DEVELOPMENT OF A PROTOTYPE OF INDUSTRIAL RESPIRATORS FOR MALAY MALE USERS

by

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LIST OF ABBREVIATIONS

ASC	:	Assumed Stretchability Coefficient
CAESAR	:	Civilian American and European Surface Anthropometry Resource Project
CV	:	Coefficient of Variation
DOSH	:	Department of Safety and Health
FDM	:	Fused Deposition Modeling
I	:	Interval
LOM	:	Layered Object Modeling
MSG	:	Maximum Size Group
RE	:	Reverse Engineering
RP	:	Rapid Prototyping
SG	:	Size Group
SI	:	Sub-interval
SL	:	Stereolithography
SLS	:	Selective Laser Sintering

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PEMBANGUNAN CONTOH SULUNG ALAT PENYARING UDARA INDUSTRI UNTUK LELAKI MELAYU

ABSTRAK

Majoriti alat penyaring udara yang digunakan dalam industri di Malaysia adalah diimport dari Amerika. Oleh yang demikian, ciri-ciri muka penduduk Malaysia tidak diberi pertimbangan di dalam proses rekabentuk. Dengan itu, kebocoran akan berlaku apabila alat penyaring udara tidak padan dengan pengguna. Kerja ini bertujuan untuk membangunkan pencontoh sulungan alat penyaring udara dan teknik baru. Pengukuran antropometrik muka dilakukan terhadap 47 sampel daripada lelaki Melayu Malaysia. Kaedah statistik telah digunakan untuk mewujudkan maklumat rekabentuk daripada data yang diperolehi. Komponen pengolokan penyaring udara daripada model muka dibuat menggunakan model tanah liat melalui kaedah kejuruteraan balikan. Pengimbas 3D digunakan untuk mengimbas komponen pengolokan. Seterusnya, model digital tersebut di contoh sulung menggunakan mesin FDM. Didapati terdapat beberapa perbezaan di dalam keputusan pengukuran anthropometrik dari hasil kerja ini dengan hasil kerja orang Amerika, iaitu orang Melayu mempunyai hidung dan bibir yang agak lebar sementara orang Amerika mempunyai bentuk muka yang lebih besar dan hidung yang lebih mancung berbanding dengan orang Melayu. Empat saiz yang berbeza (kecil, sederhana, besar, lebih besar) telah diputuskan melalui kaedah statistik. Kerja ini menunjukkan rekabentuk alat penyaring udara yang direkabentuk untuk orang Amerika tidak sesuai untuk orang Malaysia. Kerja ini juga telah mewujudkan teknik gunaan untuk pembangunan produk berdasarkan data anthropometrik, kejuruteraan balikan dan pencontoh sulung cepat. Satu ujian pengesahan mudah sampel model ke atas subjek

Melayu menunjukkan purata peratusan bocoran sebanyak 21%. Untuk penyelidikan akan datang, cadangan dibuat supaya pengumpulan data menggunakan kaedah sampel rawak dengan saiz sample yang lebih besar dijalankan dan melengkapkan penghasilan contoh sulung akhir menggunakan bahan sebenar untuk kegunaan ujian prestasi padan.

DEVELOPMENT OF A PROTOTYPE OF INDUSTRIAL RESPIRATORS FOR MALAY MALE USERS

ABSTRACT

Majority of the respirator used in Malaysian industries are imported from America. Therefore the facial characteristics of Malaysian were not considered in the design process. Thus, leakages may occur when respirator does not fit users. This study aims to develop a prototype of a half-mask respirator using some new techniques. Facial anthrophometric data collection was conducted based on 47 samples of Malaysian Malay males. Statistical method was applied to establish design information from the data. Reverse engineering was utilized to make the mock-up part of the respirator from the face model using clay modeling. 3D scanner was used to digitize the mock-up part. Then, the digital model was prototyped by FDM machine. It was found that there were some differences in measured anthropometric data of this work to that of the American, where the Malays have relatively wider nose and lip length while the American has bigger face shape and narrower nose compared to that of the Malays. Four different sizes (small, medium, large and extra large) of respirators were determined using statistical method. The study showed that, American designed respirator products are not suitable for Malaysian. Therefore, the current work also established an applied technique for respirator product development based on anthropometric data, RE and RP. A simple verification test of the sample model on Malay subjects shows that the average leakage percentage was 21%. Future research is suggested to extend the data collection with

larger sample size by using randomized sampling techniques and completing the final prototype with real material for fit performance test purposes.

