MULTIMODALITY THROUGH PHYSICAL DIGITAL DESIGN

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ABSTRACT:

This paper aims to deliver a better understanding of the relationship between the physical and virtual, two dimensional and three dimensional representations of form that are employed in the critical early stages of design. It presents findings from observations of practice undertaken to provide an initial dataset on how designers move between these representations, and of the kind and quantity of information they choose to exchange between them. Informed by these findings, and in response to the emerging need for new methods of sketching and prototyping in the digital era, it will also present a new proposal for hybrid virtual/physical digital design practice based on a significant modification of an earlier approach.

Keywords: digital form generation
1. INTRODUCTION

In the last twenty years digital technologies have become part of the fabric of our lives. We may now choose to write in word processors, to buy our groceries online or to download music from the net rather than write in longhand or shop in the High Street. We are all, whether we actively participate or not, becoming increasingly acculturated to the ideas and methods of digital ways of living and working.

Design practice itself has anticipated this change. Over the same period design representations have typically been transformed from analogue and physical forms to digital and virtual ones. The area least affected by this change, however, has been form generation: sketching, physically making marks on paper, is still the medium that product designers and architects will turn to for the initial stages of form creation. Virtual digital representations of form are commonly employed in many other areas of contemporary design practice, but not until candidate design solutions have gained the relatively fixed structure that is required for development through digital media. Although the transition from shape generation, using two dimensional physical representations, and form development using three dimensional virtual representations may involve the use of a physical three dimensional representation (i.e. a model), its function at this point will usually be to verify designs generated by sketching rather than being fully integrated in the form generation process in an iterative fashion. Confining the use of three-dimensional representations to a final verification of sketched ideas is unfortunate as it is often at this point that proposed design solutions, while perfectly satisfactory as an arrangement of two dimensional shapes, are found to be unsatisfactory when first realised as a three dimensional form.

With the proliferation of commercially available rapid prototyping devices, however, the potential now exists for physical representations to be more usefully integrated into digital design practice. These rapid-prototyped physical representations, rather than being straightforward replacements for traditional models, differ from them in the vital respect that, as physical instances of virtual digital representations, they are now also digital representations in themselves (Fig. 1).
It is this complex relationship between shape and form, generation and development, and the different modes of reasoning engendered by different design representations that lies at the heart of the first named author’s ongoing PhD research. This paper is derived from part of that enquiry, and situated in an area of increasing interest for design research in general, namely the closer integration of physical and virtual digital representations in design practice. After all, as design seeks to modify the physical world, it is timely to ask how computational design itself might be better enabled to interact with that physical world.

1.1. STRUCTURE OF PAPER

The paper is divided into three main sections. The first lays out the research problem, outlines some prior work in areas related to the research problem and concludes with a discussion and analysis of that work. The second part describes the data gathering undertaken in support of a fresh answer to the research problem, showing the two strands employed so far along with an overview of the methodology employed, and concludes with a discussion and analysis of the initial findings. The final section looks at the implications of those findings, and outlines a possible response to them, before presenting conclusions from the work undertaken so far.
2. STATEMENT OF RESEARCH PROBLEM

To generate form designers use a variety of non-verbal media: sketches, drawings and constructions, typified by Cross as part of the ‘third culture’ of design (Cross 1982). Each of these media, however, has its own set of constraints and affordances, and none can be considered as the complete answer to designers’ needs.

The survival of sketching as the de facto means for initiating design in the digital era is due to its combination of speed, malleability and availability. Sketches continue to prosper by using the materials and skills embedded in traditional design practice and, unlike their virtual counterparts, are still available when the power is turned off. Paper representations of designs may be constantly reworked and, more importantly, restructured in a way that digital design representations have so far been unable to emulate. Sketching, rather than merely being an externalisation process, can also be seen as a way of reasoning about shape (Smithers 2001), and design through drawing has been formalised to the extent that it can be viewed as a form of calculation, but calculating by manipulating shape rather than number (Stiny 2006). Designers can also be seen to engage in a dialogue with their sketched design representations (Schoen 1983), and this reciprocal relationship between design representations and design reasoning appears to be an integral part of the generative process. Unfortunately, despite these positive qualities for shape generation, sketching used on its own does not give a true sense of the three-dimensional form of a proposed design and, while digital and physical models may be used to address this shortcoming they in turn have constraints that limit their use in form generation.

