Incorporating the FreeForm Haptic Modelling System into New Product Development

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Abstract. The work presented in this paper is taken from a research project that investigates modelling and design with particular reference to industrial design and the use of different media and tools for product form-giving. The paper draws on collaborative work with product development teams at Procter & Gamble, set up to evaluate the FreeForm haptic modelling system in an industrial context. One aspect of the research has been to investigate the integration of the FreeForm haptic modelling system into new product development (NPD). In relation to this, this paper reports on potential uses and weaknesses of the system, and suggests how it could be best integrated into product development.

Keywords. FreeForm, haptic modelling, design, NPD, CAID

1 Introduction

New technologies, particularly those related to visual communication, have always had an impact on design representation and design processes. Computers, especially computer-aided industrial design (CAID) tools, have been at the forefront of such technologies [1]. During the last few years, a change from 'traditional' to 'digital tools' has taken place in industrial design. Although the establishment of 3D CAID systems has been an important milestone [2] further developments have taken place.

State-of-the-art CAID draws attention to the quality of sensations perceived by designers while modelling an artefact. In fact, recent advances in computer interface technologies for interaction and visualisation have made it possible to touch and manipulate virtual 'computer-generated' models in a way that evokes a compelling sense of touch feedback. Hence there is an increasing interest in integrating the sense of 'touch' or 'haptic feedback' in digital 3D modelling for industrial design. SensAble Technologies' FreeForm system is the first commercially available haptic system targeted at industrial designers, and comprises polygon mesh modelling software coupled to the PHANToM desktop haptic device.

Haptic (touch and force-feedback) devices allow industrial designers to experience a sensation of touch and physical presence whilst interacting with virtual models [3,4]. Designers are able to sculpt and form 'virtual clay' using similar tools and techniques employed in the physical world [5]. The system represents a significant development within

CAID modelling, by offering a new medium in which design and modelling is achieved with computers through a force-feedback interface [6]. However, as a new technology, many concerns are raised over how best to use the FreeForm system for commercial product design and, with this, what benefits haptic feedback brings to designers and, indirectly, to companies. Any discussion of the merits of the haptic functionality of FreeForm must therefore, at this early stage in the system's up-take, be considered in the content of the overall functionality and usefulness of the system in NPD. This is the approach taken for this paper.

2 Background to the Research

The work presented in this paper is taken from a research project investigating modelling and designing, with particular reference to industrial design and the use of media and tools for product form-giving. Early in the project, in order to evaluate the FreeForm system (versions 4/5), design and modelling experiments with industrial designers were conducted [7]. These experiments were followed by four months of on-site collaboration with Procter & Gamble (P&G), a multinational fast-moving consumer goods company, with the aim of assessing the system in commercial context with 'live' projects.

One aspect of the collaboration was to investigate the integration of haptic modelling into NPD. Earlier research results showed that FreeForm was very promising as a design and modelling tool for initial stages of design. However, in its current form, FreeForm has drawbacks that restrict its suitability for later stages of design [7].

To accompany the earlier findings, it was important to identify, through the work with P&G, how industrial designers model their design ideas and what tools and techniques they commonly use. For the purposes of this paper, owing to confidentiality agreements, the findings of the work with P&G have had to be concealed. In practice, this has meant that findings from specific projects have been translated into general findings in relation to a generic product development process. Projects not subject to confidentiality agreements have been used for illustrations in this paper.

3 Data Collection

This paper focuses on the collaborative work carried out with P&G, involving different product development teams across several projects at various design stages. During the work, the author took the role of investigator in some instances and industrial designer (using FreeForm) in others. Accordingly, the main research activities involved: (i) observations of P&G designers (e.g. concept and technical designers); (ii) active research participation: the first-named author worked in parallel with other designers; and (iii) P&G designers using FreeForm: designers replicated their working method on FreeForm and provided feedback.

Data were recorded during a series of interviews, one-to-one FreeForm sessions and (for the first-named author) self-directed tutorials. Casual comments from P&G staff were also noted. A formal presentation of the work was presented to P&G, provoking additional comments from staff on the integration and use of FreeForm within the company.

