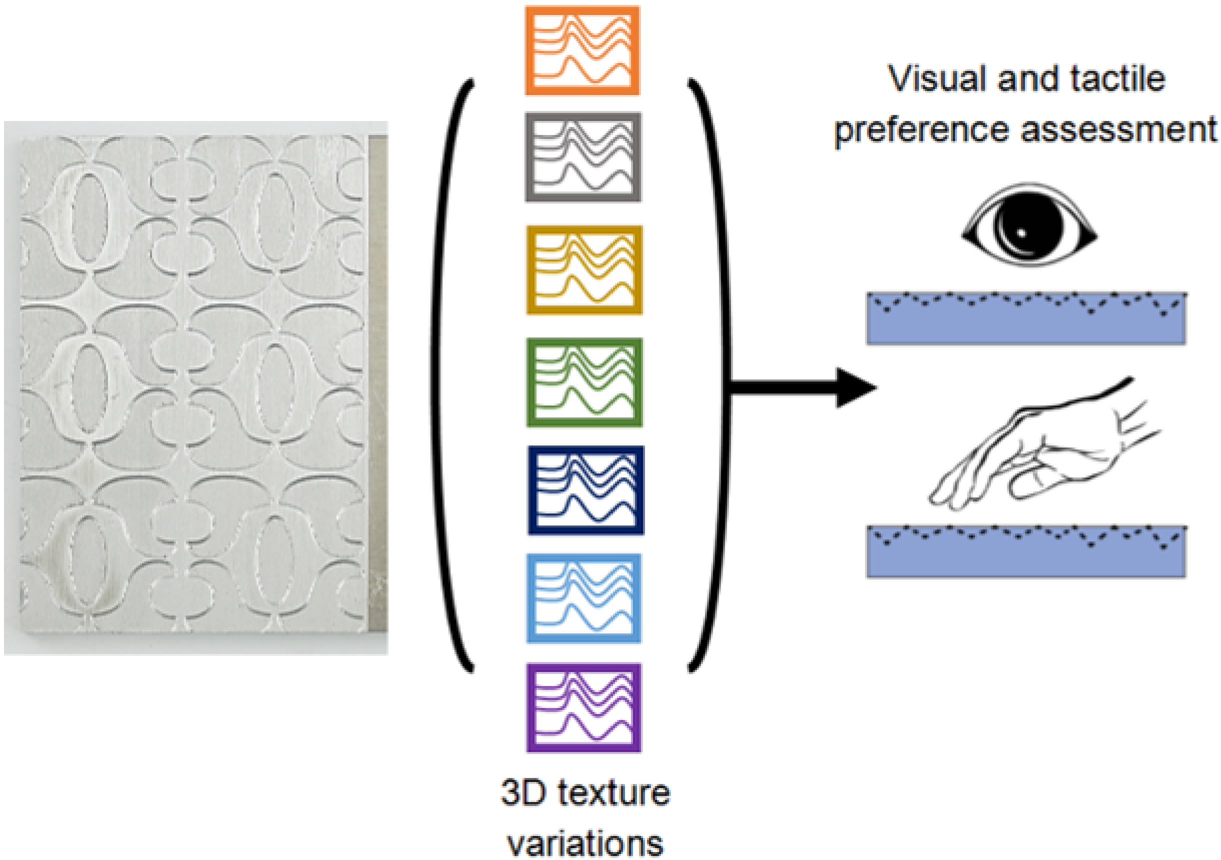

Figure 5

Overview of experimental stages; creation of texture variations followed by visual and tactile preference assessment of textures

