9 A REVIEW OF PRODUCT SKETCHING IN EARLY PHASES OF DESIGN

Prasad S. Onkar[a] **and Dibakar Sen**[b]

Centre for Product Design and Manufacturing, Indian Institute of Science, Bangalore, India.
Tel: +91-(0)80-22932923, Fax: +91-(0)80-23601975, Tel: +91-(0)80-22933137.
E-mail: [a]prasad@cpdm.iisc.ernet.in, [b]dibakar@cpdm.iisc.ernet.in

Sketching has been the chosen method of expression of product ideas in the initial phase of product design. Existing CAD modeling systems do not support the early phases of design effectively. There has been growing interest to integrate sketching and 3D modeling mainly because of recent developments in interfaces like motion trackers and haptic devices. The paper reviews the state of the art literature in the areas of conceptual design and sketching, 3D shape creation and visualization, sketch based modeling and sketch recognition to understand the scope of 3D sketching in the design process. It is observed that the majority of the literatures focus on creation of 3D models by interpreting 2D sketch strokes. Sketching behavior of the designer, while creating sketches directly in 3D needs detailed study.

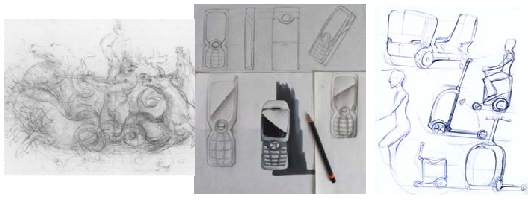
Keywords: Product Sketching, Conceptual Design, Computer Human Interaction.

1. INTRODUCTION

Sketching is one of the oldest techniques used by people to create visual depictions. Freehand sketching is a common human activity and we come across several kinds of sketches like plans, roadmaps, cartoons, and caricatures, sketches of human beings, animals and objects for different purposes. Sketches are very rich in their information content and are easy to create with just pen/ pencil and paper which are low cost, portable and easily available.

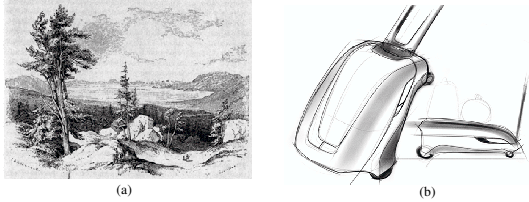
A sketch can be defined as a *form in strokes*. Figure 1(a) shows a famous creation of Leonardo Da Vinci in which the sketch stroke are vague and unclear but still a form emerges out from these stroke. In the context of product design, sketches not only communicate the form to the observer but they also give other information about the functionality, usability, aesthetics, etc. As Figure 1(b) shows the different views of the product and Figure 1(c) shows the sketch of usage of the product. Designers use sketching as a medium of expression and for communication in the process of designing. The design process generally starts with the need identification. Once the requirement is defined properly, the designers start generating the concepts in accordance with the requirement to satisfy the need. Sketching is predominantly used in this early stage of product design[1,4,5] in which concepts are generated. Sketching is a direct method of creating the visual impression i.e. it does not require compliance with any convention or standard such as selecting an icon, entering data, etc. as is the case with CAD packages or engineering drawing.

In the discussion presented in this paper, we mainly consider the process of sketching in the early phase of product design. The process of sketching involves the designers' intent, tools and methods of creating the sketch. Product sketches are different from other artistic sketches because product sketches pertain to well defined and manufacturable objects that occupy a finite space; whereas artistic sketches could be just an abstract patterns or images of unlimited spatial extent (Figure 2). The Figure 2(a) shows an artistic sketch of nature where the foreground objects as well as the unlimited space in the background are the objects of interest; and Figure 2(b) shows a product sketch with finite dimension, the space containing the object is not of much interest. Apart from product sketches, in literature we find



(a) (b) (c)

Figure 1. Different types of sketches.



(a) (b)

Figure 2. Comparison of artistic and product sketches. (a) Artistic sketch of nature, (b) Product sketch.

other type of sketches like sketches using block diagrams, symbols, process diagrams, stick figures, etc. But in the present work, the focus is on product sketches encompassing single views, multiple views, single part, multiple parts, assemblies, etc. as well as methods of creating them, as it is of direct relevance to product design. There are direct methods of crating models like clay modeling and sculpting in which a volume of material is iteratively altered to get the required shape. Such methods are out of the scope of present work because these are fundamentally different in nature; sculpting involves direct interaction with a form in a chosen material and the present work deals with sketching activity where an *impression* about a form is created on a supporting medium.