Digital virtual representations, although they may be easily modified (though not easily re-structured), and prior states readily reinstated, do not in themselves afford tactile assessment of form or a true sense of scale. Physical representations can be used to supply these qualities, and although they may require no explicit structuring in their realisation, any modifications made to them will inevitably destroy the record of previous states. Transferring these modifications from a physical representation to any other form of representation is also a cumbersome and time consuming process, which leads to them being used mostly as a final verification of a design proposal. Therefore, by the time a physical representation of form is used in contemporary design practice many significant aesthetic and functional decisions will have been made, and considerable design effort invested; even experienced designers may discover unsuspected problems with the form of a proposed design at this point. The significance of these early stage design decisions to design practice can be gauged by Roemer’s estimate that 70% of product
costs are determined within the first 20% of the design process as a whole (Roemer et al 2001). It would be advantageous then to combine the more rigorous form description abilities of physical and virtual three-dimensional representations with the flexibility, and speed, of sketching earlier in the initial stages of design. The essence of the research problem then is how to combine the positive qualities of each of these different representation systems, to combine physical and virtual representations of form iteratively and to allow multimodal assessment of digital designs in the early stages of the form generation process.

2.1 OUTLINE OF PREVIOUS RESEARCH

There are two distinctly different approaches available to resolving this research problem. The first entails keeping the representation of form completely within the virtual realm, and augmenting the modes of assessment available to a designer through, for example, force-feedback haptic devices and stereoscopic displays, and ensuring a constant flow of information between the physical and virtual realms. Much research has been carried out in this field by Giraudi and Bordegoni, of the “Touch and Design” project (Giraudi and Bordegoni 2005), and Evans et al at Loughborough (Evans et al 2005). The second approach, and the subject of this paper, is to achieve multimodal assessment of digital designs through direct physical contact. This entails creating physical representations of design proposals, either from scratch or from a virtual digital design, and only transferring information between the virtual and physical domains at discrete intervals via reverse-engineering and rapid-prototyping.

2.1.1 Combining physical and virtual representations of form

Early research at TUDelft on ‘Physical Concept Modelling’ (Broek et al 2000), focused on producing modular physical representations, carved from foam by bespoke CNC hardware (computer-controlled, heated, flexible blades) and derived from virtual digital form. Their intention was to give physical models a longer useful life by only replacing those sections that had been modified in the virtual representation. Research was also undertaken on using laser scanning, and other forms of reverse engineering, to transfer modifications made to the physical model back into the virtual representation, but no working system has been demonstrated as yet.
Research on the recursive use of computer generated physical modelling was undertaken by Simondetti of the Hong Kong Polytechnic University, however, in a series of studies covering furniture design, architectural massing and product design, but with the emphasis on ergonomic and functional assessment rather than initial form generation (Simondetti 2002).

Brunel (Prieto et al 2003) has also examined bi-directional information flow but, in contrast to TUDelft, has taken a hand-mediated rather than a wholly technological approach. By creating rapid-prototyped models, with the three-dimensional equivalent of graph paper embedded in them, they have been able to use image mapping techniques to transfer modifications made to a physical rapid-prototyped representation back to the original virtual representation. Their approach has been to photograph physically modified rapid prototyped models, and to use that photograph as a guide (loaded as a backdrop in a digital modeling program) to modify the NURBS curves defining the virtual representation, matching them to the altered curves of the physical model. Continuing work at Brunel (Qin et al 2006) has now removed the need for either an initial CAD model, or a specialised rapid-prototyped representation, by using a system of parallel lines projected externally onto the physical representation to provide the required curves instead.

### 2.2 DISCUSSION AND ANALYSIS OF PREVIOUS RESEARCH

In design practice, as well as design theory, shape generation has often been confused with form generation and, although sketching has qualities that can be seen to enable shape generation, it has distinct shortcomings when used to generate form. An example is given below (Fig. 2) where, even in the hands of a skilled practitioner, sketching would be unable to predict the changing intersection between two forms, caused by progressively reducing the diameter of the conical element in increments that are undetectable in the accompanying orthogonal view:

![Fig 2: An example of where sketching would fail in form generation.](image)
While digital modelling can be employed to answer this criticism (the object in Figure 2, for example, was created in a digital modelling program), and confining form generation to the virtual domain while augmenting assessment with a haptic interface is an initially attractive prospect, three major shortcomings with haptic interfaces remain:

- Most are distinctly punctual, i.e. point-like (Evans et al 2005), and none have as yet satisfactorily emulated full hand, palpable contact with a virtual surface (Bordegoni 2004).
- Although form assessment is theoretically constant, the device itself interferes with free exploration of the virtual form, and has a limited working volume.
- Combining virtual haptic representations with virtual visual representations can result in problems with perceptual co-location: the eye may see the virtual object in one place while the hand feels it in another.