4 Results

The FreeForm haptic modelling system has strengths and weaknesses that affect the suitability of its use at different stages in new product development. To reflect this, results have been presented in three sections: (i) FreeForm strengths, (ii) FreeForm weaknesses, and (iii) recommended use of FreeForm in new product development.

4.1 FreeForm Strengths

Quick 3D idea visualisation. Tovey and Street [8] emphasise that sketching by conventional means (e.g. 2D pen-and-pencil drawings) is quick and effective but has a disadvantage in that sketches convey 2D representations of a 3D object. In the translation process between 2D and 3D, there is a susceptibility to ambiguity or a loss of information relating to dimensions and space. Echoing this, P&G designers reported difficulty in reproducing the design intent contained in their 2D sketches into their 3D CAD models. For example, a form conceived in 2D is not always achievable in 3D.

FreeForm modelling allows designers to work quickly and freely, exploring ideas and roughing-out a 3D model without spending time on details. Designers can import 2D hand sketches (bitmaps) into FreeForm's sketching environment, where they can be used as visual guides for 3D form creation. Sketches previously saved from other FreeForm models as well as sketches from other 2D CAD packages (IGES and Adobe Illustrator formats) can also be imported into FreeForm's sketching environment. This import function provides a direct link between 2D sketching and 3D modelling, maintaining original design intent and limiting the need for cognitive 2D-to-3D translations; "it bridges the gap between 2D sketching and 3D production work" [9]. An example of quick idea visualisation from a sketch can be seen in Figure 1.

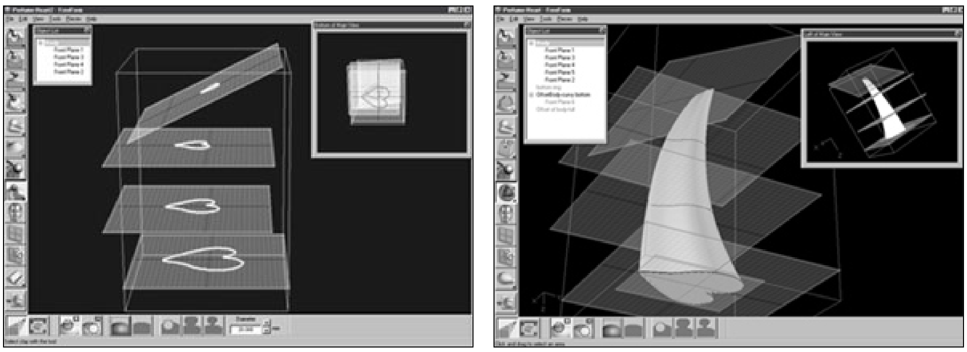

Fig. 1. Quick visualisation of a perfume bottle in FreeForm. (© 2002 Bahar Sener)

FreeForm modelling tools are metaphors of physical modelling tools, for example freehand sketching with the pencil tool, which is similar to sketching on a piece of paper. In this way, FreeForm tools are relatively self-explanatory, with the metaphors helping to explain the properties of tools in familiar terms. Metaphors can be used to introduce and explain complex concepts more quickly and more accurately than a more literal explanation [10]. The haptic functionality of FreeForm adds increased realism to the modelling tools, providing a level of interaction that surpasses previous CAD systems (e.g. sketching onto a drawing plane which can be felt to be ‘locked’ in 3D space, comparable to the physical constrains of pen-on-paper sketching). Despite the usefulness of metaphoric tools for creating 2D sketches, limitations are apparent in that FreeForm does not currently provide a high degree of precision and control when sketching. Essential tools that industrial designers use for alignment and dimensional accuracy (such as straight edges, protractors and rulers) have not yet been implemented within the FreeForm sketching environment. In this regard, all the P&G designers pointed out that sketching directly in FreeForm does not provide adequate precision. The issue of presion something of a contentious point because, as Tovey & Dekker argue [11], concept sketches can be categorised as ‘free-theme sketches’ or ‘package-constrained sketches’, depending on the purpose of the sketch. If the intention is simply to express how a product is expected to look, sketching may be considered ‘free-theme’. In contrast, ‘package-constrained’ sketches bring geometrical precision into the sketching activity. In this use, the ‘package’ refers to legislative, ergonomic and operational factors as well as dimensional constraints. Sketching directly in FreeForm is closest to ‘free-theme’, whereas sketches prepared in an external CAD package and imported into FreeForm may be of either type.

