Urquhart, Lewis and Wodehouse, Andrew (2016) Form as an abstraction of mechanism. In: Design Research Society Conference (DRS 16), 2016-06-27 - 2016-06-30, University of Brighton. ,

DRS2016
Design + Research + Society
Future-Focused Thinking

2016 Design Research Society
50th Anniversary Conference
27-30 June 2016, Brighton, UK

Form as an abstraction of mechanism

Lewis Urquhart* and Andrew Wodehouse

University of Strathclyde
*lewis.urquhart@strath.ac.uk

Abstract: There is an emergent body of research linking the nature of form to design, functionality and user experience. This paper builds on these recent studies to propose a new approach connecting conceptual-design with advanced manufacturing techniques. Using the properties of work materials and advanced forming manufacturing processes, radical approaches to design and production could be open to designers and engineers, offering novel modes of user experience. By firstly reviewing the literature on product form and its bond with the concepts within the fields of user interaction and user experience, a number of "functional mechanisms" are introduced that could potentially be integrated into this new and more homogeneous manufacturing framework.

Keywords: Form, materials, interaction, manufacturing

1. Background

Modern manufacturing technology presents designers and engineers exciting possibilities in the expression of form and function. Prominent examples include increasing sophistication of computer numerically controlled (CNC) forming technology, incremental sheet forming and 3D printing technologies. These processes present very good capabilities in terms of geometric forming options – particularly 5 axis CNC milling machine configurations, which have the ability to create complex freeform surfaces directly applicable to many consumer products. Despite the manufacturing parameters being relatively well understood, what is less closely considered within the design research community is how these processes can be used to produce particular product experiences for the user. The central aim of this work is to address this by proposing a new framework for manufacturing practices where mechanism and functionality can be articulated through form and material properties. Bridging the gulf between design knowledge and the more technical knowledge associated with manufacturing engineering, potentially creating novel experiences for the users of products.

“User experience” (UX) is an area of research that is still being developed and systematised (Vermeeren, Law, & Roto, 2010). Previously, a designer was said only to deal with the “aesthetic elements” of a product and plan how to construct its form. For the great designer and artist Bruno Munari, a designer was a “mediator between art and society” (Munari, 1966). Recent developments suggest this view is shifting somewhat – changing to a product interaction perspective, where the success or failure of a product rests on its interaction and experiential qualities. Interaction design (ID) is the process of designing whereby the user interaction with the product is expressly focused upon and enhanced. The modern approach was pioneered by Bill Moggridge in the 1980’s, developing concurrently with advances in computer technology, encompassing not just interaction with physical objects but elements of human-computer interaction (Moggridge, 2007). The developing Computer Aided Design (CAD) technology additionally allowed designers to experiment with form and function in different ways, to some extent expanding the control the designer had. It can be argued that CAD technology has had a significant impact on the development of ID by facilitating advanced processes such as CNC machining and additive manufacturing – expanding the lexicon of form that could be feasibly manufactured. Form, however must be meaningfully defined in order to understand this process fully.

2. Defining form

Form is an abstract concept and is thus difficult to define absolutely. Generally it can be described as the geometric boundaries of a particular object. More specifically, form can be abstracted to an idea known as *curvature continuity*. Curvature continuity is a geometric concept that makes up part of the theories of smoothness in mathematical analytics. What is called *G-0 continuity* is “positional”, where two surfaces share a single defined edge. *G-1 continuity* is “tangent” where the surfaces share an edge but there is no discernible break in the transition from one surface to the next. *G-2 continuity,* or “curvature” continuity is defined by surface planes having equivalent rates of curvature before joining – in this way the points of surface transition become theoretically undefinable (Foster & Halbstein, 2014). Figure 1 illustrates the differences between the geometric structures, listed as C0, C1 and C2 respectively. These geometrical definitions are a ubiquitous feature of CAD programming.

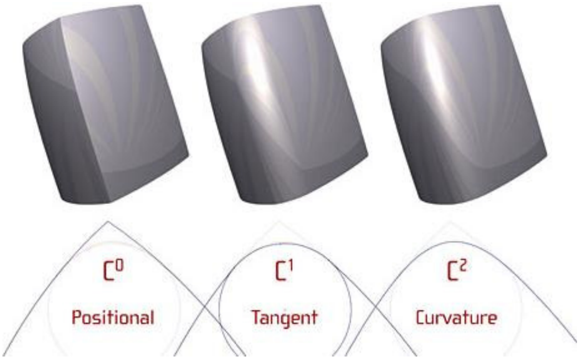

Figure 1: Curvature continuity, taken from “A Periodic Table of Form” (Holland, 2009)

In an objective sense, the C2 curve has the smoothest surface. This has been directly related to design within the framework of "concinnity". Two types of concinnity are considered, *objective* – which speeds the process of pattern finding or intelligibility of interacting with a product form example and *subjective* – defined as logical emotional cues that speed up the mental processing of an object's meaning (Coates, 2014). A sphere can be said to have the maximum amount of objective concinnity in a three-dimensional environment given its bilateral symmetry across any central axis (Coates, 2003).