CHAPTER ONE

INTRODUCTION

1.0 Introduction

This chapter presents the background to the research and thereafter the purpose and research questions. There are two major types of respirators, the atmosphere supplying or air purifying (NIOSH, 1987). Atmosphere supplying respirators provide safe, respirable air from a source other than the immediate work atmosphere. Air purifying respirators, which are the main focus of this study, rely on various means for the filtration of contaminants in workplace's air which may be harmful to workers' health. Air-purifying respirators are categorized as either negative pressure or powered air supply. Powered air-purifying respirators provide a stream of clean, filtered air from the immediate workplace at a positive pressure; an electrically-powered fan moves contaminated air through a filter before air enters the respirator's facepiece where it can be inhaled by workers. Negative-pressure air-purifying respirators, on the other hand, rely on the wearer's force of inhalation to draw air through the air-purifying filters and then into the facepiece.

Half-mask industrial respirators are by far the most commonly used type of respirators in paint spraying, agriculture, construction and transportation jobs. Workers in such industry not only depend on these respirators to reduce the risk in highly hazardous conditions, but also demand protection in their lower-risk daily operations (Zhuang & Bradtmiller, 2005).

This study focuses on negative-pressure air-purifying respirators, similar to the respirator shown in Figure 1.1. In particular, the current work addresses the half-mask respirator. This device has a facepiece that covers the wearer's nose, mouth, and chin. Appendix A shows the exploded view of half-mask respirator.

Figure 1.1 Half-mask respirator (Source:www.safetyexpress.com).

Many respirators used in Malaysian industry are imported from global companies, for example, 3M. The approved list of respirators by Department of Safety and Health (DOSH) Malaysia indicates that the majority of the respirator's suppliers are importing goods from overseas (DOSH Malaysia Official Homepage, 2007). Based on the review, recent studies on respirator design mostly involved facial characteristics of the Americans, Chinese and Koreans. Until now, there has yet a scientific approach toward respirator design based on the study of Malaysian facial characteristics (Zhuang & Bradtmiller, 2005; Yang *et al*., 2007; Han *et al*., 2004). Therefore it is essential to design respirators that have a good fit for Malaysian Malay workers.

Malaysia is a multi-ethnic country, comprises of three main races - Malays, Chinese and Indians. Malay group is selected as the sample in this case study as it is the majority of the ethnic group in the population. Referring to the latest census conducted in 2000, Malaysian population consists of 52% Malay ethnic group, followed by 24.5% of Chinese and 7.2% of Indian. From these data, male populations in particular age group from 20-29 years old are 45.1% Malay, 23.3% Chinese and 7.3% Indian in percentage (Department of Statistics Malaysia, 2001). Hence, the data of Malay male in this study would be useful and more appropriate to be considered for Malaysia's case or even for the case of other South East Asia countries.

1.1 Problem Statement

Face-fitting characteristics are the most important characteristic of respirators. This is to ensure the reliability and level of protection they offer. Face-seal leakage would occur if the respirator does not fit well to users. Many researchers acknowledged that leakages of the respirator had shown to associate with dimensional design of the respirator and the facial anthropometric dimensions (Hack & McConville, 1978; Oestandstad *et al.*, 1990; Yang & Shen, 2008). Work-related asthma is the most common disease encountered by industrial workers exposed to hazardous gases, fumes, vapors and dusts (Bardana, 2008).

There were several questions were posed during the course of this study. One of the purposes of these questions was to limit the scope of research and provide focus to the study. The main research questions include the following:

i) What is the problem faced by current respirators in Malaysia?

ii) How is the shape of respirators designed for a good fit on users?

iii) How to determine the size classification based on the anthropometric data of the target population?

iv) What are the important surface marks on the human face should be considered in designing a respirator?

1.2 Research Objectives

The main objective of this study is to develop half-mask respirator that fits the facial characteristics of Malay male workers believed to reduce face-seal leakages. This problem needs to be addressed because the occurrence of any leakages during the use of half-mask respirator could prove to be hazardous due to exposure to gaseous or fumes that are dangerous to health. In order to achieve the above objective, the following sub-objectives were identified:-

i) To determine proper facial size selection based on the results of the anthropometric data collection in order to obtain a minimum of 90% of the sample.

ii) To produce a face model by using the size selection data as a representative of the sample.

iii) To produce a sample model of the half-mask respirator based on the face model.

iv) To verify the shape of the sample model on Malay male subjects.

1.3 Research Scope and Limitations

In order to achieve a good result in this research, restrictions have to be made as to ensure the work will be focused and consistent with the given time frame. The restrictions made in this study are presented below:

1. The thesis will provide a prototype solution. This contribution can be considered as a first step in the product development.
2. The subject selection of facial anthropometric data in this study is restricted to a Malay males group only due to common features among the ethnics population i.e. different ethnics, in particular the Chinese and Indian have different features or face characteristics (Farkas *et al*., 2005).

