UNIVERSITI PUTRA MALAYSIA

SKETCH-BASED 3D MODELING OF SYMMETRIC OBJECTS FROM WIREFRAME SKETCHES ON PAPER

ZAHRAH BINTI YAHYA

FSKTM 2016 9

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By

ZAHRAH BINTI YAHYA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

April 2016

DEDICATION

Dedicated to me and all my heroes
My family,
Good friends and beloved ones
Without whom none of my success will be possible

‘When you study something profoundly, it changes the way you look at that thing, at everything else, and, at who you are”

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

SKETCH-BASED 3D MODELING OF SYMMETRIC OBJECTS FROM WIREFRAME SKETCHES ON PAPER

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April 2016

Chairperson: Associate Prof. Rahmita Wirza O.K. Rahmat, PhD
Faculty: Computer Science and Information Technology

The motivation of this work originates from recent studies on sketch-based modeling that emphasize on the reliance of the designers on traditional methods for conveying their ideas. Many studies have chosen to focus on 3D modeling from digital sketching because of the challenges and complexity of reconstructing from paper sketches. Considering the complications of paper sketching, it is still an ideation strategy proven as an effective, flexible and instantaneous tool compared to sketching with computer-based instruments. Later, this ideation is needed to be visualized in three dimensions for better understanding. Therefore, an automated application is required to transform paper sketches into three-dimensional models. This application should constitute the essential processes for a computer to understand the paper sketch junctions, depth and connections.

Feature extraction is a preliminary step before 3D reconstruction and therefore, a junction detection algorithm is proposed. The presented algorithm benefits in omitting unnecessary junctions that are problematic for object recognition in comparison to the closest algorithm to our work. The algorithm is validated by conducting manual ground truth and the results were compared with the closest and well-known methods. A high accuracy of 99.42% and a correctness of 97% have been achieved. The proposed method shows an optimum result while resolving the existing limitations.

Subsequently, object face identification is a common step to provide important information for 3D reconstruction. The proposed face identification method is based on symmetry regularities in determining the faces of the object. The previous works employed both edges and vertex properties while using a new perspective and based on our studies we understood that we can solely rely on vertex representation for the identification process. By neglecting the edges, less ambiguity is expected but the work will be open to new challenges due to the need to preserve high accuracy. The results of the validation show a complete similarity between each original face and the output from our algorithm. Furthermore, the algorithm is also evaluated by human experts and shows 100% correctness.

Hull algorithms are the most efficient and closest methods to be redesigned for connecting the resulting vertices. But they are unable to accurately reconstruct the 3D shape using only disorganized vertices. Therefore, with no pattern information, the proposed algorithm can precisely reconstruct the 3D resemblance of the original shape. By comparing these results to recent concave hull based algorithms, several performance measures were conducted to evaluate the accuracy, correctness and time complexity of the proposed method. Besides achieving the most acceptable accuracy and correctness, the time complexity of the proposed algorithm is $O(wn)$ which is mathematically proven more efficient than comparable algorithms $O(nlogn + n)$.

Overall, it is also important that the real designers could evaluate the application for their practical and daily use. Therefore, a subjective evaluation conducted among professional designers shows that the whole automated process is not only convenient, but is also time efficient and can gracefully substitute the current practice. In addition to new approach of devising the algorithm, the overall findings show major contributions to sketch-based modeling by bridging the gaps of the sketching activity in design process and the composition of an accurate digital 3D model of the sketch.