2.1 Relating form to design

Some methods have chosen to take an emotive approach to the construction of form in the knowledge that successful products engage the user at an emotional level (Crilly, Moultrie, & Clarkson, 2004). At the cognitive level, emotions serve as an "adaptive function" that can be affected by interaction with form – this event is conceptualised as an *appraisal* (Arnold, 1960). Over the past three decades, research has accumulated illustrating the importance of form in the context of user experience and how successful products are economically (see Bloch, 1995). Recent work has suggested that the form of an object articulates "interaction aesthetics" and "interaction affordances" (Xenakis & Arnellos, 2013). The interaction aesthetic influences the selection of best action possibilities with respect to an object's characteristics through a process of dynamic presupposition of interaction.

3. Relationships with User Experience

3.1 Historical context

Form and function have a very close relationship in design – one often informing the other. The radical design philosophies of the Bauhaus school in 1920's Germany tried to purge the notion of the form informing the function in any sense, dogmatically committed to the rationalist idea that form must follow the function (Droste & Bauhaus-Archiv, 2002). What is ironic is the powerful aesthetic that emerged from the Bauhaus and other modernist movements – the pieces became more recognised as articulations in form than an expression of function. Many design movements throughout the history of mass produced consumer goods have influenced aspects of what has come to be known as user experience. The iconic Burgon and Ball, "Drummer Boy" sheep shears of 1730 (Figure 2), a design which has remained largely unchanged for over 270 years, are an excellent example of innovation that delivered a uniquely functional user experience. Industrial developments in metal forming in early 18th century England meant that sheet metal could be manipulated in such a way as to induce elastic feedback through hot rolling techniques. The function was in many ways derived from the form. Interestingly, it is the manufacturing process and material properties that allow the form to be expressed at all. The processes can be seen as a harbinger of functional and usability potential. A similar effect can be seen in the work of the Bauhaus school two centuries later through the work of two of its most prominent designers.

Figure 2: Burgon and Ball sheep shears, circa 1730

Marcel Bruer and Mies van der Rohn created some of the most radical chair designs ever seen by utilising the new tubular steel components. Bruer's "Model B32" chair for example used a revolutionary cantilever support to carry the weight of the sitter (Fiell & Fiell, 1999). Van der Rohn's chair from the same period used a similar principle (Figure 3). Of fundamental importance is how these new expressions of form delivered distinct avenues of user experience underpinned by particular interactive elements. Also shown is David Mellor's 700 series chair produced almost fifty years later, illustrating the lasting influence of the Bauhaus school's techniques.

Figure 3: Marcel Bruer, Cesca armchair, 1925 (left) Mies van der Rohn, MR chair, 1927 (middle), David Mellor, Abacus 700 series chair, 1975 (right)

3.2 Interactions in design

Form can express particular interaction properties; the Burgon and Ball sheep shears for instance (functionally) relied heavily on elastic feedback which was quite directly defined by the form of the sheet metal. The study and application of Interaction Design have since influenced a huge number of consumer products. The principle is presented as a five dimensional model: 1) Words, representing semantics or meaning of the user's interaction; 2) Visual representations, referring to elements that are not within a product, mainly graphics and typography; 3) Physical object or space, referring to the tangible means of control i.e. mechanical controls or digital interfaces; 4) Time, simply how much time the user spends during a given interaction; 5) Behaviour, defined as the users' reactions to particular interaction elements implicit within a design (Moggridge, 2007).

The five dimensions have applications across different fields and for different product types, digital systems as opposed to mechanical components for example. One of the central concepts is kinetic feedback. In a mechanical sense, feedback has been shown to be hugely important with respect to user interaction with products. Some work has shown for example how simple haptic feedback mechanisms using vibration can help guide a user to greater understanding of the product (Rogers, Sharp, & Preece, 2011). A notable example is a device developed dubbed the “MusicJacket” that uses this principle to help prospective musicians learn the violin (van der Linden, Schoonderwaldt, Bird, & Johnson, 2011). Other work has used haptic feedback to improve keyboard typing experiences, considering user behaviours and not simply functional aspects of the design (Wu & Smith, 2015).

3.3 Form and affordances

The concept of *affordance* has a close connection to form, interaction and geometrical relationships. With respect to the physical form of an object, research has focused on how users attribute meaning to a geometric structure. This was originally conceptualised by James Gibson in the 1970’s as part of his work on visual perception. Gibson described an affordance as “action possibilities” latent in an object or environment (Gibson, 1979). Norman (1988) and Gaver (1991) additionally expanded the concept. Norman describes two categories of affordance; real and perceived. “Real” affordances are physical characteristics that allow some kind of operation as opposed to “perceived” affordances which are visual clues regarding how a device or object is used (Norman, 1988). Gaver’s work, alternatively proposes four “situations” of affordance; perceptible affordance, false affordance, correct rejection and hidden affordances (Gaver, 1991). This framework is illustrated below in Figure 4 – a fully perceptible and true affordance is one where an affordance exists and there is information available to establish this truth.