1.4 Research Significance and Expected Contributions

This study aims to produce a well-fitted respirator that can reduce the problem of leakage while in use that prove otherwise be hazardous to the industrial users. This new respirator is also expected to be more comfortable due to the incorporation of facial dimensions in the design criteria.

1.5 Disposition

This thesis report consists of six chapters. Chapter One describes the research background, problem statements and research objectives of the study involving the research scope, limitations and expected contributions. Chapter Two reviews relevant literature and provides the background and some theoretical basis for the study. This is followed by Chapter Three that explains the methodology of the research. Chapter Four presents results and analysis of the methods used in the thesis. In Chapter Five, a discussion on the analyzed data and results is. Finally, in Chapter Six, the conclusion of the study, the contributions, future directions and extensions of the research are presented.

Next chapter presents the literature reviews to provide the background of the research including ergonomics and anthropometry, relevant works related to the use of anthropometry in product design, Reverse Engineering (RE) and Rapid Prototyping (RP).

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter provides a review on the background knowledge of the research carried out. The topics in this chapter include the review of works previously done in the area of facial anthropometry in relation to half-mask industrial respirator. This chapter provides information of human factors and ergonomics, reviews the three levels of customer needs that are vital in design process, explores the application of anthropometric in product design in particular fit and comfort, reverse engineering (RE) and rapid prototyping (RP) where the integration of RE and RP in product development process and summary of the chapter are presented.

2.1 Human Factors and Ergonomics

In product development, anthropometry and ergonomics typically go hand in hand (Pheasant & Haslegrave, 2006). Studies that apply ergonomics principles in the design stage could help designers produce successful products. These studies can be described in few steps. First, the problems have to be identified and thereafter it is possible to take action. The chosen solution is then evaluated to see if the fix was successful.

2.2 Three Levels of Customer Needs

The main objective of designing a product is to satisfy customers in all aspects. The needs of the customer should be fulfilled through the performance of the products. Thus, customer satisfaction is important in measuring the success of a product in the market. Figure 2.1 shows the three levels customer needs for a product. This is a way to see the contribution of ergonomics to product design. Jordan (2000) describes three levels of customer needs for functionality, usability and pleasure. The following will explain the three levels in more detail.

Pleasure ↑

Usability ↑

Functionality ↑

Figure 2.1 Three levels of consumer needs (Jordan, 2000)

According to Jordan (2000), a product is of course useless if it does not work. This means that a fundamental need is to have a product with necessary functions. Otherwise, the product will bring dissatisfaction to user. In order to make the most out of the product, those who design it must understand what the product will be used for and the environment in which it will be used.

Usability concerns the ease of use of a product or a system. This is actually a common expectation from users nowadays. A usability-based approach to design looks at people in terms of their cognitive and physical abilities. This means that if a product's design is within the cognitive and physical abilities of the user, then the product will be usable for this person (Jordan, 2000). This approach tends to take a view of the user that focuses only on anthropometrics, physical abilities and cognitive abilities. The focal point of greatest concern in this study is anthropometrics.

Creating a usable product does not mean a designer is successful in creating a pleasurable product. It is simply because usability is not a factor in determining how pleasurable products are to use or it is only one of a number of factors. According to Jordan (1998), it was possible that usability and pleasure in product use are directly associated, and that making a product usable will guarantee that it was a pleasure to use. However, by considering user-centered design only in terms of usability, products will fall short of giving optimal experiences for the users.

2.3 Anthropometry

Since Alphonse Bertillon develops a system to identify criminals in France in the 19th century (NASA, 2008), anthropometry has become a valuable tool in the advancement of military science, engineering, medical science and product design.

Anthropometry derives from the Greek words *anthropos*, meaning human, and *metrikos*, meaning of or pertaining to measuring (Roebuck, 1995). Anthropometry provides body measurements that assure manufactured goods would be suitable for intended user populations (Roebuck *et al*., 1975).

Anthropometric data tells us the variety and variability of human measurements which could provide designers or engineers vital information to design, a product that is reliable for individuals within a population, hence considered the very ergonomic core of any attempt to resolve the dilemma of ‘fitting the tasks to the human’ (Sanders & McCormick, 1993).

Military science has driven research in anthropometric methods and data due to its high demand in precision, accuracy and performance. The 1988 U.S. Army Anthropometric Survey (ANSUR) database is among the most widely used and referred to anthropometric data collection. Consequently, due to the increase of awareness in the role of anthropometry for designing human related product, more updated anthropometric database has been established. Example includes the Civilian American and European Surface Anthropometry Resource Project (CAESAR) database, fully completed in 2000. This database uses new technology in data collection- the Three Dimensional (3D) Surface Anthropometry. With this technology, thousands of points in three dimensions on the human body surface were captured in just a few seconds. Obviously, it has many advantages over the manual measurement by using measuring tape, anthropometers, and other instruments. It gives detail about the surface shape as well as 3D locations of measurements relative to each other and enables easy transfer to Computer-Aided Design (CAD) or Manufacturing (CAM) tools (CAESAR, 2008).