Abstrak tesis yang dikemukakan oleh Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMODELAN 3D BERASASKAN LAKARAN UNTUK OBJEK SIMETRI DARI LAKAR RANGKA DAWAI ATAS KERTAS

Oleh

ZAHRAH BINTI YAHYA

April 2016

Pengerusi: Profesor Madya Rahmita Wirza O.K. Rahmat, PhD
Fakulti: Sains Komputer dan Teknologi Maklumat

Motivasi kajian ini adalah berasaskan kajian terbaharu iaitu pemodelan berasaskan lakaran yang menumpukan kepercayaan pereka terhadap kaedah tradisional untuk menyampaikan idea-idea mereka. Banyak kajian memberi tumpuan kepada pemodelan 3D dari lakaran komputer disebabkan cabaran dan kerumitan membina semula dari lakaran kertas. Mempertimbangkan komplikasi lakaran kertas, ianya masih strategi penjanaan idea yang terbukti sebagai alat yang efektif, fleksibel dan cepat berbanding lakaran dengan instrumen berasaskan komputer. Kemudian idea ini perlu dipaparkan dalam bentuk tiga dimensi untuk pemahaman yang lebih baik. Oleh itu, aplikasi automatik diperlukan untuk menukar lakaran kertas kepada model tiga dimensi. Aplikasi ini perlu membentuk proses penting untuk komputer memahami simpang, kedalaman dan sambungan kertas lakaran.

Pengekstrakan ciri-ciri adalah langkah awal sebelum pembinaan semula 3D dan oleh itu, algoritma pengesanan simpang dicadangkan. Faedah algoritma yang dibentangkan telah mengabaikan simpang yang tidak perlu dan bermasalah untuk pengecaman objek berbanding dengan algoritma yang paling berkaitan dengan kajian ini. Pengesahsahihan algoritma ini dijalankan dengan mengadakan data lapangan (ground truth) dan dibandingkan dengan kaedah yang popular dan berkaitan dengan kajian ini. kejituan yang tinggi iaitu 99.42% dan ketepatan 97% telah dicapai. Kaedah yang dicadangkan menunjukkan keputusan yang optimum sambil menyelesaikan permasalahan yang sedia ada.

Seterusnya, pengecaman muka objek merupakan langkah untuk menyediakan maklumat penting bagi pembinaan semula 3D. Kaedah pengecaman muka yang dicadangkan adalah berdasarkan kenalaran simetri dalam menentukan muka objek. Kaedah terdahulu telah menggunakan ciri-ciri tebing dan bucu, manakala dengan pendekatan baharu dan berdasarkan kajian kami, kita boleh bergantung sepenuhnya kepada perwakilan bucu bagi proses pengecaman muka objek. Dengan mengabaikan maklumat tebing, kurang kekeliruan dijangka tetapi kajian telah membuka cabaran baharu kerana keperluan untuk mengekalkan ketepatan yang tinggi. Keputusan pengesahsahihan menunjukkan keserupaan yang lengkap di antara muka objek asal dengan muka objek yang telah dihasilkan

menggunakan algoritma yang dicadangkan. Tambahan lagi, algoritma ini juga dinilai menggunakan persepsi kepakaran manusia dan menunjukkan 100% ketepatan.

Algoritma Hull adalah yang paling berkesan dan kaedah yang paling berkaitan untuk direka semula untuk menyambung mercu dihasilkan. Tetapi ia tidak dapat membina semula dengan tepat bentuk 3D menggunakan mercu tidak teratur. Oleh itu, tanpa maklumat corak, algoritma yang dicadangkan dapat membina semula bentuk 3D bersamaan dengan bentuk asal. Ia juga telah dibandingkan dengan algoritma permukaan cekung (concave hull) yang terbaharu. Beberapa penilaian prestasi telah dilakukan untuk menilai kejituan, ketepatan dan kerumitan masa kaedah yang dicadangkan. Selain mencapai kejituan dan ketepatan yang tinggi, algoritma yang dicadangkan juga telah mencapai kerumitan masa $O(wn)$ yang secara matematik dibuktikan lebih efisyen dari algoritma standing iaitu $O(nlogn + n)$.

Keseluruhannya, adalah penting bagi pereka sebenar untuk menilai aplikasi yang dicadangkan untuk keperluan praktikal harian mereka. Oleh itu, penilaian subjektif telah dijalankan di kalangan pereka professional menunjukkan keseluruhan proses automatik yang dicadangkan bukan sahaja mudah tetapi juga efisyen dari segi masa dan boleh menggantikan praktis semasa. Selain dari pendekatan baharu dalam pembinaan algoritma, penemuan secara keseluruhan juga menunjukkan sumbangan besar kepada lakaran berasaskan pemodelan dengan merapatkan jurang aktiviti lakaran dalam proses reka bentuk dan komposisi model tepat digital 3D dari lakaran kertas.