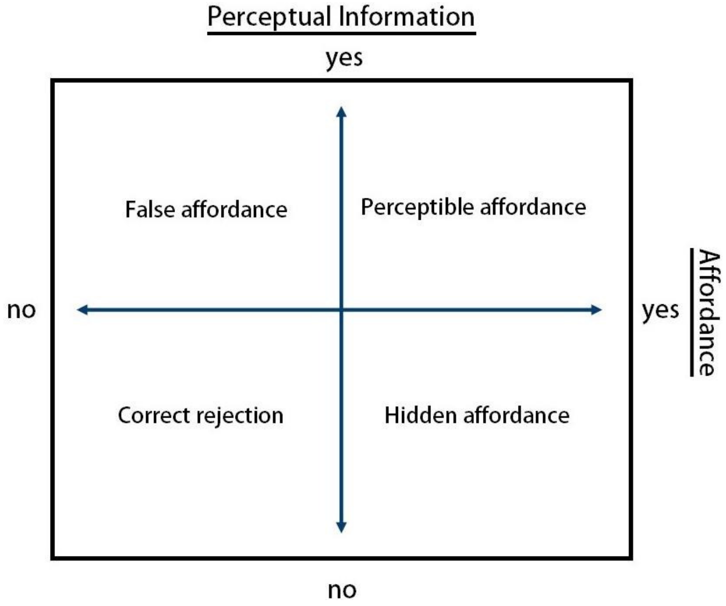

Figure 4: Situations of affordance – adapted (Gaver 1991)

The concept has continued to be explored extensively in a design context partly due to the prominence the graphical interface now has in modern civilisation. The graphical interface and indeed, its relationship with physical components will be an important consideration for future designers. Norman (1999) points out for example that there are both *logical* and *physical* constraints associated with affordances, understanding of which will be valuable. The concept of affordances in design can generally be seen as a critical component in any functional interaction and has implications for any theories of interaction and form.

3.4 Eliciting emotion

As described earlier, emotions serve as a form of adaptive function that can be affected by interactions with objects. More specifically, an *appraisal* event is defined as a response to both an object's form and function, acting as a precursor to an emotional reaction (Frijda, 1986). Research work in this area has been growing steadily in recent decades (Desmet & Hekkert, 2014). Seminal work by Norman for example has proposed three forms of emotional design; the *visceral*, the *behavioural* and the *reflective* (Norman, 2004). Other models have focused on a number of key parameters that emotive response is a function of; appraisal, concern, product and emotion (Desmet, 2003). Principally, it is clear that the user's emotive experience of a designed system can have a profound effect on the overall success of a product.

Alberto Mantilla's salt and pepper shakers (Figure 5) are a paradigmatic example of emotion used to enhance a product experience with the form explicitly expressing love and compassion. One study has proposed that positive emotive responses can be derived explicitly from how the form relates to the function. If, it is suggested, the form seems to articulate "exciting" features, then the design will have a more positive response at the emotional level, inducing a so called "WOW!" response in the user (Desmet, Porcelijn, & van Dijk, 2005).

Figure 5: Hug Salt & Pepper Shakers, Alberto Mantilla

4. Defining functional interactions

A number of examples have been explored in the previous sections concerning how form can influence and in some cases define the function of a product. Modern technological products rely heavily on a large range of mechanistic structures in order to function fully. For example, the push-button - despite being a ubiquitous electro-mechanical component – has only come to prominence over the last century where huge arrays of consumer goods started to require systems of mechanical feedback. By looking at a range of consumer products, this section will identify a number of tangible mechanical/functional interactions that play important roles in modern design and have since acquired some cultural significance.

4.1 Interaction mediums and mechanisms

By broadly examining a small range of consumer products, it is clear that mechanistic structures and components play a significant role in the nature of modern design. This section will identify a range of discrete interaction mechanisms and mediums and deconstruct their respective significance in a user interaction context. Other work has already gone some length to categorise distinct functional controls understood from the perspective of affordances (You & Chen, 2007) but, it is limited to the deconstruction of a single product with multiple command switches (stereo cassette recorder). The approach taken here will look at a wider range of products from a more functionalist perspective. Four distinct interaction mechanism classes were identified; pressing configurations, folding configurations, twisting or turning configurations and compressible configurations.

4.1.1 Pressing configurations

One of the most commonly seen mechanisms within consumer products and industrial technology is a pressing mechanism. The push-button has become a ubiquitous component, universally understood – as You & Chen (2007) put it, the structure of the object has “pressability”. This relates to Gaver’s (1991) framework for affordances; a button displays perceptual information, intelligible to a user, and presents an affordance opportunity creating a real perceptible affordance. Below shows a small sample of consumer products in which button-like mechanisms play an important role (Figure 6).

Figure 6: Buttons used in consumer products (Clockwise from top left – Apple iPod, Nokia push-button mobile telephone, standard calculator interface, emergency stop button, Toshiba laptop keyboard)

As a mechanical and electrical component, the button is incredibly modular taking on a huge variety of forms. It has been suggested that the form of a push button, when recognised, has distinct semantic meaning depending on its configuration within a product structure or a piece of information that explains what the button does (a play or pause symbol for example). In understanding the form of the object, a user can then manipulate it accordingly and receive feedback of a certain form (Krippendorff & Butter, 1984). The extent of the button's cultural significance can be seen in the prevalence of skeuomorphic design archetypes where a digital interface might mimic real-world objects (Derboven, De Roeck, & Verstraete, 2012).