2.3.1 Anthropometric sampling

Basically, there are two types of sampling methods, a mathematical approach called probability sampling and a non-mathematical approach, known as non-probability sampling. In a probability sampling, there are four different types of sampling method; a simple random sampling, stratified random sampling, systematic sampling and cluster sampling. Non-probability sampling can be categorized into four primary types; convenience sampling, quota sampling, judgment sampling and snowball sampling (Bluman, 2009).

The central limit theorem applies for large enough sample sizes. A large enough sample size depends on how much the population distribution deviates from a normal distribution. Typically, if the sample size is greater than 30, then it is sufficient to consider as large enough. The larger the sample size, the better the normal approximation is (Pelosi & Sandifer, 2003).

2.3.2 Anthropometric Data Collection Technology

In anthropometry, photogrammetry refers to a process of obtaining measurements by means of photographs, while stereo photogrammetry refers to the special case, where two or more cameras are used to obtain 3D information of objects from their 2D images (Douglas, 2004). Figure 2.2 shows the imaging equipment of stereo photogrammetry. The systems showing two digital cameras mounted apart on a box and a control frame comprises of a chin and head rest with vertical supports each side and eleven well-distributed control markers mounted on it (Meintjes *et al*., 2002).

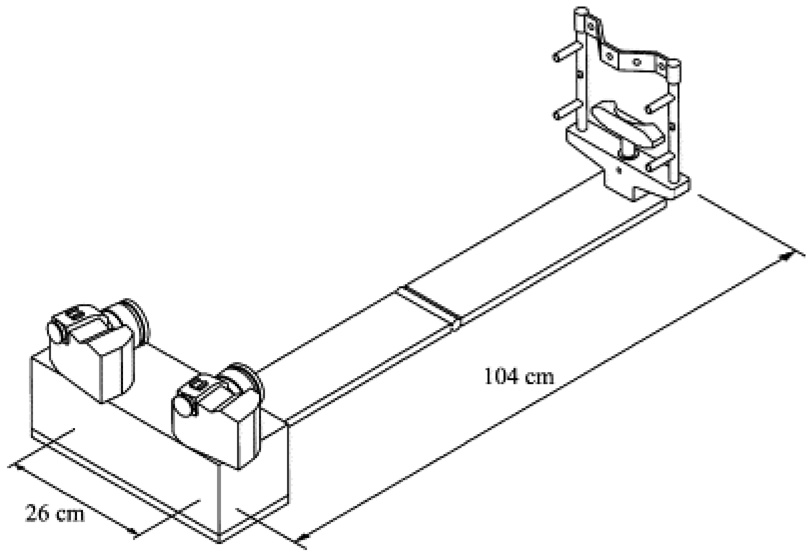

Figure 2.2 Diagram of equipment for capturing stereo images (Meintjes *et al*., 2002).

The 3D laser scanning is the most current technology available. To date, a number of large anthropometric surveys using 3D laser scanning have been conducted around the world, such as CAESAR (Robinette *et al*., 1999), Size UK (Bougourd *et al*., 2004), Size China project that focused on measurement of head and face data across China through 3D digital scanning of sample populations (Size China, 2008) and recently a collaborative project between retailers, universities and companies that was intended to measure children aged 4-17 across the Great Britain by using 3D Body Imaging Scanner (Shape GB, 2009).

2.3.3 Sample of Using Anthropometrics Data in Consumer Product Design

Anthropometry had long been used by designers in both military and commercial industries to assess the range of body sizes within their target population. With the help of these comparative measurements, the development of well-fitted, comfortable and safe products, such as spectacles frame (Kouchi & Mochimaru, 2004), hand tools (Nag *et al*., 2003), ear-related products (Jung & Jung, 2003; Liu, B.-S., 2008), motorcycle helmet (Gilchrist *et al*., 1988) and respirators (Hughes & Lomaev, 1972; Liau *et al*., 1982; Oestenstads *et al*., 1990; Coblentz *et al*., 1991; Oestenstads & Perkins, 1992; Kim *et al*., 2003; Han & Choi., 2003; Han *et al*., 2004; Zhuang & Bradtmiller, 2005; Yang *et al*., 2007; Yang & Shen, 2008) are possible.