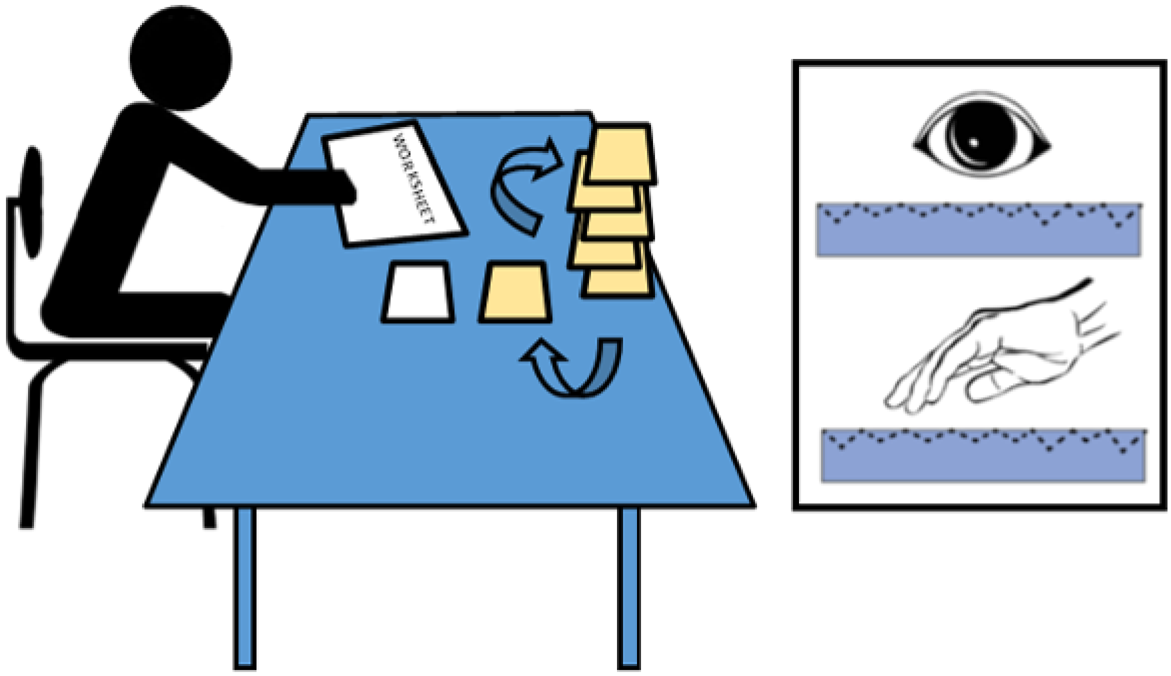

Figure 6

Second stage of experimentation; guided visual and tactile preference assessments of the 28 textured plates. Each participant was given a “datum plate” in order to assess against 6 “comparison plates”