4.1.2 Folding configurations

Collapsibility and space saving features are a common trait in many modern day products. The furniture manufacturers Ikea for instance aim to flat pack all of their designs. The ability to fold to either adapt the form of an object for functional reasons or as a space saving measure can be a vital characteristic for the success of a design. At Figure 7 a variety of folding structures are displayed. One of the most commonly used examples of a folding structure is that of the modern laptop computer. Due to the demands of modern-day work, computing power needed to be portable. The simple fold down the middle of the product, usually facilitated by a simple hinge mechanism allows the computer's total surface area to reduce by half. This effect is seen more radically in the case of collapsible chairs, lamps or perambulators which can reduce in size by approximately three quarters.

Figure 7: Folding mechanisms used in consumer products (Left to right – Anglepoise lamp, Apple Macbook computer, spectacles collapsing)

Notably, the folding structure of these products in many ways articulates the form of the product. In a collapsed state, the form is latent within the object. When a book, a lamp or a chair is manipulated or unfolded, a new form is articulated that also provides a function for the user, new affordance options and windows of user experience.

4.1.3 Turning configurations

Variety in component and product form can be associated with distinct meanings and distinct emotions for the user (Desmet, 2012). Turning or twisting structures are often used within the design of electronic interfaces to articulate specific functions or produce a subtle emotional experience, a volume control dial often uses a twisting mechanism as opposed to a button push for example. A number of examples are shown at Figure 8. The twisting of a digital camera lens creates functional feedback in the form of focusing the image that the user is observing through the screen interface. Similarly, the turning of a door knob facilitates the door opening or the turning of knobs on an instrument amplifier will alter aspect of the soundwaves produced. Turning mechanisms are also used as a directional modulator in robotic automation systems or TV and computer monitors for example.

Figure 8: Twisting mechanisms used in consumer products (Left to right – Nikon SLR digital camera focusing, turning door knob, instrument amplifier knobs)

4.1.4 Compressible configurations

Compressibility is an essential element of many products, although it is seen less often than pressing or folding structures. The principle elements are object change, movement or deformation caused by a certain mechanical event. An armchair for example achieves particular aspects of its function by allowing its structure to compress when a weight is applied. Other examples shown at Figure 9 derive their function purely from the ability to compress and manipulate their forms in particular ways – when a small amount of compressive force is applied to open scissors, the product will facilitate cutting, and similarly a stapler will complete a mechanical operation that releases a staple when a compressive force is applied.

Figure 9: Compressive mechanisms used in consumer products (Left to right – Biro pen release mechanism, scissors, latch mechanism on a bag strap, stapler)

There are other examples that could be examined within the classes of functional mechanisms in addition to the examples explored in the previous sections. These were selected on the basis that they are very commonly seen in a wide range of consumer goods.

This goes some way to help categorise distinct functional characteristics that have a strong connection to user interaction, and these are summarised in Table 1.

Table 1: Summary of interaction classes

Class of Interaction	Characteristics	Product examples
Pressable configurations	Movement or deformation of the component structure	Push-buttons; mobile phones, cameras, computer keyboards, music devices, interface systems
Folding configurations	Collapsibility of the structure, modulation in shape following an axial plane	Anglepoise lamps, books, laptop computers, folding chairs
Turning configurations	Component can rotate around a central axis	Camera lens focus, door handle, water taps, hi-fi volume control
Compressible configurations	Components can be squeezed together or deformed to achieve a particular end	Seating, scissors, staplers, springs

4.2 Linking form to manufacturing processes

What is noticeable about the examples cited in section 4.1 is in most cases the mechanistic structure has only been delivered through the combination of discrete component parts. In a sense the structure or form of the object is not fully homogeneous – a function cannot be produced from the form alone but relies on an assemblage of components. Attempting to abstract mechanism, or an assemblage that produces mechanism by purely using material properties and advanced processing techniques is beginning to be explored in both the practical design world and within academia.

One study has explored emotion and interaction in design by exploiting elastic properties of the manufacturing materials - using elastic movement as a means of emotional expression (Niedderer, 2012). The study focuses on manipulating silver through advanced laser welding techniques to enhance its elastic or spring-like properties facilitated by the silver's relatively low modulus of elasticity. Niedderer (2012), using design emotion focused work from other authors, creates three variations of a design for a fruit bowl – each one utilising the aforementioned elastic properties in distinct ways, but in each, the essential property of elasticity articulates the function of the product.

Similar work by Neri Oxman (2012) has proposed a much more technical approach to design where the production materials have adaptive functions, created in a single 3D-printing process. The approach is named "Material Computation" and presents a radical approach to form finding by utilising digital analysis of material properties as a function of environmental and structural performance (Oxman, 2012). One of the prototypes Oxman has developed is a chaise longue named "Beast" produced using an advanced multi-material 3D printing process – the form becomes adaptable to the user, relieving pressure at key compression points (Figure 10).