Kouchi & Mochimaru (2004) analyzed the proper sizing of spectacle frames on Japanese male faces. The study was based on the normalized model of the three-dimensional face form that made of 56 Japanese adults aged between 18 and 35 years. The 56 subjects were classified into four groups based on analysis of the distance matrix and average form was calculated for each group. A new spectacle frame was designed for each of the average forms, and prototype frames were constructed. To verify the newly design spectacles, 38 subjects were participated in the validation experiment. The result of the study demonstrated that product design based on 3D models of human face is useful in improving the fit of mass produced products. The new frames were confirmed to not slip in spite of smaller tightening forces than conventional frame designs. The new frames have been on the market since July 2001 and were generating favorable comments. The study addressed that face forms and dimensions vary significantly between ethnic groups and further analysis of face forms with regard to ethnicity would further improve significantly the fit of spectacles frames.

Nag, Nag and Desai (2003) investigated 95 hands of Indian women working in informal industries. Fifty one dimensions of the hand included lengths, breadths, circumferences, depths, spreads and clearances of hand and fingers involved in this study. The anthropometric sliding and spreading calipers were used as well as the measuring tape and handgrip strength dynamometer. They have found out that hand length has significantly correlated with the fist, wrist and finger circumferences. In addition, the grip strength was found to be statistically significant with hand dimensions. Their study also showed that the hands' circumferences of Indian women were smaller than the American women. Finally they concluded that the present data on Indian women's hands may be useful for ergo-design application of hand tools and devices such as soldering tools, pliers and wire strippers.

Jung & Jung (2003) studied on the dimensions and characteristics of 600 male and female Korean subjects aged 17 – 89. Their work explored the differences between the ears of Koreans and Westerners, and the difference in the dimensions of right and left ears. Major findings of their study are i) the dimensions of ears are significantly related to age, weight and height, ii) male have a higher correlation between age and ear dimensions, and iii) Korean males have bigger ears than western male. They suggested that, when designing anthropometric products, the change in body parts due to aging need to be considered. The study also suggested that headphones and earmuffs used as industrial safety devices should be 1 cm bigger than the current models. Ear-cup earphones should be made in small, medium and large sizes and the length of the ear hole should be applied to a percentile of 75. Further, oval shape earphones would be best to prevent slippage.

Study done by Liu (2008) incorporating anthropometric into design of ear-related products. The ear hole length, the ear connection length and the length of the pinna were measured by superimposed grid photographic technique. 200 subjects age 20–59 was selected for this study and divided into four age stratifications. They were selected by using convenience sampling and have no history of trauma or congenital anomalies. The analysis of variance (ANOVA) was used to investigate the effect of gender and age on ear dimensions. The results showed that there were no significant differences in any ear dimensions across age groups. The results also showed that all ear dimensions had significant gender effects. The results indicated that right ears had larger dimensions than left ears. Liu (2008) concluded that to develop an ear product, the product should be making available in various sizes to accommodate difference users. The product diameters and the shape of the ear should also need to be considered as the ear hole and pinna are not circular.

Gilchrist, Mills and Khan (1988) have done a survey of head, helmet and head form sizes related to motorcycle helmet design in the UK. There were over 500 motorcyclists and young adult participated in this survey. They found that, by using the range of head forms, people with large circumference heads have both larger than average head length and head breadths. They also stated that, head are not symmetrical about the mid-sagittal plane. Another finding of their study suggested that the gap at the front and rear of the helmet should be the most essential in term of helmet retention, and there will be a range of values of the gap among the population. They also concluded that, there was a slight variation in length/breadth from one manufacturer to another, so that a motorcyclist may find one brand that fit him better than the other. Further, the study also addressed that different ethnics group may need different helmet sizes because there was an indication that Chinese students had more spherical heads than UK students.

An anthropometric survey of Australian males in designing respiratory equipment was done in 1972 (Hughes & Lomaev, 1972). The study involved 538 men age from 15 to 80 years being measured by using vernier sliding caliper and measuring tape. The subjects comprised of two groups of population, general population and industrial population. The results of the study indicated that there was no statistical significant difference in mean facial size between the group of general population and the group of industrial population.

Liau, Bhattacharya, Ayer and Miller (1982) studied about the anthropometric parameters for design of respirators. They have selected 243 workers involved in the fit-test program to get the anthropometric data. The data that they have collected were from two direct facial measurements and five indirect facial measurements. The direct facial measurements were nasal root breadth and face length while the indirect facial measurements were nose length, nose protrusion, chin length, mouth width and face width. Based on their correlation analysis on the facial measurements, they stated that the most important parameters in half mask respirators were face width and mouth width.

A study by Oestenstad and Perkins (1992) showed that the fit of the half mask respirator could be predicted by selecting wearers' facial dimensions. Fit factors and 12 facial dimensions measured on 68 volunteers participated in this study, which consist of 30 female and 38 male subjects were analyzed. Their objective was to determine if facial dimensions for a group of subjects were predictive of the fit factors measured while one brand of half-mask respirator was worn. The respirator used was one of three sizes (small, medium or large) of the US Safety Series 200 half-mask respirator. They found that facial dimensions were good predictors of respirator for this group of wearers and half-mask respirator tested in this study. Lower face length was consistently indicated as being correlated with fit. These results would indicate that dimensions other than those currently used may be more appropriate to define a half-mask respirator test panel.