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First and foremost, praise and glory to Allah the Almighty who is the source of my strength and my life. I thank Allah for His immense grace and blessing every stage of my entire life.

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My special thanks go to my friends and colleagues particularly my Computer Graphics lab mates for their support and help. Their friendship helped me out in many ways and made the life warm and colorful. My thanks extended to all staff in Faculty of Computer Science and Information Technology for their direct and indirect help.

I certify that a Thesis Examination Committee has met on 18 April 2016 to conduct the final examination of Zahrah binti Yahya on her thesis entitled "Sketch-Based 3D Modeling of Symmetric Objects from Wireframe Sketches on Paper" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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I hereby confirm that:

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This is to confirm that:

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LIST OF ABBREVIATIONS

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
ADG	Angular Distribution Graph
analyS3D	An Automated 3D Reconstruction from Paper Sketches
ARD	Automatic Relevance Detection
CAD	Computer Aided Design
CoG	Center of Gravity
DFS	Depth-First Search
FN	False Negative
FP	False Positive
GIS	Geographic Information System
GT	Ground Truth
GUI	Graphical User Interface
KNN	K-Nearest Neighbour
MCP	Minimum convex polygon
MPF	Minimal Potential Face
R2	Real Coordinate Space with Two Dimension
R3	Real Coordinate Space with Three Dimension
RBF	Radial Basis Function
RGB	Red Green Blue
SBM	Sketch-Based Modeling
SP	Seed Point
SVM	Support Vector Machines
TP	True Positive
TN	True Negative
UPM	Universiti Putra Malaysia
VB 6.0	Visual Basic 6.0

CHAPTER 1

INTRODUCTION

This chapter aims at presenting a brief background about 3D reconstruction from paper sketches and the importance of sketching. This is followed by the research motivation and the deficiency of Computer Aided Design (CAD) and Sketch-based Modeling (SBM) systems. The details of problem statements, objectives, significance of research, scope and limitations are also included in this chapter.

1.1 Background

There is no definite meaning of what conceptual design is. It has different goals in various sub disciplines; such as in mechanical design, architectural design, industrial design and interior design (Horváth, 2005). There are however some common elements in all observable forms of conceptual design which are product attributes rather than product characteristics like: comfort, ergonomics, texture, colour, decoration and appearance (Ran, Wang, & Zhu, 2011). The conceptual design stage has a tremendous impact on the product cost because of the factors involved in design decision. Furthermore, this phase is vital due to the affects the decisions have on the detail design phase. Whereby choosing appropriate tools have significant influence because they can affect the whole design process (Horváth, 2005). The position of the conceptual design through the entire production process is shown in Figure 1.1. After an idea emerges, it needs to be visualized through a sketch, later it has to converge with other design solutions before it is mapped into three-dimensional models for the visual communication process.

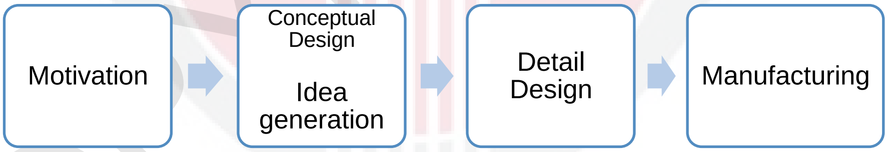

Figure 1.1: The flow of a design process

A freehand sketch that creates a graphical representation is a powerful tool for conveying an idea and prevalent at the conceptual design phase (Rodgers, Green, & McGown , 2000). The manifestation of idea can be transmitted either using pencil and paper or stylus and computer which can be referred as paper sketches and digital sketches respectively as shown in Figure 1.2. Alternatively, designers may also use software such as *SmartSketch*, *Pro/Concept* and *AliasStudio* for sketching. Subsequently, the sketch is interpreted and transformed into a 3D model for acquiring design immersion and providing insight for designers. It is further used as a mechanism of communication among designers and sometime stakeholders in brainstorming sessions as suggested by Gingold et al. (2009). The process of 3D modeling can be manually done using any CAD system such as AutoCAD, SolidWorks, and Google *SketchUp*.