Figure 10: Prototype for "Beast" (Oxman, 2012)

4.3 The possibilities within advanced manufacturing processes

This work has focused on a number of important aspects in design, namely form, function and interaction potential latent within the structure of products. However, as stated previously, these interaction qualities usually are derived from an assemblage of smaller component parts as opposed to a more homogeneous structure. Niedderer (2012) and Oxman (2012) have shown some of the potential for applying advanced material understanding and state-of-the-art processes to achieve new expressions in form. This section will explore the possibilities within advanced manufacturing technology, opening new avenues of form and function. The design phenomenon can be illustrated graphically, where the production process becomes the route or medium of form creation (Figure 11). The character of the form then leading to particular interaction qualities that affect the user.

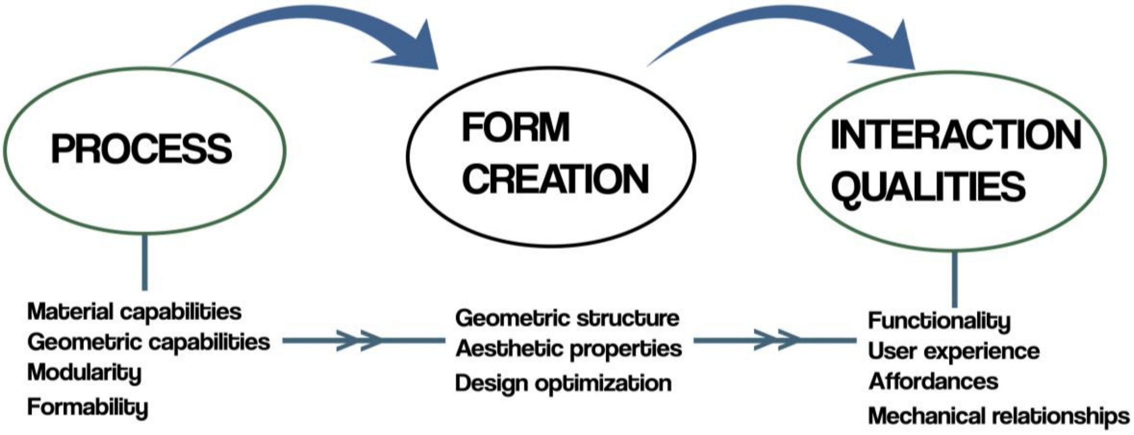

Figure 11: Proposed design framework

4.3.1 Additive manufacturing

Additive manufacturing is one of the most exciting new technologies that is being studied today. It is of particular interest here given its scope in terms of form creation. The process gradually builds a component in layers giving it excellent geometric potential. There are a huge variety of additive manufacturing processes each with weaknesses and strengths. However, in the context of this study some variants have the potential for strong interaction qualities – novel approaches that are not feasible given other techniques. Multi-material additive manufacturing for instance has a huge amount of potential. The principal quality is the ability to vary material properties where materials can be functionally graded, varying in hardness, flexibility, stiffness, surface texture and colour with the LENS additive process for example (Gao et al., 2015). Exploiting these processes has successfully produced radical pieces of art and multi-component assemblies with compliant (component-less) joints (Meisel, Gaynor, Williams, & Guest, 2013). Additional features include the printing of fully functioning electrical assemblies such as integrated circuits, sensors and other components with piezoelectric properties (Gao et al., 2015).

4.3.2 Computer Numerical Control

Manufacturing systems utilising Computer Numerical Control (CNC) range in uses and complexity. Two process have been identified that utilise CNC techniques – machining and Incremental Sheet Forming (ISF) – which are of interest in this study. The geometric and functional potential of both of these processes have not been explored fully. ISF process is newer and by its nature less predictable, but could potentially offer a broad range in terms of geometric forming options and embedded functional behaviour. In the case of machining, the process has a foundation in positional geometry where a cutting tool is commanded by a computer programme to perform a particular operation in a specifically defined special location (Madison, 1996). A cutting tool can work in multiple axes depending on machine configuration and this presents significant geometrical control for manufacturers, including the creation of freeform complex surfaces (Lasemi, Xue, & Gu, 2010). This offers interaction opportunities in the construction of metal components in particular. Would it be possible to machine very finely a component and achieve functional characteristics from its form?

ISF differs fundamentally in not being a subtractive process but uses gradual deformation in sheet metal to form parts. ISF machines are typically integrated with CNC systems and are capable of producing extremely complex geometries in sheet metal although the process is constrained by shear stress properties of the work metals (Bambach, Cannamela, Azaouzi, Hirt, & Batoz, 2007). One research effort, focusing on the formability of aluminium using ISF has been carried out concluding that the formability of a sheet depends greatly on the material strain path (Shim & Park, 2001). Similar work has tested uniformity of sheet metal thicknesses and created a theoretical model of thickness strain distribution post forming (Kim & Yang, 2000). The study used complex geometries akin to freeform surfaces to test the validity of the model and was able to derive an accurate picture of strain distribution, this is shown below where the darker sections indicate higher strain forces (Figure 12). Might it be possible to isolate regions of a sheet metal using ISF to create mechanistic features, elastic flexibility in specified areas that have been subjected to a specific strain distribution for example?