Quick design modifications. FreeForm allows designers to try out many design iterations very quickly, and also allows experimentation with extreme ideas to see if they work visually [12]. Deforming the model in FreeForm is (i.e. changing its form), for example, as Knight states [13], a form-creation method “…that simply cannot be achieved any other way at such speed”. Deformation of the whole model or of a localised area is possible without a loss of detail. Deformations are created with a box that surrounds the model, where manipulation of the box allows stretching, pulling, squeezing, bending, tapering, and general re-shaping of the virtual clay, all of which can be observed in real-time. Models can also be scaled up or down. Figure 2 gives an example of box deformation.

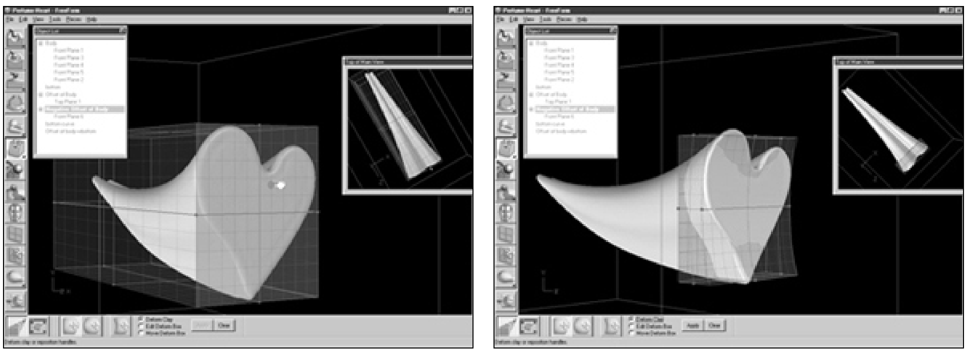

Fig. 2. Example of FreeForm deformations on a perfume bottle. (© 2002 Bahar Sener)

For many CAD packages, particularly parametric modellers (e.g. Pro/Engineer, SolidWorks), 3D deformation is not readily achieved; models are usually created in their final intended form from the outset of modelling. Nonetheless, there are several exceptions, including 3DStudio Max, Rhinoceros and LightWave3D packages, in which 3D deformations are facilitated using modelling aids, such as control points and deformation curves. These aids help to control the amount and shape of a deformation of a model about a set of axes. Deformation curves are used to define changes in scale, twisting, tapering, and bevelling along a path. They are also used to define the influence area (i.e. beginning, end, and centre of deformation) as well as limiting deformation to a section of the model. In contrast to the control afforded within these CAD packages, deformations in FreeForm are more trial-and-error and it is more challenging to create a specific deformation. A lack of numerical dimensional feedback compounds the problem of precision. However, these reservations need to be weighed against the speed and ease with which complex deformations can be created in FreeForm compared to solid and surface modelling packages.

Realistic imaging. FreeForm has, until recently, provided only primitive 3D painting options for the colourisation of models, although the method of painting employed is unique. Model surfaces can be painted in real-time with haptic feedback, making the process of model colourisation much more akin to the strokes of an artist's brush rather than a mechanical task of highlighting surfaces for the software to colourise. Now, with the introduction of the Visual Communication Package (VCP) [14], high quality photo-realistic imaging can be achieved, removing the need to export models to an external CAD package in order to create high quality renderings. With FreeForm VCP, models can be rendered with lighting, materials, and environment settings. The rendering commands are straightforward and less complex than those used in a specialist package such as 3DStudioMax. In addition, unlike some CAD packages where models are built with wire frame or mesh structures, FreeForm models do not require rendering in order to show how they will look as finished artefacts. FreeForm's standard modelling environment presents virtual clay models to a high degree of realism as if they are made of clay. Figure 3 shows an example of a model within FreeForm's standard modelling environment and then subsequently rendered.