The concern is, the process of this transformation is separated or disconnected from the sketching process and also handled by draftsman rather than designer. Due to this, efficiency is interrupted because of misinterpretation that may occur when the idea is translated to the 3D model. Preliminary studies[1] conducted with professional designers affirm that an effort for this task is required to synchronize the artistic ability owned by the designer and contradict to draftsman whom always looks for precision and detailing. To avoid this, the designer needs to explain the ideation and verbally clarify the ideas to the draftsman. Obviously this method is time consuming due to the repeated communication and the time taken to create the 3D model. It can be seen that, the integration between sketching and 3D modeling can fulfill the demand of shortening the design process. For that reason, many researchers have presented methods of automatically converting 2D sketches into 3D models. This could be implemented as 'an intermediate interface' for CAD systems.

Paper sketching Digital Sketching

Figure 1.2: The ideation through two major types of sketching (Chansri et al., 2014)

There are considerable researches which explore the potential of automatic reconstruction from sketches which are called sketch-Based Modeling (SBM) systems as shown in Figure 1.3. Previous studies have reported that the majority of work is focused on the reconstruction from digital sketches rather than paper sketches due to the reason that the information available from the electronic media can aid the process (Ku, Qin, & Wright, 2006; Pusch, Samavati, Nasri, & Wyvill, 2007; Shesh & Chen, 2004). However, to use digital tools in support of sketching is somehow controversial. It is almost impossible to imitate the ‘pencil and paper’ interface and reproduce the subtlety of traditional sketching into digital tools. In a survey (Won, 2001), it was found that paper sketching is more effective for delivering ideas and provides more freedom to express it on the paper than on a computer. In addition, in the study by Olsen, Samavati, Sousa, & Jorge (2009) they recommended that digital tools are not an appropriate medium to convey ideas as the flexibility of idea development reduces. Chansri & Koomsap (2012) stated that the limitation and complex 3D reconstruction from paper sketches make the research less attractive. Regardless of the difficulties, some researches explored the potential automatic reconstruction from paper sketches as can be found in (Chansri & Koomsap, 2014; Farrugia et al., 2014; Haron, Mohamed, & Shamsuddin, 2012; Marti, Regincós, Villanueva, & López-Krahe, 1995).

[1] An interview and observational study have been conducted on experienced designer from industry and Faculty of Design and Architecture UPM. The observation involves the sketching mode and the process of transferring into 3D model.

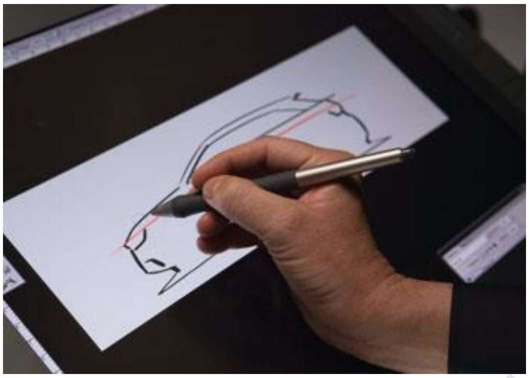

Figure 1.3: Sketch-based Modeling system - The input is acquired from stylus pen position on the interface. Adapted from *www.carbodydesign.com*

In view of the aforementioned issues, the ultimate goal of this research is to integrate the paper sketching and the 3D modeling creation by providing complete digitalization at conceptual design phase. Although some advancements are made by integrating sketching with 3D modeling and are embedded in *Autodesk AliasStudio* (Tools, 2006), it is however does not provide the automatic conversion from paper sketches into 3D models. Whilst various research has been extensively targeting the sketch-based modeling technology, paper sketch remain largely undiminished. The main challenge in this work is to deals with less information for the 3D reconstruction process than online sketching based algorithms. Nevertheless, it is worth to preserve the designer's preferences to use conventional tools because by providing the flexibility and freedom, the designer's productivity can increase. The advantages of paper sketching that also contribute to its popularity have been included in the following sections.