2. SKETCHING IN CONCEPTUAL DESIGN

Sketching plays an important role[1,2] in the initial phases of product design especially in the conceptual design stage. In the field of product design, the sketches pertain to 3D objects. Hence the designers have to create the impression of a 3D object on 2D paper. Traditionally, pen/pencil paper based sketching has been used in the conceptual design stage.

2.1. Need for Sketch

The initial product sketches made by the industrial designers for concept exploration are generally untidy, vague and incomplete.[1,5] Several theories have been proposed in literature to explain the reasons for this kind of sketching practices. Gombrich[6] studied the sketches made by Leonardo Da Vinci and claimed that Leonardo was the first to advocate the use of untidy and vague sketch strokes for visual invention. Tversky[7] identified several scenarios when people draw the sketches and discusses about what sketches say about the thinking of the designers. The author also discussed different issues related to the cognitive activities of sketching and derived that designers sketch as a way of visual externalization of their thoughts. There are other ways externalizing the ideas for example writing with text or verbalizing with words. Generally, in product design, the products are physical artifacts which occupy some space. Hence sketches convey spatial information directly and also visual information. Fish and Scrivener[1] Analyzed how the sketches are stored and analyzed in the mind based on the cognitive psychology theory of mental imagery model. They argued that the sketches assist the translation between the spatially depictive and structurally descriptive modes of representation by forming

percept image hybrids. They mention that sketches are incomplete visual structures that amplify the inventive and problem solving uses of mental images by denotations, by making indeterminate signs and translation between descriptive to depictive representations. Schon and Wiggins[8] gave a detailed conversation of the designer in a design process and analyzes the design process and concludes that designing is reflective conversations with medium having a basic structure "seeing–moving–seeing". Goldschmidt[5] analyzed the protocols of the design process and divides the design process in "moves" and "arguments". In that, arguments can be of "seeing as" and "seeing that" Based on this, the author argued that the dialectic between "seeing as" and "seeing that" will transform abstract ideas in to physical coherent form. This is termed as interactive imagery. Based on this author asserted that[9] visual thinking is rational mode of reasoning especially in the design process. Suwa *et al.*[10] studied the design process at greater detail and devised a coding scheme for cognitive activities of the designers. From this protocol analysis they also found that the sketching not only serves as external memory but also enhances thinking by providing visual cues. Cross[11] gives a historical perspective of sketching process and makes remarks based on the observation of sketches made by well known designers and architects. He argues that sketching enables the designer to handle different level of abstraction simultaneously, also assist problem structuring and promote recognition of prominent features. Prucell and Gero[2] reviewed the role of unstructured and ambiguous sketch occurring in the early design process and which is thought to be associated with innovation and creativity.[1,5,8,11,12]

2.2. CAD and Sketch

Presently, computers are being extensively used in the design process. Initially computers were used for 2D drawings. Later, development in geometric modeling has led to emergence of the CAD tools where in, object models can be created and visualized as 3D; 3D visual impression of the product concept also provides a better understanding about the product.[1] However, the designer has to follow sequence of operations to create CAD model of an object. This regimental procedure reportedly[3,4] hinder the creative exploration of design. CAD models are crisp and definite. Hence it is not much popular and not used extensively in the early phase of design. But CAD tools mainly provide 3D space for modeling objects and visualization which is helpful in understanding 3D shapes. So there is a need to develop a system which has the advantages of sketching like direct interaction and quick and advantages of CAD like manipulating 3D space and visualization of 3D models. The need for computer based sketching tool in the early phase of conceptual design is expressed by several designers. Earlier it was felt that it is difficult if not impossible to automate the process design[8] but the tools to support the designer are much needed. Fish & scraviner[1] identified the deficiencies in the traditional sketching process as compared to a computer assisted sketching interface. Lim *et al.*[4] conducted a survey to identify the requirements for developing a computer assisted sketching (CAS) system, in which the respondents expressed following view that they preferred to sketch using pencil and ball point pen on paper in the conceptual design phase. Also the survey identified deficiencies in using the existing CAD modeling tools for conceptual design like, they are time consuming, different than sketching, expensive and poor result etc. and they preferred to use isometric and perspective views and the most preferable sketching procedure identified was reference line — outline — detailed lines — shading. It is also identified that none of the existing systems support shade and shadow recognition. Similar requirements are also expressed by other researchers.[3,14,15]