Kim *et al.* (2003) conducted a study to provide facial anthropometric data for Koreans and analyzed the association between facial dimensions and respirator fit factors for three brands of quarter-mask respirators. A total of 110 volunteer subjects, consists of 70 male and 40 female university students were used in the study. They went through the fit testing procedure by using the three most widely used brands in Korea. Further, 12 facial dimensions were then measured by using sliding and spreading calipers and measuring tape. The results of the study showed that Koreans males and females have different facial dimensions as compared with those of White males and females. Further, they also found out that the Korean males had better respirator fit than females regardless of respirator brands tested. Statistical analysis showed that facial widths and lengths found in the study should be considered in designing respirators for the Koreans.

Zhuang and Bradtmiller (2005) have created the largest anthropometric database on civilian heads and faces in U.S. The database provides the information regarding the face dimensions of civilian respirator users for design and sizing applications. Dimensions were chosen to maximize their utility in the design and testing of new respiratory protection equipment. It is a normative database characterizing the variability of people for the cost effective design in particular for head and face's wear product. A total of 3997 subjects were measured using traditional methods and 1013 of them were also scanned using 3-D head scanner. A stratified sampling plan was used with three age strata, two gender strata and four race/ethnic group strata. This study showed that dimensions are critical to the design and sizing of respirators.

A study on racial differences in respirator fit testing by Yang, Shen and Wu (2007) showed that facial anthropometric measurements of 461 Chinese subjects were different from those of American groups. The volunteer subjects consisted of 270 males and 191 females. The range of ages of the subjects was from 23 to 43 year old. 10 critical facial dimensions were measured in this study because of the close relationship to the performance of respirators as studied by Oestenstad *et al.* (1990) and Han and Choi (2003). Sliding and spreading anthropometric calipers and plastic tape were used in the measurements. They concluded that the anthropometric survey in their study may more representative of facial characteristics of the current Chinese civilian population.

The differences found between the facial dimensions of Chinese and those of American indicated that this study can provide respirator industries the anthropometric data on different race groups to meet the needs of their customers.

Yang & Shen (2008) conducted a pilot study on anthropometric dimensions of the Chinese population for half-mask respirator's design and sizing. The total of 461 students and teachers were volunteered in the dimensions survey. The subjects consisted of 270 male and 191 female. The range of ages of the subjects was between 23 to 43 years. The subjects were measured by using spreading and sliding anthropometric calipers and plastic tapes. 10 facial dimensions were measured during the survey. Based on the results, the anthropometric values of face width for the Chinese were higher than of the American and Australian. Additionally, the anthropometric values of face length for the Chinese were lower than of the American. The study concluded that the higher value of face width and the lower value of face length of the Chinese should be considered in the process of design and sizing of half-mask respirators.

The role of incorporating anthropometry is vital in life-protecting clothing and equipment. Safety equipment such as respirators would rely upon anthropometric data for fitting measurement on users. Han *et al*. (2004) developed prototypes of half-mask facepieces specifically for the Koreans by using anthropometric data captured by 3D digitizer. The study was based on the perception that the main cause of face-seal leakage was the poor fit of the inner part of the elastomeric body facepiece. A total of 50 subjects were measured using 3D scanner. The results of the anthropometric data were used to make three different sizes of face models (large, medium and small). The selection of the three sizes models were based on statistical analysis and the most concentric-shaped face that fulfilled the mean digits of the mean face for each size group. This process was done by using a craft techniques. The prototype of the inner part of facepiece was designed from the mean face from each size group. Rapid Prototyping (RP) was used to make the physical model of the facepiece before it was transformed into silicon models via silicon moulding. Simple wearing test at the laboratory level was also done and the result shows that the fit was improved than that of the other existing models.

2.4 Reverse Engineering

Reverse engineering (RE) is often associated with the act of copying an original design for competitive purposes, but this perception is quickly changing. According to Varady *et al.* (1997), conventional engineering transforms engineering concepts and models into real parts while RE on the other hand transforms real parts into engineering models and concepts. RE is often used in the process of copying a part when there are no original drawings or documentation available. The RE procedure can be characterized by the flowchart in Figure 2.3.