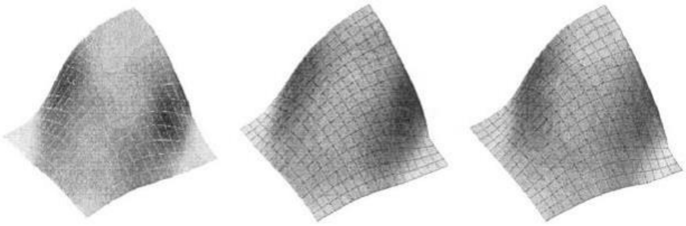

Figure 12: Strain distribution on section of formed part using varying ISF forming methods (Kim & Yang, 2000)

5. Towards abstracting mechanism into form

A number of interactive mechanisms were identified that are commonly seen in modern consumer products including pressable, folding, turning and compressible structures. Firstly considering pressable structures - as detailed earlier the most common example of this phenomenon is the push-button. With respect to the framework introduced, what we must ask here is whether advanced processes can be used to create the mechanistic properties of a button in a single material – the mechanism latent within the form of the component. Two examples have been proposed and are shown below (Figure 13), using thin-walled structures to induce flex characteristics. Using materials with distinct properties such as a low elastic modulus, particular forms – using defined form guidelines like the three modes of curvature continuity described in section 2 - could be created that would potentially exhibit mechanistic qualities. Structures similar to the ones presented could conceivably be created using any of the advanced manufacturing processes mentioned in section 4.3 and experimental work would be required to determine which form, material and which process would give positive results. The proposed pressable structures shown at Figure 13 could conceivably be manufactured a number of ways. Subtraction from a piece of solid material (metal or plastics) would present challenges in terms of attaining thin walled cross sectional areas but may be the most economically viable option. The parts could also be made by additive manufacturing or using ISF, however, these pose respective problems in terms of structural integrity of the work materials and geometric capability of the process (see Ceretti, Giardini, & Attanasio, 2004 for more detail). Such an experiment would be valuable, both to test the capabilities of CNC technology and also to examine the functional characteristics of the formed components.

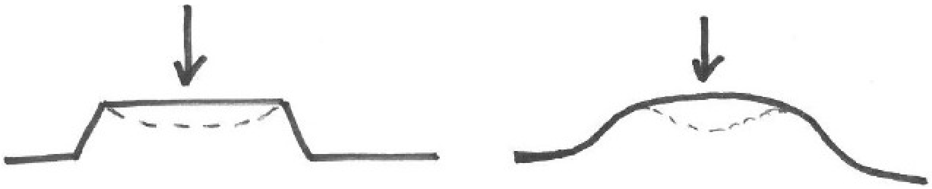

Figure 13: Pressable structures

Foldable structures were the second interaction mechanism identified. Creating a homogeneous part that can fold in the manner of a hinge poses some fundamental problems mostly in terms of fatigue life. Multi-material 3D printing has the potential to create such structures as has already been demonstrated by Meisel and others (2013) with the development of compliant joints. Subtractive CNC machining methods could also be applied here and such a study (especially with a focus on metal machining) would be a worthwhile conceptual examination. The concepts in Figure 14 could theoretically fold over themselves but would need to be carefully considered structurally and mechanically. It can be envisioned that a structure similar to those shown would replace the casing of a laptop computer; making the object more homogeneous, a function latent within the form.

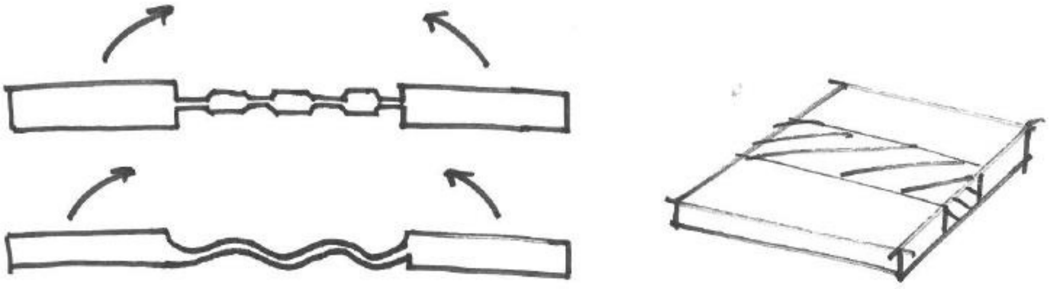

Figure 14: Folding structures

Lastly, compressible structures and turning structures were proposed as interaction mechanisms. These forms pose some challenges and are not as frequently seen amongst consumer products. With respect to compressible structures, it is proposed that something akin to a folding structure, subtracted from a piece of solid material using CNC machining methods could conceivably create a compressible structure (see Figure 15a overleaf). Such a component would pose challenges in terms of fatigue life, but an investigation examining the use of different materials and form variations may be worth considering. Multi-material additive manufacturing could facilitate a turning mechanism of some description. Considering the bottom image Figure 15b, if a component part was manufactured using an additive process with a flexible material variant positioned centrally, a simple twisting or turning movement could be achieved. There is scope to utilise these formations in sectors such as consumer electronics, reducing parts and making available novel forms of interaction for the user of a device. Additive manufacturing techniques are also suited to creating compressible structures – if a component had gradations in structural hardness, discrete compressible sections could potentially become part of a larger homogeneous structure.