2.3. Requirements for CAS

Shapir *et al.*[3] have identified some of the requirements for such a system which allows the designer to explore the design space and to assist him in the process of concept generation. One of the main requirements identified was, the interaction method should not disturb the design process by cutting the line of thought via the imposition of performance of system orients tasks. The interface should be direct and should provide feedback to the user and also provide sufficient workspace for the designer to create models. Igarashi *et al.*[14] have outlined the requirements for drawing system for creating CAD

models based on cognitive processing time. These requirements are relevant for sketch based systems for other domains as well.[16,17]

3. SKETCHING IN 3D MODELING

One of the early methods to interact with computer with a non-discrete interface was the *Sketchpad* by Sutherland[18] which proved to be very effective for interactive computer graphics. Since then, several techniques have been developed to store and process the digitized data of sketch strokes and interpret this data to create 3D shapes. Techniques like curve beautification and curve fairing[19,20] modifies the sketch strokes by approximation (smoothening) without losing the overall shape of the curve. This is mainly done to eliminate the device related errors. After processing the digitized information by such techniques, the shape information is obtained which is known as sketch recognition. The information can be further used to create 3D models.

3.1. Indirect Methods

Sketches are conventionally 2D representations of 3D objects and the computer interfaces used for creating them were also 2D. In literature we find that the creation of 3D models from 2D sketches has been a major topic of research. It started with the conversion of shop floor orthographic drawings into CAD models where often the engineering drawings with annotations have been referred to as sketches. The shop floor drawings are digitized and different orthographic views are interpreted to construct 3D CAD models. Pugh[21] proposed a sketch based solid modeling tool in which a 3D wire frame model is created by drawing sketches to represent the edges of the model. The program checks for surface topology and identifying vertices based on geometry. Similar tools have also been developed which are mainly built on sketch recognition techniques.[22,23] The construction methods of 3D models from 2D sketches are mainly of two types, namely gesture based methods and reconstruction methods. A detailed survey of reconstruction technologies and methods is given by Company *et al.*[24] The reconstructions of CAD models from 2D views are dimensionally accurate because they use the numerical data of the elements in the sketches (engineering drawings). Systems where sketches are used as templates,[53,54] the designers interactively make and modify 3D models using the 2D sketch merely as a visual reference within the same environment. Such systems are more versatile but quality of conformity between the sketch and the CAD model depends purely on the designer's skill. However, there is still no method of incorporating the full visual rendering features of a sketch into the CAD model. Even in the advanced sketch based interfaces[52] captures only the gross shape of the product in the sketch.

3.2. Direct Methods

Direct methods of creating 3D shapes involve direct interaction with the medium of expression mainly through hand motion and gestures without any intermediate operations like clicking icons or entering data. The following subsections discuss the creation of 3D curves and surfaces through such interactions.

3.2.1. Sketching 3D curves

In Ref. 25 a tool for direct modeling 3D curves using a plane palate and stylus interface tracked by sensors has been presented. The palate interface defines the local co-ordinate frame in which the strokes are created and later transformed as required. In Zeleznik *et al.*[26] first a curve is drawn in 2D and then its shadow is interactively manipulated to generate the 3D curve. In tape drawing, a standard industrial practice, a black photographic tape roll is held drawn from non-dominant hand and from the other hand the tape is pressed against a large display board to stick the tape against the board. This is useful as compared to sketching because of the fact that it is difficult to draw long straight lines and undoing and editing of tape drawing is easier than sketching. Inspired from this, Balakrishnan *et al.*[27] provided a digital tape drawing environment where a digital projector projects the sketch on a large

display area of 8 × 6 feet and the motion of two hands are tracked by electromagnetic motion tracker. The work has been extended in Ref. 27 for non-planar 3D curves by drawing series of 2D curves using 2D tape drawing technique. First the designer creates a curve in any one orthographic view and then a 3D curve is generated by drawing another curve in other orthographic view and projecting on the profile of the earlier curve. Front designers[28] have demonstrated the use of motion capture system for creating freeform 3D curves in space by moving ones hand in space. The system does provide a direct interface to create 3D curves but the designers do not get the feedback on the location of hand. The accuracy of the sketch depends on the choreography of the designer. A desktop haptic device based tool for creating spatial curve called "drawing on air" is proposed by Keefe *et al.*[29] which is based on the tape drawing technique with haptic feedback. Significant improvements in the sketching performance and outcome have been validated in the reported experiment.