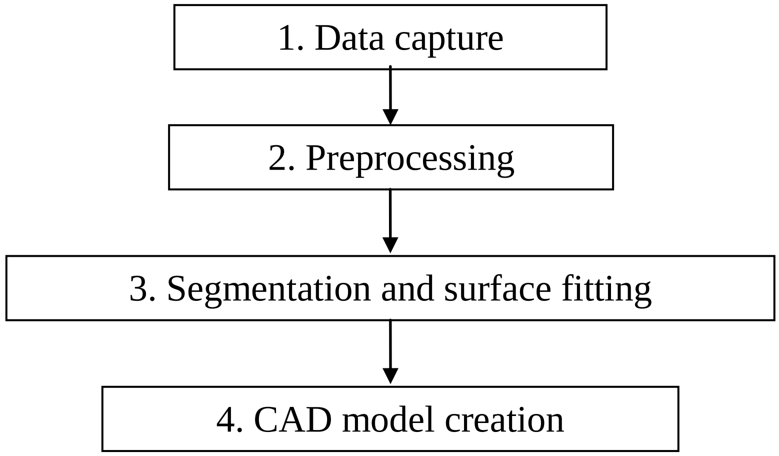

Figure 2.3 Basic phases of reverse engineering (Varady *et al*., 1997)

RE is now considered as a part of contemporary product design and manufacturing process (Sokovic and Kopac, 2006) especially in the design of complex surfaces which are very difficult to create on conventional route in modern CAD-software (Sokovic *et al*., 2005). Figure 2.4 shows the example of sequences of RE in product design. The sequences of RE starts with digitizing of a physical model using 3D-scanner. Data generated during the digitizing process were in digital points cloud data format. These X,Y,Z coordinates data are transformed into conceptual model supported by CAD system using model reconstruction system software. Finally, the conceptual model may then be used to produce the prototype of the shape using either CNC or RP machines.

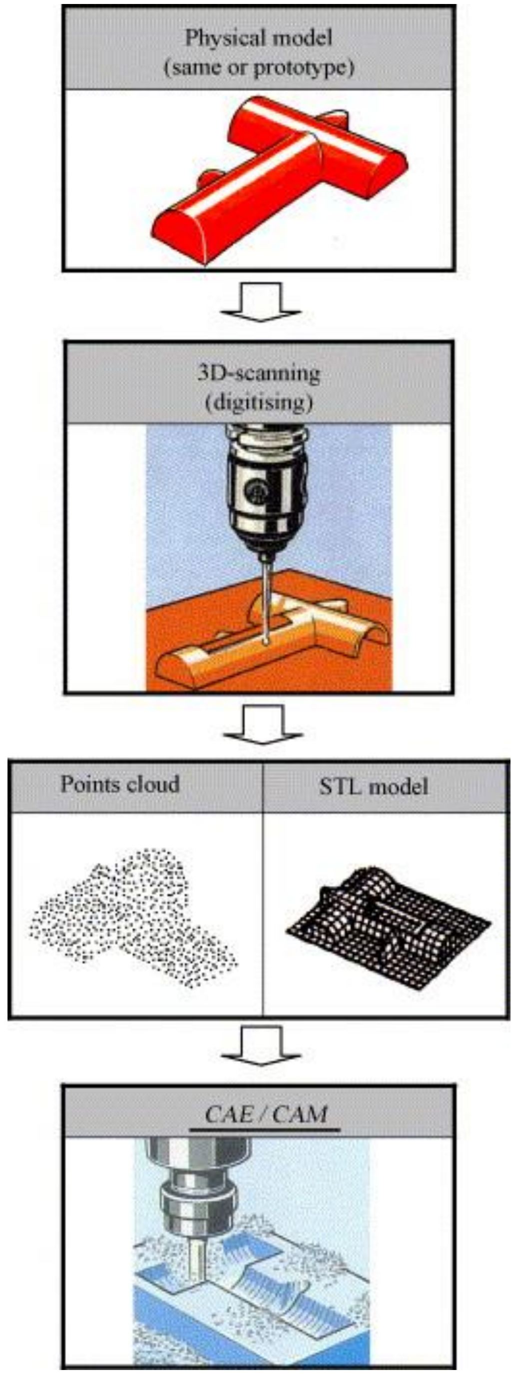

Figure 2.4 Example of the sequences of RE in product design process (Sokovic & Kopac, 2006)

2.5 Rapid Prototyping

Rapid prototyping (RP) is a terminology used to describe a range of new technologies for producing accurate parts directly from CAD models with just a minimum need of human intervention, normally in a few hours (Pham and Gault, 1998). RP takes virtual designs and transform them into physical model. Virtual designs are made in a CAD program and by transforming them into cross sections, the machine can produce the actual model. The procedure is done by using layers of liquid or powdered materials. These layers are often glued or fused to create the final shape. Figure 2.5 shows the classification of RP according to how they form layers of material to build the RP model.