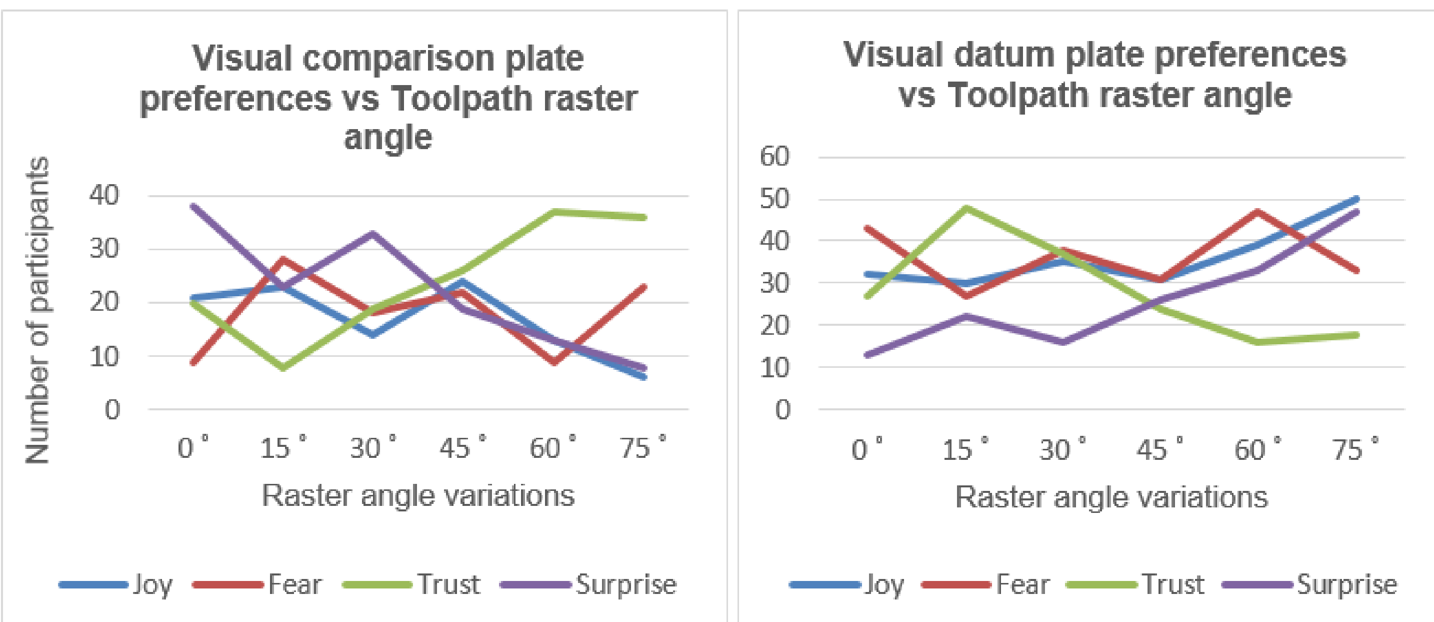

Figure 7

Visual preference trends for comparison plates and visual preference trends for datum plates

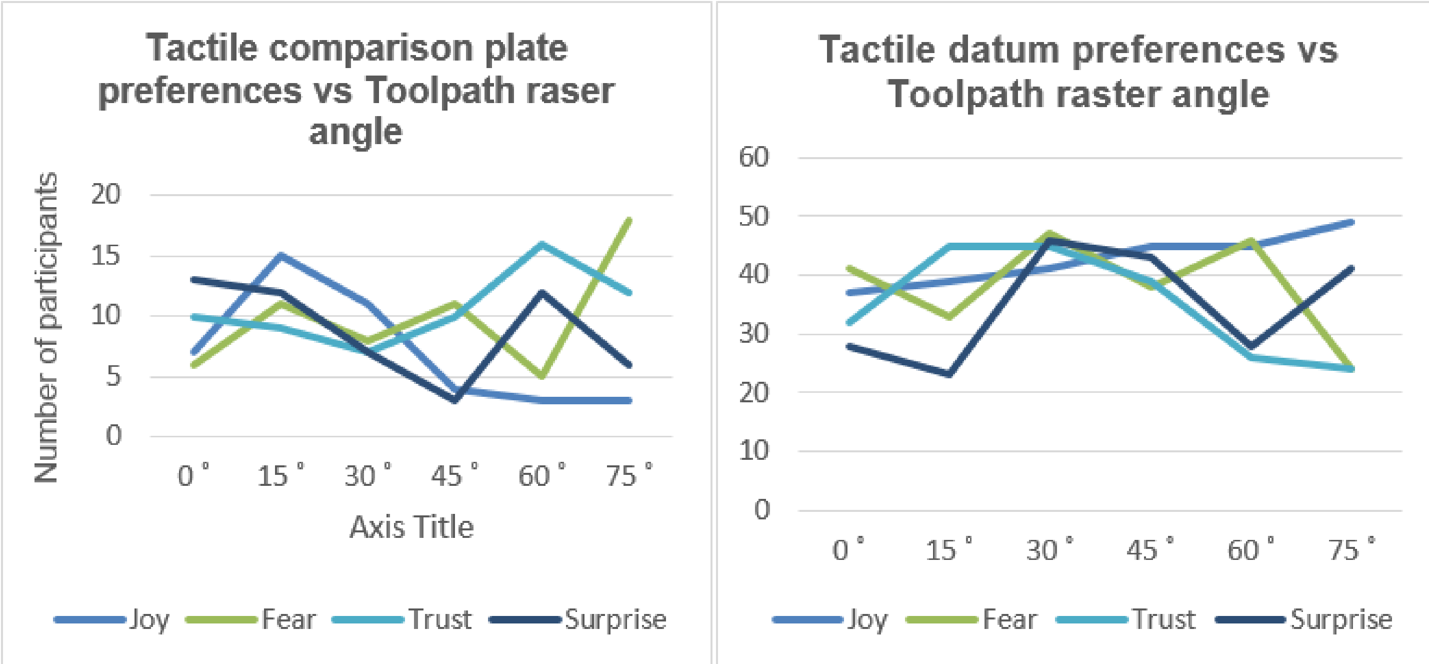

Figure 8

Tactile preference trends for comparison plates and tactile preference trends for datum plates