3.2.2. Sketching surfaces

Initial methods for direct creation of 3D surface have been demonstrated by researchers by gestures of hand motion.[31] Virtual reality based tools.[32,33,36–38] Such methods are not intuitive to the designer because the designers do not have the control over what they are sketching. Teddy,[34] a sketching interface for 3D free form design in which the user draws the 2D sketches of silhouettes and system automatically constructs 3D polygonal surface model based on the sketch strokes. A curved and flat surface for creating interactive 3D surface is also developed.[35] Recently, creation of free form surface from network of curves is developed[36] which uses topological triangulation technique.

4. SKETCHING TOOLS

Pen/pencil and paper has been the most common interfaces used by the designers in the early phases of design for 2D physical sketching. This has variations like pencils with different colors and different darkness which further enhances the richness of the sketch in its information content. As far as computer interfaces are concerned, in the initial days, the interaction with computers was through card reader, magnetic tape, keyboard, mouse etc. Until Sutherland came up with SketchPad,[18] a light sensing device used to interact with computers by line drawings. Since then there has been growing interest in sketch based interfaces. Pen and tablet interfaces like WACOM[55] have been used for creating sketches. Computer interfaces have evolved over time and today the most widely used type is WIMP (Windows, Icons, Menus and Pointers) Interfaces. Typically, these interfaces are 2D in nature. The CAD tools use these interfaces to create 3D models in virtual space. Hence, CAD models are 3D but they are created from drawings made in 2D. Hence creation of arbitrary freeform surface has been a major challenge to the researchers in CAD community. Developments in motion trackers made it possible to explore 3D space directly and also to use this information to create arbitrary freeform surfaces. This technology has been used for sketching spatial objects by moving hand in space.

4.1. Virtual Reality Based Tools

Developments in the field of virtual reality enabled direct manipulation of objects in 3D space. One such application of virtual reality technique for creating freeform surface has been demonstrated by Schkolne *et al.*[37] The interface here is a glove with sensors attached. Virtual reality based 3D sketching tools like Holosketch[32] made the user as a part of the virtual environment. Holosketch is a virtual environment with head tracking support. Here 3D shapes are created by moving hands in air. The movement of the hand is tracked by motion sensors to create 3D shapes. Another related work is Spacedesign,[36] a mixed reality approach in which workbench — like 3-D display is used for visualization of free hand sketches of surfaces. It also provides a mathematical representation of digital free form models. A virtual environment for modeling 3D objects through spatial interaction is proposed by Nishino *et al.*[33] in which a set of 12 bimanual hand gestures used to create and manipulate 3D objects in virtual environment. The spatial hand gestures are used for grouping, ungrouping, morphing multiple objects and other transformations like scaling, translation and rotation. Cave Painting[38] is also an application

for creating freeform shape in virtual environment. 3DM[39] is another tool which attempts to integrate the CAD and drawing techniques with a six degree of freedom Head mounted display for visualization. These interfaces are capable of sensing the location but they are not capable of giving feedback to the designer about the location. To overcome this problem tools using haptic devices have been explored which are capable of giving force and torque feedback.

There are other interfaces for direct 3D input such as SKETCH by Front designers[28] using the motion trackers to track the motion of the hand and then to create the corresponding 3D curve. Recently a novel 3D sketch input device called 3D tractus[41] has been demonstrated in which a 2D sketching tablet is placed on a height adjustable platform. Another method demonstrated by Nancy Diniz[42] is to track the light in two different views and construct the surface based on the two views.