1.2 The Importance of Sketching

Sketching as defined by Römer, Pache, Weißhahn, Lindemann, & Hacker (2001) is an important activity used by most designers to generate their ideas. The sketch is usually rough, uncertainty and consists of various representations to intensify the flavor of the object as illustrated in Figure 1.4. Jenkins & Martin (1992) mentioned that the roughness is important in terms of flexibility and speed and suited the short-term memory of the brain. Besides, by preserve the appearance ambiguity it can affect the conceptual design and retain the continuous flow of ideas. Designing in the context of conceptual design is related to the design problem and therefore it is crucial that the sketching process is supported by the following attributes:

- **Speed and freedom**

  Speed and freedom of sketching mean the ability to transfer the idea rapidly in a short time because the arrival of a new idea is unforeseeable. This can be achieved by using a pencil or pen and paper as it is economical and accessible throughout any time and situation. Because of this freedom, several studies (Contero, Varley, Aleixos, & Naya, 2009; Qin, Wright, & Jordanov, 2001; Stones & Cassidy, 2007) concluded that paper sketches is still a favorite among designers compared to digital instruments.

- **Availability**

  The easy accessibility of this tool makes this a common method for designers. The use of pencils, let designers to depict their ideas easily by adding parts or suppressing others and they can also reject what they have drawn and begin with a new sketch as reported by Bilda, Gero, & Purcell (2006).

- **Analysis**

  According to Akin (1978) and Scrivener, Ball, & Tseng (2000), the design process allows designer to discuss and review the ideas in order to discover errors and correct the design. Goldschmidt (1991) described this process as an idea critique session between designers. In some cases, customers also like to provide input on the design during the design review session. The need of real-time information exchange between stakeholders and designers is essential in order to optimize the design process and establish the final design.

Conclusively, paper sketches seem more efficient because they are more convenient, subtle, economical and accessible. These attributes make paper sketches to be the most popular among designers (Farrugia, Camilleri, & Borg, 2014; Gingold, Igarashi, & Zorin, 2009; Lim, Qin, Prieto, Wright, & Shackleton, 2004; Tovey, 1989). The principal target of the conceptual design is to produce a big number of solutions or ideas in a short time. This requires rapid and easy ways that allow designers to express their ideas openly and comfortably. Another capability of this conventional way of sketching is that it is also easy to learn and does not need much experience and is suitable for designers in any level. Thus, it can accelerate the development of ideas and enhance the creativity in the conceptual design phase.

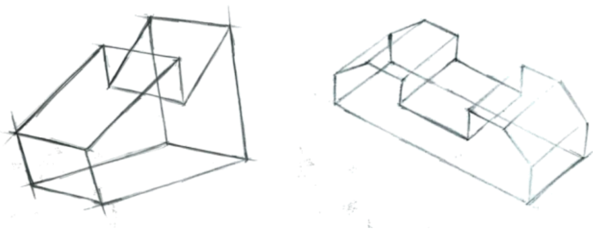

Figure 1.4: An example of some rough sketches

1.3 Research Motivation

The motivation for this work stems from important gaps and issues that have been identified. These gaps are a detachment of sketches and 3D modeling tasks and also the deficiencies of CAD and SBM systems existing in the conceptual design phase.