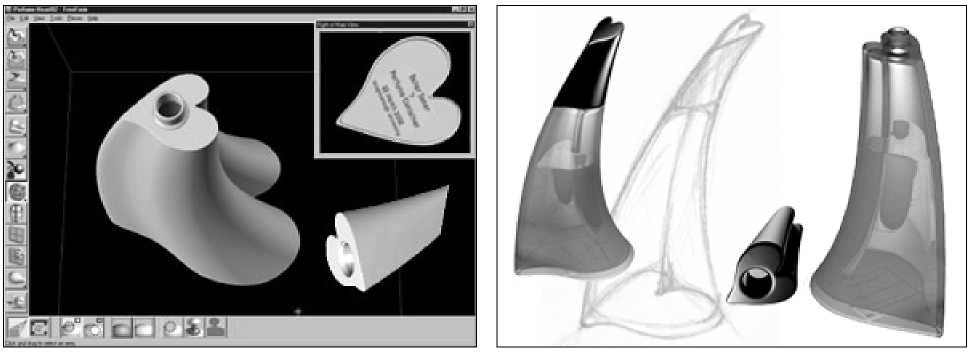

Fig. 3. FreeForm model before rendering (left) and after (right) (© 2002 Bahar Sener)

Early physical models. FreeForm models can be created as physical models through the STL file exchange format. This is an industry-standard polygon mesh format used for creating physical parts, particularly by rapid prototyping methods. STL files have limited use for form manipulation; they are generally created once a design is finalised or whenever a physical prototype is required. Physical models created from FreeForm are typically block models, used for early testing of usability, ergonomics and form [15]. By creating physical models early in a project, industrial designers can address potential design and manufacturing issues and can make ergonomic evaluations before a commitment of time and money is made to furthering a design proposal. Examples of time savings and cost reduction through the use of FreeForm-derived prototypes have been reported by companies in the toy, promotional, jewellery, collectibles, giftware, and ceramics sectors [5,16]. One of these companies, Equity Marketing, creators of promotional toys, has stated that working with rapid prototypes created through FreeForm has enabled their design and development process to transform from a serial process to a faster, more flexible one [16]. As this case shows, FreeForm is well adapted to the modification of products based on block models, such as changing the expressions of toy characters, changing sizes and modifying proportions.

Organic form creation. Designers working at companies spanning toy, footwear and ceramics products, who are skilled in hand modelling of clay and wax, sometimes face challenges in creating physical models of their design proposals because those proposals are often highly curved, intricate and organic in form [17]. Similarly, consumer products having organic forms, rather than geometric shapes based on lines, circles and arcs are relatively challenging to model with CAD. Even with dedicated surfacing programs such as Rhinoceros, complex surface shapes can be difficult to construct and, in some cases, require the designer to re-think the whole modelling approach [18].

FreeForm is promoted as a system that is able to fill a niche market in modelling, as it blends the intuition and expression of physical modelling with the power and productivity of CAD modelling [19]. For example, using amorphous virtual clay helps designers to create organic forms that are difficult (or sometimes impossible) to create in other modelling media [20]. Figure 4 shows an example of a highly complex organic form created in FreeForm. As P&G designers pointed out “it wouldn’t have been possible to create such a complicated form in another CAD package, (for a physical model) you have to give it to pattern-makers so that they could model manually”. The haptic feedback also adds much personal satisfaction and enjoyment to CAD modelling, resembling manual working of clay with clay tools. As well as emulating real sculpting, FreeForm also offers additional functions that are not possible with real clay, such as working on the inside of a model.

Fig. 4. ‘Mr Sheep’, a highly complex organic form created in FreeForm (© 2002 Bahar Sener)

3D Texturisation. In some CAD packages (e.g. SolidWorks, Pro/Engineer), 3D texturisation is effectively impossible, being prohibitively time-consuming and difficult to model using the available palette of modelling tools. In other packages (e.g. 3DStudio Max, Alias Studio Tools, Rhinoceros), 3D texturisation is achieved by bump maps applied to model surfaces, causing surfaces to appear ‘bumpy’ or irregular. When a model is rendered with a bump map, lighter (whiter) areas of the map appear to be raised whereas darker (blacker) areas appear to be low. However, bump textures are only simulations created for rendering purposes and do not exist as surfaces on the model and, as a result, will not be present on corresponding physical models.