Furthermore, the requirement for a structured digital representation to drive a haptic interface can be seen to conflict with the unstructured nature of the early design process, based as it is on inevitably vague and incomplete information.

If we accept that representation switching is inevitable, or even desirable due to the different constraints and affordances of each representation (we can only reason about shape and form so far in each), then the necessity to remain in the virtual domain does not seem so compelling. Employing physical models of digital design proposals, instead of the haptic augmentation of virtual representations, would allow designers to experience the tactile and visual properties of their designs unimpeded and in the round (Fig. 3). Switching between virtual and physical representations is a common enough experience in everyday life: this paper, for example, was written by transferring rough, hand written notes into a text editor, editing and expanding those notes on-screen, printing out that text before scribbling yet more notes over it, typing these changes back into the on-screen version, and so on through many more cycles. Although previous design research has attempted to emulate this apparently fluid alternation between physical and virtual representations, none of the proposed solutions has yet gained widespread acceptance in design practice, what has become apparent from previous research is that simpler, ‘interactive’ physical models are more useful to the early stage process than detailed ones (Broek et al 2000).
Fig 3: Freedom of form assessment and interaction available with physical objects.

However, both TUDelft's Physical Concept Models, and the initial process proposed by the Brunel group, share the same flaw as haptic interfaces in that they require an initial CAD model, and are therefore dependent on an inflexible and predetermined digital structure. Although later work at Brunel (Qin et al 2006) has done away with the need for a pre-existing CAD representation, an inflexible digital structure would still be imposed on the virtual representation by their choice of reverse engineering method - projecting parallel lines on to the physical object to create the contours used to derive NURBS curves from - which would lack the flexibility required to digitally reconstruct any possible surface.

Because design research lacks a substantial dataset on how physical objects function in the form generation process to build a theoretical framework on (Oxman 2006), it is inevitable that earlier attempts to bridge the gulf between physical and virtual representations in digital design have been less than wholly successful. Enquiries such as those undertaken by Giraudi and Bordegoni or Evans et al, which have begun to look at how physical design representations are created, have so far been driven by the desire to emulate hand making processes, intending to replicate them in the virtual domain through haptic interfaces rather than exploring the differing affordances of digital media (they argue that it is the cognitive load imposed by digital interfaces that keeps digital tools from being effectively integrated in the early design process). An alternative thesis, and the one investigated in this paper is, is that it is the inflexibility of structuring of digital representations, the difficulty of changing their structure in response to emergent design solutions generated by the fluid nature of the early design process, which is the reason that digital representations have not been successfully employed in design practice at this point. Therefore,
rather than aiming to produce yet another bespoke digital tool that is likely to remain within the confines of the research lab, this enquiry is directed toward discovering more appropriate ways of using existing digital design tools, and gaining a better understanding of what appears to be happening during this critical initial phase of the design process.

3. DATA GATHERING (OBSERVATION OF PRACTICE)

The observation of practice undertaken for this enquiry has focused on how designers switch between representations of form when generating initial design solutions. As this entails observing the evanescent process of making representations, rather than the fixed physical results of that process, video has been used to document it, combined with retrospective interviews and video analysis to try and make explicit the non-verbal reasoning employed by participants in that process. The area of interest is essentially information transfer: what strategies do designers adopt in practice; how often do they switch between representations, what kind, and amount of information do they actually transfer between representations when they do?

3.1 OVERVIEW OF METHODOLOGY

When disseminating the results of these observations it is obviously impractical to separate the process, the intended object of study, from its products. Observing live projects also inevitably raises the issue of protecting the intellectual property of those involved. In addition, the complex phenomena that arise from the interaction of designers with a number of physical and virtual design representations, over an extended period of time, would generate potentially huge amounts of data that would be too unwieldy for efficient analysis. To obviate these problems it has been necessary to set up artificial tasks and to observe these instead. These artificial tasks, however, have been designed to encompass meaningful chunks of practice: large enough to include multiple representations of form, while still small enough not to swamp potential understanding.
3.1.1 First data collection exercise: One hour design task

The first round of data collection consisted of a one hour long design task, immediately followed by a retrospective interview to allow the participant to add a commentary to the video of their task. The retrospective interview was directed by the researcher and was intended to elicit verbalisations of the participant’s intent at various points during the task.