A brainstorming session is a platform for designers to discuss, review and choose the final idea generated via sketch. As the sketch cannot be visualized in all dimensions, the main idea is immersed. Thus, it needs to be transformed into a 3D model. Furthermore, by predicting or looking at 3D models, we can help designer to carry out more ideas. Another issue can be highlighted as reported in (Dani & Gadh, 1997; Sungwoo & others, 2002; Schweikardt & Gross, 2000), the conversion of 3D model is time consuming as it requires repeated communication between the draftsman and the designer to clarify the design ideas. Even though some research has pointed the potential of CAD tools to substitute sketching activity at conceptual design stage, but it is not suitable due to several issues discussed in the following:

1.3.1 CAD systems limitations

Computer Aided Design (CAD) is computer-based tools to assist architects, engineers and designers in their design activities. For instance, CAD is used in the design process specifically in the detailed design phase and concentrates on 3D modeling and documentation (Römer et al., 2001). In general, CAD is used in geometry authoring such as 2D vector-based drafting, building drafting, 3D parametric surface, and solid design modeling. The commercial CAD systems such as *AutoCAD*, *Rhino* and *Solidworks* have high reputations in the modeling process and some of them incorporated with sketching modules. However, they do not support the environment of conceptual design process as it is aimed at detailed design and they also could not help the designer to shape the ideas. In the phase of sketching, the designers are left alone with their conventional sketching tools, either using stylus pens or plain pencil and paper to come up with the rough idea. The interface of commercial CAD systems are based on gestural sketching which consists of restrictive gestural drawing styles and can trigger user frustration that can disrupt the ideation task as asserted by Akers (2007).

1.3.2 Sketch-based Modeling System Issues

Due to the CAD limitation, sketch-based modeling system such as *Teddy* (Igarashi, Matsuoka, & Tanaka, 1999) and *CIGRO* developed by (Company, Contero, Conesa, & Piquer, 2004) is to expedite the process by providing the natural sketching interface. Although they are powerful tools, but these devices are usually inconvenient and discouraging especially for novice users as claimed by Farrugia et al. (2014). These systems have placed a burden on the designer, and easily distract the designer's mood and feeling while they are capturing their inspiration. Even though the latest technology claims the device provides an interface like paper and the stylus is operated like a pencil; then again it cannot be as flexible as traditional methods. To produce the uncanny ability and sensation represented by the pencil gestures which is synchronized to a human cognitive process is hardly achieved by any machine mimicking the pen or pencil.

1.4 Problem statement

The main problems are the miscommunication between designer and draftsman, the iterative time-consuming task and the sketch-based modeling being based on digital sketch. The understanding of this problem is derived from the following technical sub-problems:

i. The current techniques are not well-suited for the line drawing images that have been segmented from a 2D sketch. Some detectors cannot handle meaningful junctions and therefore extract unwanted junctions that occurred from the overlapped lines. Furthermore, some algorithms are also sensitive to the curvy line that is formed by some pre-processing techniques. Thus, false junction detections may recur.

ii. After the exhaustive search of the faces, the performance of the algorithm is still inconsistent and the identified object faces are also not guaranteed to be accurate. For high accuracy of the 3D reconstruction, all the regularities must be included in current methods which make them also suffer with a worst case complexity. Using few regularities and modifying the weights might give a good trade off but still the depth value recovery process is needed based on cognitive understanding.

iii. Although there are a number of shape formation algorithms mostly based on concave or convex hull, there is no optimal solution to solve the problem from a random set of points. In fact, the design of the algorithms has various approaches to customize the ambiguous description of shape reconstruction. The algorithm should also be capable to obtain a low time complexity if it deals high number of inputs without reaching an exponential case problem.

1.5 Objectives of Research

The main objective of this study is to propose a sketch-based modeling system from two-dimensional paper-based sketches to eliminate the time consumption on repetitive 3D modeling task. The main approach is to integrate techniques supporting the contributions into a unified convenient practical system for designers to obtain 3D models based on sketches in one process without human intervention. To achieve the ultimate objective, these objectives must be achieved:

i. To propose a technique for junction detection from 2D sketch images based on a novel edge-based method.

ii. To propose a technique of object face identification from 2D vertices representation based on symmetry regularities. The technique also proposes the depth value derivation from the identified face.

iii. To propose a splitting and recombination technique of object shape reconstruction from the faces of the object for 3D modeling.