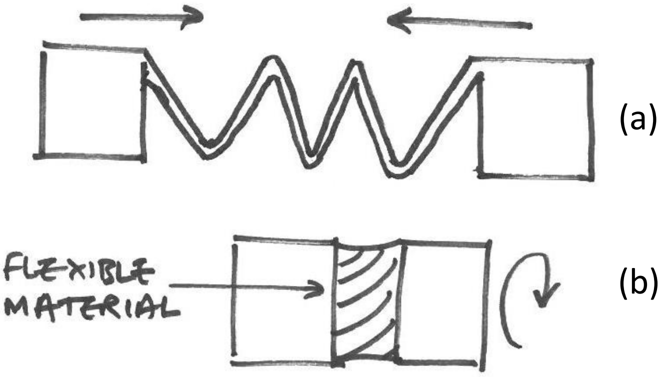

Figure 15: Compressible (a) and turning (b) structures

6. Conclusions

This paper initially examined the literature concerning the theories of form and user experience and introduced a categorisation of differing interaction modes with consumer products by focusing on a number of key mechanisms. These types of interactions were categorised as a function of a reliant mechanism and defined as "configurations" that facilitated a particular user interaction; pressable configurations, folding configurations, turning configurations and compressible configurations.

From here an examination of several state-of-the-art processes was carried out. There was an explicit focus on processes that provided excellent geometric capabilities (CNC machining and additive techniques) and those that could very directly change the properties of the workpiece (ISF and multi-material additive techniques). With respect to these manufacturing techniques, a number of form explorations were proposed with the aim of creating mechanistic but homogeneous structures from forming material in a particular way. Pressable structures that flex and deform could be produced using a very accurate CNC machining process or ISF. It was proposed folding structures could be created with accurate CNC processes, however the geometric structure would have to be considered very carefully and both compressible and turning forms could be created using additive techniques, producing homogeneous mechanistic configurations.

More work is needed in this area of engineering. The relationship between materials, key manufacturing processes and form is too often ignored. We therefore propose focusing primarily on how variations in form and manufacturing process can enhance design functionality and user experience. Successfully integrating these would expand the lexicon of design understanding and the possibilities within the engineering of mechanisms.

7. References

Arnold, M. B. (1960). *Emotion and Personality, Volume 1*. Columbia University Press.

Bambach, M., Cannamela, M., Azaouzi, M., Hirt, G., & Batoz, J. L. (2007). Computer-Aided Tool Path Optimization. *Strategies*.

Bloch, P. H. (1995). Seeking the Ideal Form: Product Design and Consumer Response. *Journal of Marketing*, *59*(3), 16. doi:10.2307/1252116

Ceretti, E., Giardini, C., & Attanasio, A. (2004). Experimental and simulative results in sheet incremental forming on CNC machines. *Journal of Materials Processing Technology*, *152*(2), 176–184. doi:10.1016/j.jmatprotec.2004.03.024

Coates, D. (2003). *Watches Tell More Than Time: Product Design, Information, and the Quest for Elegance*. McGraw-Hill.

Coates, D. (2014). Advances in Affective and Pleasurable Design (p. 535). Independent Publisher.

Crilly, N., Moultrie, J., & Clarkson, P. J. (2004). Seeing things: Consumer response to the visual domain in product design. *Design Studies*, *25*(6), 547–577. doi:10.1016/j.destud.2004.03.001

Derboven, J., De Roeck, D., & Verstraete, M. (2012). Semiotic analysis of multi-touch interface design: The MuTable case study. *International Journal of Human-Computer Studies*, *70*(10), 714–728. doi:10.1016/j.ijhcs.2012.05.005

Desmet, P. M. A. (2003). A multilayered model of product emotions. *Design Journal, The*, *6*(PART 2), 4–13. doi:10.2752/146069203789355480

Desmet, P. M. A. (2012). Faces of product pleasure: 25 positive emotions in human-product interactions. *International Journal of Design*, *6*(2), 1–29.

Desmet, P. M. A., & Hekkert, P. (2014). Special Issue Editorial : Design & Emotion.

Desmet, P. M. A., Porcelijn, R., & van Dijk, M. (2005). How to design wow. Introducing a layered-emotional approach. *Proceedings of the Conference Designing Pleasurable Products and Interfaces, TU Eindhoven, Eindhoven*, (2005), 71–89.

Droste, M., & Bauhaus-Archiv. (2002). *Bauhaus, 1919-1933*. Taschen.

Fiell, C., & Fiell, P. (1999). *Design of the 20th century*. Taschen.

Foster, S., & Halbstein, D. (2014). *Integrating 3D Modeling, Photogrammetry and Design*. Springer Science & Business Media.

Frijda, N. H. (1986). *The Emotions*. Cambridge University Press.