4.2. Haptics Based Tools

Haptic devices are capable of exploring 3D space and giving force and torque as a feedback to the user. Details regarding haptic devices and technology can be found in a survey by Srinivasan *et al.*[50] One of the applications developed based on haptics was to paint through a virtual brush model.[51] For this a physics based interaction of the paint brush with the object is modeled and haptic forces are rendered accordingly. Such methods are not suitable for sketching because in 3D sketching there is no medium of interaction. Diehl *et al.*[40] have proposed a method for quick creation of CAD geometries and recognition of 3D geometries from sketches. Recently Keefe *et al.*[29] has developed a 3D line illustration tool called 'Drawing on air' in which the designer creates 3D line by using one or both hands. The interface used is Phantom™ haptic device and sensor to track the non dominant hand. The use of haptics in modeling 3D shapes is gaining importance since it helps in providing depth perception to the scene.

5. SKETCHING USED IN OTHER DOMAINS

In the early phases of design, the designers mainly explore the form, function and usage of the product. Sketching is mainly used for exploring form. The functionality and behavior of the system is not much explored in the early stages. With the advent of sketch understanding techniques,[44,45] there are programs developed[43] to interpret the sketch strokes and recognize the elements in the sketch performs physics based simulation of the sketched system. There are other methods which uses sketch based animation[46,47] which can be used to animate the system using sketches. Such tools are helpful in early stages of design to explore the functionality of the system.

At the same time in the early phases of design when the designer starts sketching the concepts, instead of creating a new sketch, suppose if he wants to search for existing similar sketches then search engines like Princeton shape search library[48] can be useful. Currently it searches 3D shapes by using text, 2D sketch, or an existing model as key. The performance of such system can be greatly influenced by using 3D sketch as a key. Still this needs to be addressed as there is no literature found in this area.

In a complex product development organization, the decisions made in the design stage affects other domains of organization like manufacturing, packaging, etc. So it is useful to include experts from other domain in the early phases of design through collaboration. Presently, we find a collaborative tool[49] for designers, potentially located in geographically distant places, can interact with a common scene at the same time they can have the different view of the same scene. But there is a need to explore on cross domain collaboration through sketches which is more useful in the early phases of design.

6. SUMMARY

Sketching has been the choice of the designers in the early phases of designer; sketching is useful in enhancing the creativity of the designer through its visual vagueness possibly because it represents the state of mental process better than a crisp drawing. With the use of computer in the early phase of design, it is identified that there is a need for better tool to support the early phases. Several sketch

based modeling tools are developed for creating curves and surfaces but most of the tools are based on 2D sketching and that too for fast creation or editing of crisp CAD models. This approach looses rich annotative attributes of sketches and enhanced visual attributes such as intended usage method and relative sizing with respect to the user of the product. Sketch based techniques developed in other domains can also be studied and modified to incorporate in the sketching tools to enhance the role of sketching in the early phases of design.

Novel user interfaces like virtual reality devices and haptic devices enabled the direct user interaction in 3D. However the tools developed based on these devices are still in primitive stages in the sense that mostly they deal with single strokes. Advanced haptic interfaces enable direct interaction in 3D but their use for ab initio form generation, as pencil sketches for product form exploration on paper, cannot be found. Use of motion tracker as 3D digitizer has been reported for product conceptualization; however since there is no in-situ feedback, its use requires an expert choreography to create meaningful forms, thus limiting its applicability.

REFERENCES

[1] Fish, J. and Scrivener, S. (1990). Amplifying the Mind's Eye: Sketching and Visual Cognition, *Leonardo*, 23(1), 117–126.

[2] Prucell, A. T. and Gero, J. S. (1998). Drawings and the design process. *Design Studies*, 19(4), 389–430.

[3] Shapir, O., Goldschmidt, G. and Yezioro, A. (2007). Conceptual Design: An Operational Prescription for a Computer Support System. *IEEE 4th International Conference on Computer Graphics, Imaging and Visualization*, 513–521.

[4] Lim, S., Qin, P., Wright, D. and Shackleton, J. (2004). A Study of sketching behaviour to support free-form modeling from online sketching. *Design Studies*, 25(4), 393–413.

[5] Goldschmidt, G. (1991). Dialectics of sketching. *Creativity Research Journal*, 4(2), 123–143.

[6] Gombrich, E. H. (1966). Leonardo's method for working out compositions. *Norm and from, Studies in the Art of the Renaissance*.