The population for this exercise included three male and three female participants drawn from a variety of professional and academic backgrounds, from three nations (on two continents), and reflected varying degrees of experience in design and a diversity of cultures. It consisted of:

- Three product designers, with experience ranging from five to twenty years.
- Two product design masters students.
- One visual effects design undergraduate.

The task itself involved answering a brief to generate a design for a domestic iron, by producing a proposal for the handle area to fit onto an existing base. Participants were supplied with drawings and a rapid-prototyped model of the base area of the iron. An iron was chosen as something that would naturally result in a more organic form, which all participants would be familiar with, and which would be equally amenable to both modelling and drawing. Rather than presenting the task as one specifically geared to creating physical representations, participants were requested to produce any form of representation, two or three-dimensional, that would allow ergonomic assessment within the stipulated one hour time limit. In an effort to reduce the artificiality of the exercise, four out of the six tasks were recorded in the normal environment used by the participants rather than in the lab.

Analysis was undertaken by marking up video (using Focus III video analysis software) where actions such as assessment activity and transitions between representations could be identified. This data was subsequently used to create timelines of the activities (see Fig. 11).
3.1.2 Second data collection exercise: Digital structure Task

The purpose of the digital structure marking task, in addition to providing a natural progression from the one hour design task (see section 3.2), was to test a subsidiary thesis that there has been an acculturation of digital practices in contemporary design, i.e. that there is an increasing body of tacit knowledge about digital representations, and that designers would be able imagine the structure required to build a virtual digital representation from examining a physical object.

The population for this exercise consisted of four participants drawn from the previous group (the three practicing product designers and the visual effects design undergraduate student) and was carried out in a similar spread of locations. In this exercise participants were presented with a collection of physical representations of digital designs, and were asked to describe how they would create virtual versions of them.

The objects used (Fig. 4) were produced through surface modelling (right), feature based parametric solid modelling (centre pair) and a combination of both (left).

The centre pair was actually produced from the same file, i.e. had the same digital structure, but were handed in relation to each other as well as having the top profile and the loft profile curves parametrically altered (could participants identify that these objects had identical digital structures?).
3.2 DISCUSSION AND ANALYSIS OF OBSERVATION OF PRACTICE

Because there has been little research on how designers actually interact with physical representations in the era of digital design it has been necessary to gather an initial dataset, not only to work from but also to help shape the direction of the rest of the enquiry. This can be seen in the second data collection exercise, which was informed by findings from the one hour design task where the majority of participants reported that the next step in their normal design process would be to create a virtual digital representation. The one hour design task therefore illustrates the initial stage of form ideation through two and three-dimensional physical representations, while the digital structure task illustrates the transition from physical representations to virtual ones.

Although these are initial findings, some distinct features have been observed that were felt to be worth reporting. Participants in the one hour design task chose three routes to answer the design brief. Four produced blue foam physical representations in addition to sketches, one sculpted a clay representation in addition to sketches, and one produced sketches alone. A striking feature that was apparent in all participants’ answers to the design brief was their choice of predominantly orthogonal views when sketching out design solutions (Fig. 5):

![Fig 5: An example from the first data collection exercise; the design is worked out through orthogonal views.](image-url)
In addition, when visually assessing the supplied base, participants would often hold it in such a way that it could be viewed orthogonally (Fig. 6), sometimes even closing one eye to remove any sense of stereoscopic depth perception.