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., … Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design*, *69*, 65–89. doi:10.1016/j.cad.2015.04.001

Gaver, W. W. (1991). Technology affordances. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems Reaching through Technology - CHI '91*, 79–84. doi:10.1145/108844.108856

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception: Classic Edition* (Vol. 20). Psychology Press.

Holland, G. (2009). A periodic Table of Form: The secret language of surface and meaning in product design.

Kim, T. ., & Yang, D. . (2000). Improvement of formability for the incremental sheet metal forming process. *International Journal of Mechanical Sciences*, *42*(7), 1271–1286. doi:10.1016/S0020-7403(99)00047-8

Krippendorff, K., & Butter, R. (1984). Product Semantics: Exploring the Symbolic Qualities of Form. *Innovations*, *3*(1984), 4–9.

Lasemi, A., Xue, D., & Gu, P. (2010). Recent development in CNC machining of freeform surfaces: A state-of-the-art review. *CAD Computer Aided Design*, *42*(7), 641–654. doi:10.1016/j.cad.2010.04.002

Madison, J. (1996). *CNC Machining Handbook: Basic Theory, Production Data, and Machining Procedures*. Industrial Press Inc.

Meisel, N. A., Gaynor, A., Williams, C. B., & Guest, J. K. (2013). Multiple-Material Topology Optimization of Compliant Mechanisms Created Via PolyJet 3D Printing. *Solid Freeform Fabrication Symposium*, 980–997. doi:10.1115/1.4028439

Moggridge, B. (2007). *Designing Interactions*. MIT Press.

Munari, B. (1966). *Design as Art*. Penguin Books.

Niedderer, K. (2012). Exploring Elastic Movement as a Medium for Complex Emotional Expression in Silver Design. *International Journal of Design*, *6*(3), 57–69.

Norman, D. A. (1988). *The Psychology of Everyday Things*. Basic Books.

Norman, D. A. (1999). Affordance, conventions, and design. *Interactions*, *6*(3), 38–43. doi:10.1145/301153.301168

Norman, D. A. (2004). *Emotional Design: Why We Love (or Hate) Everyday Things*. Basic Books.

Oxman, N. (2012). Material Computation. *Manufacturing the Bespoke: Making and Prototyping Architecture*, 256–265.

Rogers, Y., Sharp, H., & Preece, J. (2011). *Interaction Design: Beyond Human - Computer Interaction* (Vol. 6). John Wiley & Sons.

Shim, M. S., & Park, J. J. (2001). The formability of aluminum sheet in incremental forming. *Journal of Materials Processing Technology*, *113*(1-3), 654–658. doi:10.1016/S0924-0136(01)00679-3

van der Linden, J., Schoonderwaldt, E., Bird, J., & Johnson, R. (2011). MusicJacket—Combining Motion Capture and Vibrotactile Feedback to Teach Violin Bowing. *IEEE Transactions on Instrumentation and Measurement*, *60*(1), 104–113. doi:10.1109/TIM.2010.2065770

Vermeeren, A., Law, E., & Roto, V. (2010). User experience evaluation methods: current state and development needs. *Proceedings: NordiCHI 2010*, 521–530. doi:10.1145/1868914.1868973

Wu, C.-M., & Smith, S. (2015). A haptic keypad design with a novel interactive haptic feedback method. *Journal of Engineering Design*, *26*(4-6), 169–186. doi:10.1080/09544828.2015.1030372

Xenakis, I., & Arnellos, A. (2013). The relation between interaction aesthetics and affordances. *Design Studies*, *34*(1), 57–73. doi:10.1016/j.destud.2012.05.004

You, H., & Chen, K. (2007). Applications of affordance and semantics in product design. *Design Studies*, *28*(1), 23–38. doi:10.1016/j.destud.2006.07.002

7.1 Image references

Images sources online with permissions are as follows, including the image description and the source site;

- *Burgon and Ball sheep shears:*
  http://www.tractorsupply.com/tsc/product/ideal-instruments-burgon-ball-sheep-shears?cm_vc=-10005 (with permission from Burgeon and Ball)

- *Marcel Bruer B32 chair:*
  http://www.knoll.com/ (with permission from Knoll)

- *Mies van der Rohn armchair:*
  http://www.knoll.com/ (with permission from Knoll)

- *David Mellor chair:*
  With permission from and provided by David Mellor Design

- *Hug salt and pepper shakers:*
  With permission from and provided by Alberto Mantilla

All other images are either original photos or drawings by the authors or taken from freely available stock photographs. All images are free for commercial and personal use, do not infringe on any copyright and are sourced from the following online sites;

- https://www.pexels.com/
  The images sourced are as follows; *Apple Macbook*

- http://www.freeimages.com/
  The images sourced are as follows; *Apple iPod, Nokia phone, standard calculator, emergency stop button, modern scissors, stapler, Nikon camera, instrument amplifier*

About the Authors:

Lewis Urquhart is an Engineering Doctorate student in the department of Design Manufacture and Engineering Management. His research primarily focuses on unifying manufacturing engineering with understanding in user experience and design interaction.

Andrew Wodehouse is a Senior Lecturer with research interests in product interaction, creativity and design innovation. He has led EPSRC, AHRC, KTP and Carnegie Trust projects across these areas.