[7] Taversky, B. (2002). What do Sketches say about Thinking? *Proceedings of AAAI Spring Symposium on Sketch Understanding*.

[8] Schon, D. A. and Wiggins, G. (1992). Kinds of seeing and their function in designing. *Design Studies*, 13(2), 135–156

[9] Goldschmidt, G. (1994). On visual design thinking: The viz-kids of architecture. *Design Studies*, 15(2), 158–174

[10] Suwa, M., Prucell, T. and Gero, J. (1998). Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions. *Design Studies*, 19(4), 455–483.

[11] Cross, N. (1999). Natural intelligence in design. *Design Studies*, 20(1), 25–39.

[12] Do, E. (2005). Design sketches and sketch design tools. *Knowledge Based Systems*, 18(8), 383–405.

[13] Goel, V. (1995). Sketches of Thought. The MIT Press, Cambridge, Massachusetts.

[14] Igarashi, T., Kawachiya, S., Matsuoka, S. and Tanaka, H. (1997). In Search for an Ideal Computer-Assisted Drawing System. in *Proceedings International Conference on HCI.*

[15] Casper G. C. van Dijk. (1995). New insights in computer-aided conceptual design. *Design Studies*, 16(1), 62–80.

[16] Herbert, M. D., Study Drawings in Architectural Design: Their Properties as a Graphic Medium. *Journal of Architectural Education*, 41(2).

[17] Ullman, D. G. (1990). The importance of Drawing in the mechanical design process. *Computers and Graphics*, 14(2), 263–274.

[18] Sutherland, I. E. (1964). SketchPad: A man-machine graphical communication system. in *DAC '64: Proceedings of the SHARE Design Automation Workshop*, 6.329–6.346.

[19] Harada, T. and Yoshimoto, F. (2004). Automatic curve fairing system using visual languages. in *Geometric Modeling: Techniques, Applications, Systems and Tools*, 302–327.

[20] Heloise, H. H. and Newton, R. A. (2005). Recognition and beautification of multi-stroke symbols in digital ink. *Computers & Graphics*, 29(4), 533–546.

[21] Pugh, D. (1992). Designing solid objects using interactive sketch interpretation. in *Proceedings of the ACM Symposium on Interactive 3D Graphics*.

[22] Eggli, L., Brüderlin, B. D. and Elber, G. (1995). Sketching as a solid modeling tool. *Proceedings of the Third ACM Symposium on Solid Modeling and Applications*.

[23] Grimstead, I. J. and Martin, R. R. (1995) Creating solid models from single 2D sketches. *Proceedings of the Third ACM Symposium on Solid Modeling and Applications*.

[24] Company, P., Piquera, A, Conterob, M. and Naya, F. (2005). A survey on geometrical reconstruction as a core technology to sketch-based modeling. *Computers & Graphics*, 29, 892–904.