![Fig 6: Examining the base orthogonally, and emergence from the shell nature of the object.](image)

The presence of a physical object was also significant in all cases. Even the participant who chose not to make a three-dimensional physical representation of her design proposal, and who reported that she would normally have moved directly from sketching to producing a virtual representation, engaged in visual and tactile assessment of the supplied base. The shell nature of the supplied object also triggered emergent design solutions, as can be heard in comments she made during the design task:

"The way you’ve designed this model as a shell makes me think about the design of an iron differently: because it’s a shell, it’s thin layers… …if I want to make it light, I let you see the edge, I let you see the thinness of it, or illuminate it to (make you) think that there’s more volume behind it… …so really you just need the thin shell of the entire thing…"

### 3.2.1 Hybrid modes from 2D to 3D

In those exercises where participants did go on to make a physical representation of form there was a further distinctly orthogonal phase in the transition from the initial two-dimensional representations and the final, fully three-dimensional physical representation, as can be seen in the sequence of images taken from a video of one of the exercises below (Fig. 7-10):
Fig 7: The initial 2D orthogonal phase.

Fig 8: Transition from 2D orthogonal to 3D orthogonal.

Fig 9: Transition from 3D orthogonal to full 3D.

Fig 10: Working in full 3D and refining the form.
This distinctly orthogonal phase, interposed between sketching out the proposed form and realising it fully in three dimensions, can be seen in the upper four bars of the timeline shown below (Fig. 11). The lower four bars record information transfer between representations and clearly illustrate that information was only transferred between them at discrete intervals. The representations employed, and by inference the mode of reasoning about form at each stage, is illustrated by the icons at the top of the time bars.

Fig 11: Timelines showing when, and for how long, each representation was employed, and when information was transferred between them over the one hour duration of the exercise.

### Representation mode

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<tr>
<th>Representation mode</th>
<th>Time (minutes)</th>
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<td>2D orthogonal</td>
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<td>3D orthogonal</td>
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<td>2D perspective</td>
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<td>3D full</td>
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### Information transfer

<table>
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<td>Physical - 2D</td>
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3.2.2 Hybrid modes from physical to virtual

The digital structure task was originally only intended to produce finished artefacts (sketches, notes, or a marked object), but the decision to video the pilot of this exercise revealed so much additional information that it was decided to record all subsequent ones.

In the example below (Fig. 12-15) the participant correctly identified that the object had been made in a feature-based solid modelling program, and was able to give a detailed description of how she would recreate the object in a feature-based modelling program.
Her first act was to trace around the supplied object to produce orthogonal views of it, reasoning that the virtual version would also be created initially from ‘cut’ features derived from orthogonal
sketches. In both tasks, participants also reported the use of 2D scanning, or photographing orthogonal views (see Fig. 7), and employing these as backdrops in digital modelling programs to build virtual geometry over.

3.2.3 Orthogonal thinking

It seems clear from the data collection undertaken so far that designers are still linked to orthogonal two-dimensional thinking when engaging in three-dimensional form creation. The reasons for this may be largely historical: drawing as the ‘normal’ medium of design has been with us since the Industrial Revolution when it was adopted as a convenient method of production control (Baynes and Pugh 1981). This two-dimensional paradigm has been perpetuated into the digital era by the ready availability of display technologies such as computer monitors and desktop printers. Even though virtual digital form is held in a three-dimensional database, unless rapid-prototyping is employed it will still be presented to designers through a two-dimensional medium. Although participants employed various strategies to transfer orthogonal information from physical representations to virtual ones, it would seem from their responses that the compound-curved organic forms used in the data collection exercises would severely tax these strategies. An interesting, and significant, remark made by a number of participants, and which was also observed taking place during the digital structure task, was that they would sometimes draw contours directly onto objects, but purely as an aid to understanding form rather than using these curves directly to produce virtual representations.

3.3 IMPLICATIONS OF THE INITIAL FINDINGS

Design practice knows how to represent form through structured CAD representations, such as NURBS surface modellers or feature-based solid modelling. It has the capability to create physical representations from virtual representations through rapid-prototyping, and to turn physical representations into virtual geometry through reverse-engineering. What it does not have is a way of preserving the structure of those digital representations through this cycle, or of being able to change that structure ‘on the fly’ during the early stages of form creation to accommodate emergent design solutions. As the two data collection exercises have revealed that only
orthogonal, structural information was transferred between representations, and then only at discrete points, a hand mediated approach based on the existing skills set of contemporary designers may offer a more appropriate way forward than hardware based reverse-engineering solutions.