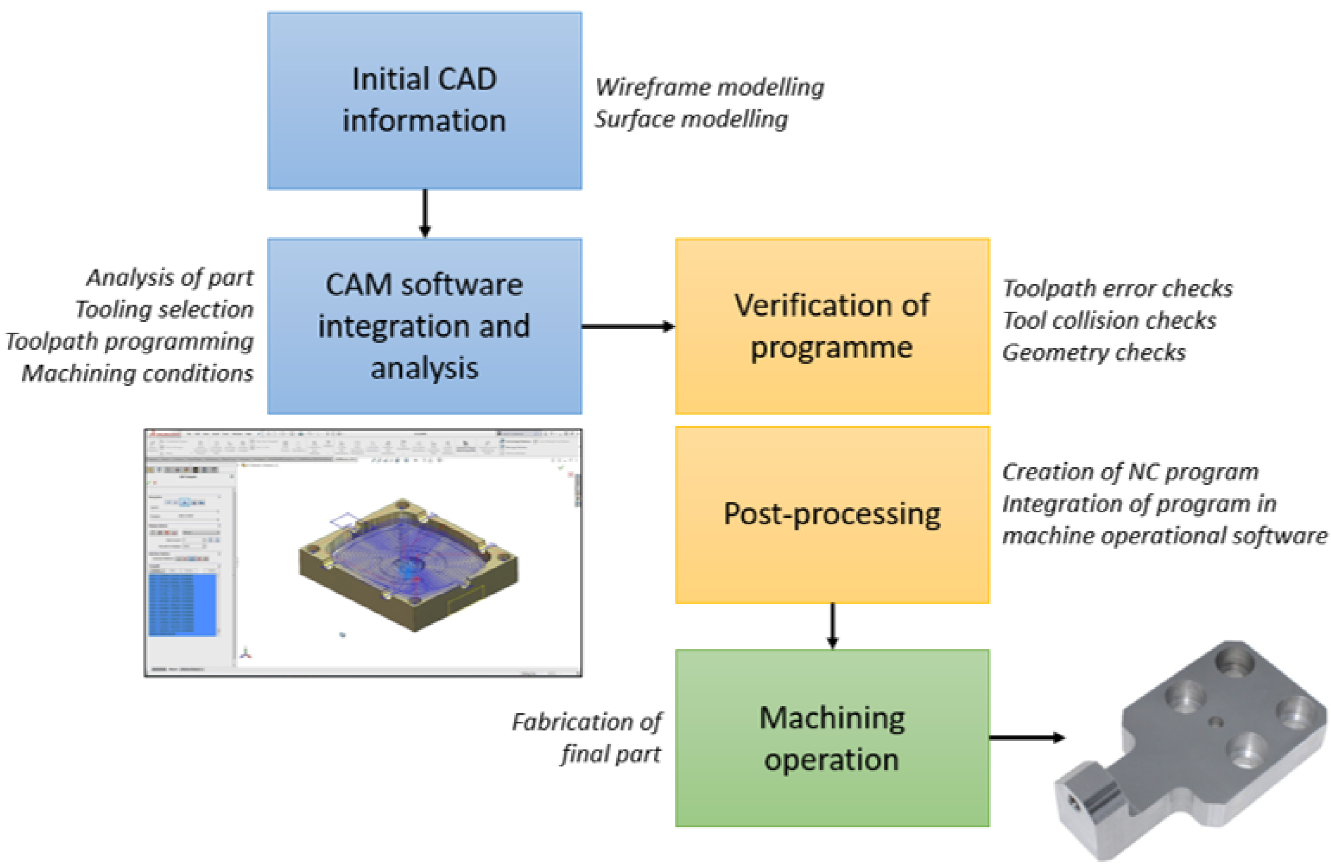

Figure 9

As-is CAM architecture