A major strength of the FreeForm modelling system is its ability to create genuine 3D texturisation. This can be created in at least two ways. First is the creation of a relief feature on a model using the ‘emboss with image command’. Uses of embossed features include the texture of a linoleum counter top and a relief pattern on a ceramic tile [5]. A second method of creating 3D texturisation is ‘real time sculpting’ with a variety of carving tools, including user-created tools (Figure 5). This powerful form creation facility does not exist in any commercially available CAD package and provides a very effective and intuitive way of creating desired patterns. Haptic feedback is an essential element in the creation of 3D texturisation with the second method providing the designer with the means and control to carefully shape surfaces with customised pattern in real-time.

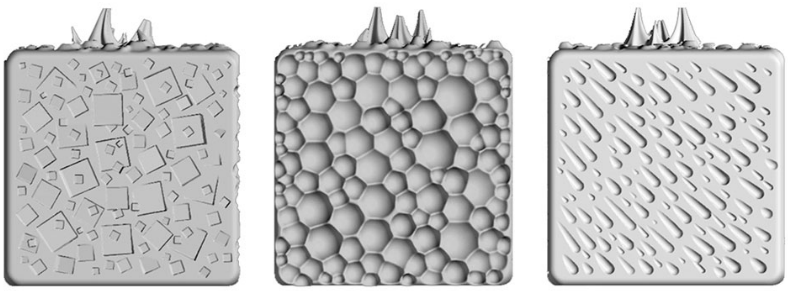

Fig. 5. A FreeForm cube with multiple 3D texturisation (© 2002 Bahar Sener)

Despite its effectiveness, texturisation has some drawbacks; most notably the inability to repeat textures within the same model or from previously-created models. This is not seen as a problem for one-off products but is a concern for products where consistency of form is required, such as consumer products intended for mass manufacture. Owing to limitations in its current modelling engine, FreeForm is unable to provide a ‘copy texture’ command or to allow the creation of a ‘texture library’ which can be quickly applied to model surfaces. The only work-around for this is for the designer to make personal notes or assumptions on how a texture has been created (e.g. with which tool shape, size, clay resolution) and attempt a manual reproduction. Where large areas are involved, manual reproduction can be painstaking and time-consuming. Another limitation is that users cannot select from a range of clay types based on known properties, such as the range of clays offered by Chavant [21].

Team communication. P&G’s designers placed emphasis on the importance of team communication in product development but noted that verbal descriptions, particularly between colleagues based at different locations, often lead to misunderstandings and misinterpretation of design intent and mismatched ‘mind’s eye’ views of a product. To this end, FreeForm is accompanied with a freely downloadable viewer, ‘FreeForm-View’, which allows models to be shared between product development team members and across the Internet [5] to aid communication. Using the viewer, FreeForm files can be viewed in 3D, measured, labelled and annotated and then e-mailed for further review and design discussion. This facility allows quick communication of design ideas at any stage amongst researchers, designers and engineers, as well as wider communication with production partners, management, licensors, mould makers and so on. As a related point, the haptic functionality of FreeForm allows product team members to touch and make evaluation of the form of a product proposal without the need to order a physical prototype, saving time and money. An extension to this would be long-distance evaluation, for example over the Internet, as reported recently [22].

4.2 FreeForm Weaknesses

Weaknesses of FreeForm are rarely reported. Nonetheless, in its current stage of development, FreeForm has some limitations which directly affect its effectiveness as a modelling tool within NPD. According to P&G's designers, the areas below were the most significant shortfalls of FreeForm.

Precision. SensAble's promotional literature describes FreeForm as offering "…unlimited expression; it captures the flexibility and expressiveness of clay, and eliminates the need to worry about geometry while modelling." [23] Similarly, Hickey refers to FreeForm as meriting "…careful attention from industrial designers limited by the constrains of 3D modelling systems, and manufacturers seeking to create multiple, differentiated products while speeding time to market." [24] FreeForm is clearly positioned differently to existing CAD packages, where emphasis is commonly placed on precision modelling.