Although transferring strictly orthogonal information is relatively straightforward, a different approach would be required to cope with the kind of compound-curved surfaces that are now possible in virtual digital design. Could the practice of marking contours directly onto physical objects, along with technologies and skills already available to designers, be used to provide this? As human vision seems peculiarly well set up to recognise contours and to reconstruct three-dimensional form from them (Marr 1983), and those same contours, or very similar ones, are used in NURBS surface modelling to build virtual three-dimensional objects from, then marking digital structures directly onto physical objects might be used to enable information transfer from physical to digital representations, and to preserve the structure generated by the designer - rather than swamping it in geometry as happens with current reverse engineering practices - by employing image mapping methods similar to those used in the Brunel proposal discussed earlier in this paper. The significant differences between the Brunel approach and the one proposed in this paper are that:

- As the marks drawn onto the physical object also represent the structures required to make digital representations from, the structure of a virtual digital representation can now be modified by simply redrawing it on a physical object.

- This approach recognises the augmented skills set now available in contemporary design practice, and has the potential to deal with all classes of surfaces.

- By combining physical assessment with digital representations of form, this proposal can also be seen to function as a multimodal interface for digital design.

### 3.3.1 Transferring structure from 3D physical to 3D virtual representations

To illustrate this concept a method for transferring digital structure information between virtual and physical representations, based on marking digital structures onto physical objects, will be examined. To match the availability and ease of use of sketching it will employ only the normal skills set and equipment available in most design practices: i.e. digital photography, digital
modeling software, pencils and paper. It should be understood, though, that the process illustrated represents an attempt to establish the absolute minima required for transferring information from physical representations to virtual ones, rather than an ideal solution to the research problem. The essence of this approach is simply to work the rules of perspective backwards, i.e. to put the chicken back in the egg.

Fig 16: Digital structure drawn directly onto a physical representation.

The first step is to draw the required digital structure onto the surface of a physical form (Fig. 16). The marked object is then placed on a sheet of A4 paper, or some other flat regular object of known dimensions, and photographed from at least two dissimilar viewpoints. The photographs, which should be framed to include the whole of the reference object, are then imported into the perspective window of a digital modelling program. The paper, or other reference object, is then drawn to scale in the plan view of the modelling program to serve as a guide to match the camera position of the perspective window with that of the photographs. The curves marked on the physical object are then traced over the first photograph in the perspective view, and projected onto the plan view (Fig. 17).

Fig 17: Matching the camera view and tracing the curves.
Surfaces are then created between the point representing the camera position and the curves in the plan view (Fig. 18).

The process is now repeated with the second photograph, and the intersection between the two sets of surfaces used to create NURBS curves (Fig. 19) which can be used to generate a digital surface (Fig. 20). By matching the virtual camera view with an object of known dimensions the resulting virtual geometry will be modeled at the correct scale automatically.
4. CONCLUSIONS

As understanding and manipulating form is at the heart of many design activities, anything that enhances designers’ agency in these areas would be highly significant to the design process as a whole.

Traditional design practice, both in sketching proposed designs and developing them through draughting, has been most successful where the relationship between shape and form is predictable and understandable, and by limiting itself to orthogonal views and particular classes of surfaces only. The relationship between shape and form in design, however, is not straightforward. In form generation they exist in a complex interdependence, as shown by evidence of a distinct orthogonal phase interposed between the initial two-dimensional shape representations, and the later three-dimensional form representations employed by participants in the one hour design task. Evidence of this interdependence was also observed in the digital structure task, where orthogonal information was consistently sought by participants as a simplifying assumption to allow them to understand compound-curved forms sufficiently to be able to recreate them in digital media. For the purposes of this enquiry, though, it has not been necessary to establish whether it is the culture of ‘design through drawing’ that leads to orthogonal thinking, or whether this orthogonal thinking is part of how we naturally apprehend three-dimensional form. What has been established is a common thread of practice, a common culture of form manipulation amongst a culturally and professionally diverse group of practitioners.

CAD, rapid prototyping and reverse engineering, when taken together, present an opportunity to rethink how form is generated in design. Retaining the use of physical objects in form generation would result in a truer understanding of form in the critical early stages of design and, if modifications made to a physical representation of a digital design can be successfully transferred to its virtual counterpart, then the physical representation can also be seen to function as a multimodal interface for digital design.

If sketching is a way of thinking rather than just an aid to memory, and drawing is a way of calculating with shapes when you don’t know what you’re going to see and do next, then making physical objects can be seen as calculating with three-dimensional forms when you don’t know what you’re going to see and do, and manipulate, next.

Form generation in digital design will inevitably be more than just traditional draughtsmanship.
5. REFERENCES


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