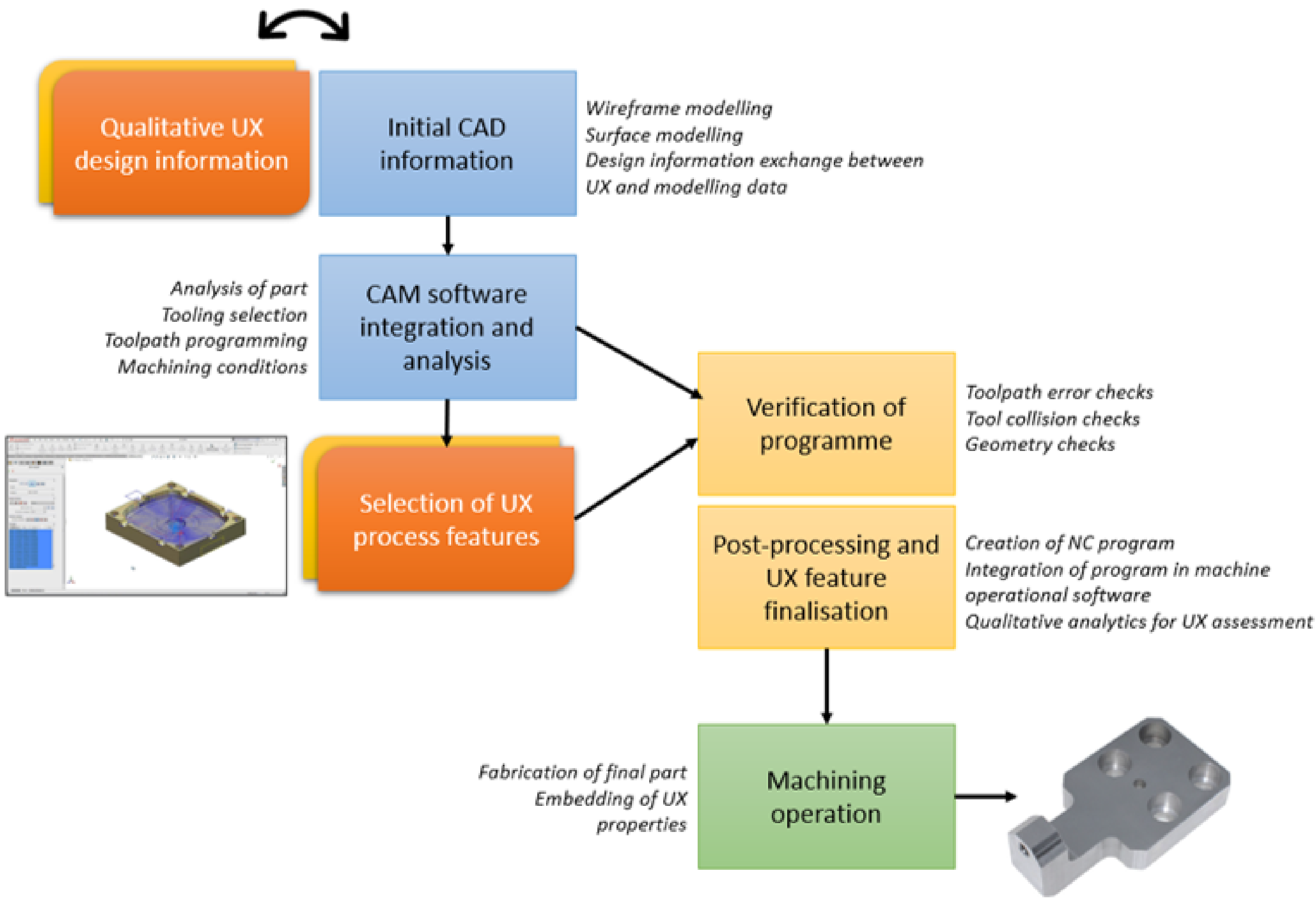

Figure 10

To-be CAM architecture integrating human-factors and UX concepts