The unsuitability of CAD programs for idea generation in conceptual design has been commented upon by many authors [e.g. 6,25,26,27,28,29,30]. One of the underlying reasons for the unsuitability that current CAD programs operate on the basis of precision modelling and geometric construction, leaving no room for expressive techniques such as intentional ambiguity, a quick annotation, or a personal style [31]. Criticisms of CAD are also laid at input devices. The ubiquitous computer mouse and keyboard are restrictive when compared to the expressive and articulated movements and nuances of a skilled artisan's toolkit [32]. FreeForm is differentiated from other CAD programs most notably by its geometrically unconstrained modelling and haptic interaction. However, the freedom of form experimentation afforded by FreeForm, and indirectly by the PHANToM device, raises issues of imprecision that run throughout the use of the system. Imprecision arises because FreeForm's modelling tools in sketch (2D) and 3D environments cannot be constrained by way of, for example, alignment and snap points. The issue here is that, during early stages of design, imprecision is seen as beneficial, aiding quick idea generation. However, later on in the design process, as products become more defined and prepared for manufacture, imprecision is undesirable. The issue of imprecision raises two practical points. The first is the extent to which FreeForm models find use in later stages of product development (models may be considered too imprecise to be exported for use in other CAD packages). The second concerns the ability to create geometric shapes alongside more organic shapes (cited as a requirement of any modelling package by P&G's designers).

Data exchange. With reference to the evaluation of product proposals for consumer goods, block physical models of the kind of producible from FreeForm are inadequate for functional tests, such as reliability, durability and performance, as well as for checks on part fits and assembly [15]. Functional prototypes are commonly created using CAD data from an engineering package (e.g. SolidWorks, Pro/Engineer) and to facilitate this, models created in FreeForm can be exported in the STL file format, but as previously mentioned the usefulness of STL files for model modification is severely limited.

FreeForm can also output model geometry as IGES curves, a well-supported file format for 2D and 3D data exchange between different CAD systems. Once a model is created, users can manually define (via the haptic-based PHANToM) where to create model curves for export. FreeForm does not include automatic creation of IGES curves and so they must be created manually: a very time consuming, difficult and sometimes impossible process, especially if the surface of the model is highly complex (e.g. dense texturisation, sharp corners). A rapid prototyping specialist at P&G emphasizes the importance of file exchange, stating "mould makers need IGES files, not STL. It (STL) is only for direct prototyping." P&G designers expressed concerns over the limited data exchange options in FreeForm and the subsequent limitations that this poses for downstream compatibility and re-use of FreeForm models, in particular within SolidWorks. Despite several modifications from version 4 to version 6, FreeForm file export functions remain a weak point.

Technical drawings. Industrial designers prepare drawings of preferred product proposals as a bridge to engineering detailing. These drawings present functionality, size, colour, features, materials and key dimensions, as well as indicating production methods of different components. Modern CAD packages provide facilities for automatically creating technical drawings from 3D models, achieving results more accurately and in less time compared with freehand drawing or drafting with a 2D CAD package. FreeForm does not provide such facilities for creating technical drawings and so, regardless of the limitations of FreeForm data exchange, designers must export models to an external CAD package to create technical drawings.

Engineering detailing. FreeForm excels in the creation of organic external surfaces of products but is weak for the creation of engineering details including wall thickness, ribs, snap fits and assembly features. Engineering detailing requires a precision of modelling and geometric control that is purposefully absent from FreeForm. P&G's designers highlighted technical problems of re-using and detailing FreeForm models in SolidWorks via STL and IGES export.

Finite element analysis (FEA). FEA is a computer technique for predicting the response of product structures and materials to exposure to phenomena including forces, heat and vibration. FEA is used by P&G designers to gain insight into the likely performance and behaviour of product proposals. FreeForm does not offer FEA and, as before, FreeForm models must be exported to an external CAD package for FEA.