[25] Sachs, E., Roberts, A. and Stoops, D. (1991). 3-draw: A tool for designing 3d shapes. *IEEE Computer Graphics and Applications*, 11(6), 18–26.
[26] Cohen, J. M., Markosian, L., Zeleznik, R. C., Hughes, J. F. and Barzel, R. (1999). An interface for sketching 3d curves. *Proceedings of the symposium on Interactive 3D graphics*, 17–21.
[27] Balakrishnan, R., Fitzmaurice, G., Kurtenbach, G. and Buxton, W. (1999). Digital tape drawing. in *Proceedings of User Interfaces and Software Technology*, 161–169.
[28] http://www.landliving.com/articles/0000001161.aspx
[29] Keefe, D., Zeleznik, R. and Laidlaw, D. (2007). Drawing on air: Input techniques for controlled 3d line illustration. *Transactions on Visualization and Computer Graphics*, 13(5), 1067–1081.
[30] Grossman, T., Balakrishnan, R., Kurtenbach, G., Fitzmaurice, G., Khan, A. and Buxton, B. (2002). Creating principal 3d curves with digital tape drawing, in *Proceedings of Computer Human Interaction* 121–128.
[31] Zeleznik, R., Herndon, K. and Hughes, J. (1996). SKETCH: An Interface for Sketching 3D Scenes. *Proceedings SIGGRAPH*, 163–170.
[32] Deering, M. F. (1995). Holosketch: A virtual reality sketching/animation tool. *ACM Trans. Computer-Human Interaction*, 2(3), 220–238.
[33] Nishino, H., Fushimi, M. and Utssumiya, K. (1999). A virtual environment for modeling 3D obejcts through spatial interaction. *IEEE International Conference on Systems, Man, and Cybernetics*.
[34] Igarashi, T., Matsuoka, S. and Tanaka, H. (1999). Teddy: A sketching interface for 3d freeform design. in *SIGGRAPH '99: 26th Annual Conference on Computer Graphics and Interactive Techniques*, 409–416.
[35] Ijiri, T., Igarashi, T., Takahashi, S. and Shibayama, E. (2004). Sketch interface for 3D modeling of flowers. in *ACM SIGGRAPH*.
[36] Fiorentino, M., de Amicis, R., Monno, G. and Stork, A. (2002). Spacedesign: A mixed reality workspace for aesthetic industrial design. *International Symposium on Mixed and Augmented Reality*, 86, 318.
[37] Schkolne, S., Pruett, M. and Schröder, P. (2001). Surface drawing: Creating organic 3D shapes with the hand and tangible tools. *Proceedings of SIGCHI. ACM*, 261–268.
[38] Keefe D. F., Acevedo, D., Tomer, F. and Moscovich (2001). CavePainting: A Fully Immersive 3D Artistic Medium and Interactive Experience. *Proceedings of the Symposium on Interactive 3D Graphics*.
[39] Butterworth, J., Davidson, A., Hench, S. and Olano, M. T. (1992). 3DM: A three dimensional modeler using a head-mounted display. in *Proceedings of the Symposium on interactive 3D Graphics, ACM*, 135–138.
[40] Diehl, H., Mller, F. and Lindemann, U. (2004). From raw 3d-sketches to exact CAD product models — concept for an assistant system. *Eurographics Workshop on Sketch Based Interfaces and Modeling*.
[41] Lapides, P. and Sharlin, E. (2006). The 3D Tractus: A three-dimensional drawing board. *Horizontal Interactive Human-Computer Systems*.
[42] Diniz, N. (2005). An Approach on 3D Digital Design. *Master's Thesis*, Univ. of London.
[43] Alvarado, C. and Davis, R. (2001). Resolving ambiguities to create a natural sketch based interface. *Proceedings of IJCAI-2001*, 1365–1371.
[44] Sezgin, M., Stahovich, T. and Davis, R. (2001). Sketch Based Interfaces: Early Processing for Sketch Understanding. *Proceedings of PUI*.
[45] Hammond, T. and Davis, R. (2004). Automatically Transforming Symbolic Shape Descriptions for Use in Sketch Recognition. in *Proceedings of AAAI*.
[46] Davis, J., Agrawala, M., Chuang, E., Popoviæ, Z. and Salesin, D. (2003). A sketching interface for articulated figure animation. in *Proceedings of the ACM Siggraph/Eurographics Symposium on Computer Animation*.
[47] Thorne, Burke, M. and van de Panne, D. (2004). M Motion Doodles: An Interface for Sketching Character Motion. *ACM Transactions on Graphics*, 23(3), 422–429.
[48] http://shape.cs.princeton.edu/search.html
[49] Fan, Z., Chi, M. and Oliveira, M. M. (2003). A sketch-based collaborative design system. *Computer Graphics and Image Processing* 2003. SIBGRAPI 2003. 125–131.
[50] Srinivasan, M. A. and Basdogan, C. (1997). Haptics in virtual environments: Taxonomy, research status, and challenges. *Computers and Graphics*, 21, 393–404.
[51] Baxter, B., Scheib, V., Lin, M. C. and Manocha, D. (2005). DAB: Interactive haptic painting with 3D virtual brushes. in *ACM SIGGRAPH*.
[52] Kara, L. B., D'Eramo, C. M. and Shimada, K. (2006). Pen-based styling design of 3D geometry using concept sketches and template models. in *Proceedings of the ACM Symposium on Solid and Physical Modeling*.
[53] http://gnomonology.com/tutorial/224
[54] Sang-Uk Cheon and Soonhung Han (2008). A template-based reconstruction of plane-symmetric 3D models from freehand sketches. *Computer Aided Design*, 40(9), 975–986.
[55] http://www.wacom.co.in/