1.6 Significance of Research

This study investigates an approach for reconstructing 2D paper sketches to 3D models. The motivation of the research is to bridge the gaps of the activity in the conceptual design stage. That is, the outcome of this research should be able to integrate the designer requirement while maintaining their flexibility. The reconstruction algorithm should be fast and capable to interpret complex images and produce an accurate 3D model.

This thesis can be viewed from two different perspectives:

From the design process viewpoint, the main contribution of this thesis is that the proposed system can make the communication and brainstorming process quicker and fluent. The proposed solution also can minimize the design process cycle, slash unnecessary repeated activity and therefore reduce cost and increase productivity.

From the computer science viewpoint, the main contribution is the new approach to the problem of 3D model reconstruction from 2D sketches. It is associated with sketch interpretation using only junction data, a new perspective on feature detection from drawings and a more efficient 3D geometrical reconstruction.

1.7 Scope and limitations of Research

The thesis focuses on automated 3D reconstruction from paper-based sketches. The input data are paper sketches that are scanned into the proposed 3D reconstruction system. However, for the purpose of this thesis, the focus is limited only to geometrical and symmetrical 2D sketches. This work is a complete application that will be used by designers, practitioner and educator for the design process and education purposes.

- We do not consider sketches that involve holes in this study due to the reason that a hole is an object positioned in between a bigger object.

- Non-manifold objects are not considered: This restriction can be justified on the grounds that man-made objects are manifold. Further, we assume rather than check that the wireframe represents a manifold polyhedron.

1.8 Thesis Organization

This thesis is composed of seven chapters, including this introductory chapter. Chapter 2 describes the previous and related works on the 3D reconstruction, junction detection, face identification and object shape reconstruction methods. Chapter 3 illustrates the methodology used in the research. Chapter 4 describes the work on junction detection algorithm from sketch images. Chapter 5 describes the novel algorithm of face identification from the 2D vertices and depth value derivation. Chapter 6 describes the proposed efficient algorithm for object shape reconstruction to produce the complete 3D model. Finally, the conclusion is drawn in chapter 7 with emphasis on the contributions and the results of utilizing the overall system consisting all contributions and future work.

The thesis structure for research in UPM can be divided into three styles based on the School of Graduate Studies guide to thesis preparation book (2009). The second style has been chosen for this thesis where a thesis is divided into four parts, which are the introduction, literature review, research methodology and conclusion. Each research chapter represents a separated study that has its own introduction, methodology, results and discussion. Thus, this thesis has four research chapters which complement the technical elements that form the subject of discussion. Consequently, the overall organization of the thesis is as follows:

Chapter 1: Introduction

This chapter serves as the introductory to this thesis. It starts with a conceptual design and sketching process background. Next, a motivation of do the research is also explained. Moreover, this chapter clarifies the problem statement, research objectives, significance and scope and limitation of research.

Chapter 2: Literature Review

This chapter serves as the literature review of the entire research. It reviews prior research on sketch-based modeling system, junction identification, face identification and depth value derivation and object shape reconstruction.

Chapter 3: Research Methodology

In this chapter, the overall research methodology is explained. Furthermore, this chapter clarifies data acquisition, dataset creation, implementation, experimental design, validation and brief details of each research chapters.

Chapter 4: Junction Detection from Sketch Images

This chapter details the junction detection using edge-based method. The chapter starts with an introduction, the proposed methodology of the algorithm, implementation, results and discussion, and the advantages and disadvantages of the algorithm.

Chapter 5: Face Identification and Depth Value Derivation

This chapter details the object face identification and depth value derivation. The chapter starts with an introduction, the proposed methodology of the algorithm, implementation, results and discussion, and the advantages and disadvantages of the algorithm.

Chapter 6: Object Shape Reconstruction

This chapter details the object face reconstruction from the identified faces. The chapter starts with an introduction, the proposed methodology of the algorithm, implementation, comparison, results and discussion, and the advantages and disadvantages of the algorithm.

Chapter 7: Conclusion

This final chapter concludes the whole research, highlights the contributions and also includes the overall evaluation of professional designers, and proposes recommendations for future work.

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