Volumetric calculations. Volume calculations are critical for some products (e.g. products containing liquid: coffee maker, bottles). FreeForm modelling does not provide volumetric calculations.

Part assembly. Separate parts can be created in FreeForm, however they cannot be linked to each other as an assembly.

File size. Since FreeForm is based on polygon meshes, highly complex models (e.g. those containing 3D texturisation, see Figure 4) can become very difficult to handle as a result of very large file size. Such models are slow to compute even on a well-specified workstation. As a work-around, FreeForm provides different levels of detail when modelling, ranging from coarse to fine, with coarse models responding much more quickly to editing. Nonetheless, FreeForm files remain very large (e.g. 350 MB for 'Mr Sheep' in Figure 4), placing high demands on downstream computing resources. In the case of 'Mr Sheep', the original STL file was rejected by one rapid prototyping company on the basis of being too large to open. To reduce file sizes, the number of facets in the polygon mesh can be reduced but this in turn risks a loss of detail on highly textured areas.

4.3 Recommended Use of FreeForm in New Product Development

A recurrent feature of NPD is the search for strategies that enable time-to-market to be quickened and development costs to be reduced [5, 31]. The use of 3D CAD tools is a prominent factor in achieving these goals, ultimately as part of a completely digital development process. Between different design companies the use of 3D CAD tools varies, with different emphasis being placed on design, modelling, simulation and tooling. Nonetheless, NPD programmes are broadly similar between projects and companies and can be usefully summarised by a generic model offered by Ulrich & Eppinger [33]. In this model, NPD progresses across five main phases:

Concept development: the needs of the target market are identified, alternative product concepts are generated and evaluated, then usually a single concept is selected for further development.

System-level design: the definition of the geometry and the functional specification of the product are made and a preliminary assembly process is decided upon.

Detail design: the specifications of the product geometry, materials, tolerances of all the unique parts and purchase needs from suppliers are decided.

Testing and refinement: the construction and evaluation of multiple pre-production versions of the product are made.

Production ramp-up: the product is made using the intended production system.

By comparing the strengths and weaknesses of the FreeForm system identified in this paper against the above phases, recommendations can be made for how best to integrate the system into NPD. Table 1 lists these recommendations against each of the NPD phases.

Table. 1. Integration of FreeForm Haptic Modelling System into New Product Development

NEW PRODUCT DEVELOPMENT					
Mission Statement	Concept Development	System Design	Detail Design	Testing & Refinement	Production Ramp-up
Integration of FreeForm Haptic Modelling System	- Initial product ideas - Quick 3D product concepts - Initial prototypes (block models) - Initial form assessment - Initial ergonomics assessment - Initial usability assessment - Team communication / feedback	- Evaluation of product concepts - Secondary prototypes (block models) - Secondary ergonomic assessment - Team communication / feedback	- 3D texturisation - Photo-realistic rendering - Team communication / feedback	- Final development prototypes - Evaluation of prototypes	- Final presentation (block) models

5 Conclusions and Future Research

The collaborative work with P&G provided a commercial context for identifying strengths and weaknesses of the FreeForm haptic modelling system.

The system has powerful and flexible tools that from the designer's perspective have both beneficial and detrimental attributes. Owing to the 'free' modelling nature of the software – being able to model relatively free of constraints – FreeForm is well suited to early phases of NPD. In addition, FreeForm's haptic functionality provides designers with a level of interactive form creation and evaluation that up until now has not been possible with commercially-available CAD packages. In this sense, FreeForm's strongest contributions to NPD are in the areas of initial idea generation, form exploration, prototyping, and early assessment of ergonomics and production issues. Its main shortfalls arise from a lack of constrained modelling, leading to issues of imprecision and inappropriate model data for downstream modifications. In future developments of FreeForm, a balance must be struck between addressing these shortfalls and enhancing established strengths. Consideration must also be given to more conceptual matters, such as whether haptic modelling tools should (or should not) be purposely directed away from later phases of NPD, where traditional CAD packages already excel. Research into ways of enhancing haptic modelling systems to better suit the form-giving needs of industrial designers is currently underway within the Department of Design and Technology, Loughborough University.

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