Wohlers (2006) conducted a survey on RE application in the industries worldwide, and found that approximately 17% of RP parts are used as functional models, whereas 13.5% as visual aids for engineering. Industries use 11.1% in patterns for prototyping tooling, 10.9% in pattern for cast metal, 10.3% for fit and assembly tests, 9.6% in rapid manufacturing process, 9% for presentation models and the rest for tooling components, ergonomic studies, visual aids for toolmakers, quoting, among others.

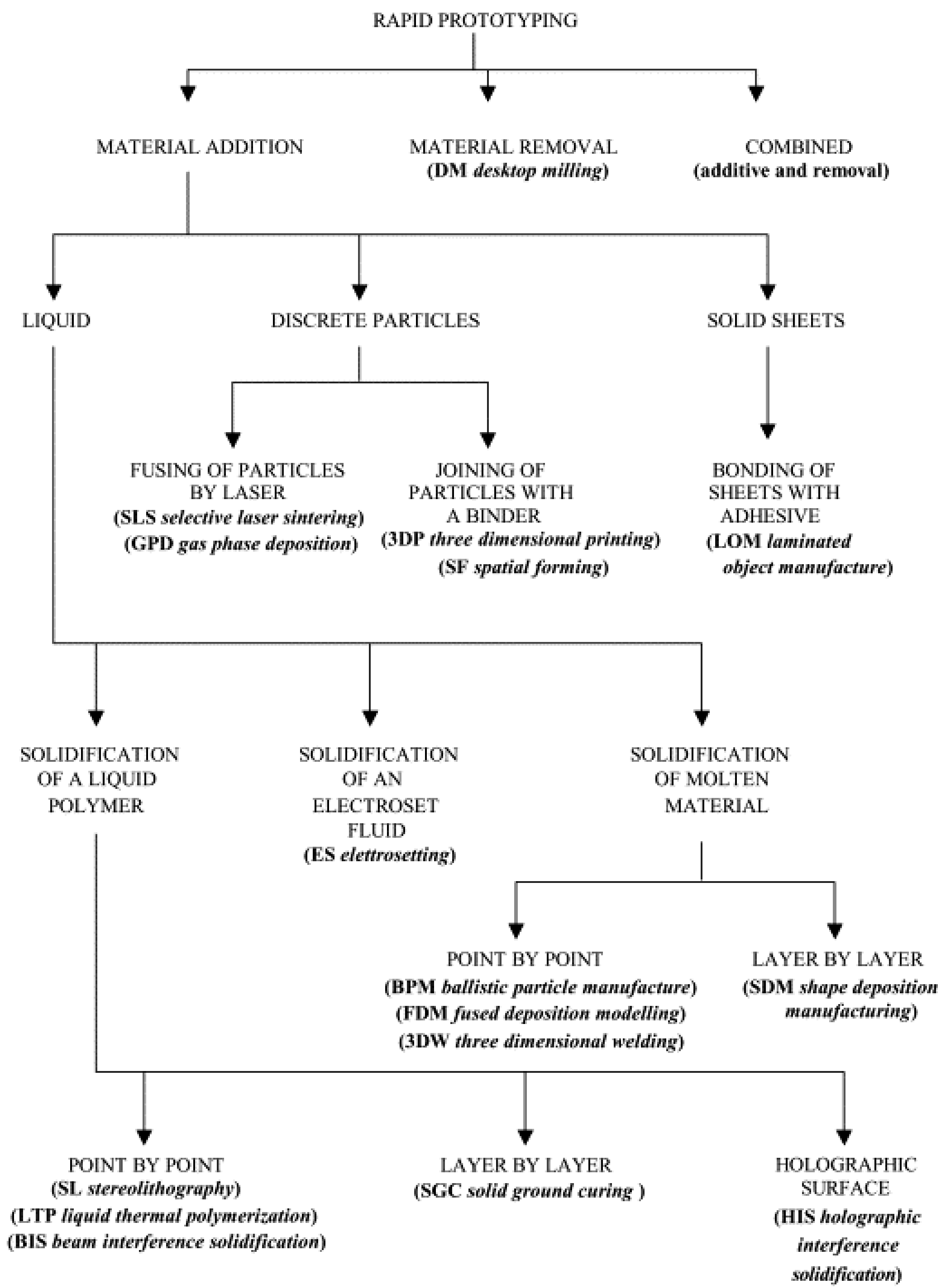

Figure 2.5 RP classifications (Kruth, 1991)

The standard interface between CAD and RP is the file format Stereolithography (.stl). This format approximates the surface of the CAD model with triangles. The more complex the surface is, the more triangles are to be produced. In general, these technologies manufacture products by adding layers of material (or laying down material) rather than by a metal removal process (i.e. machining). In essence, RP converts 3D CAD data into physical models without the need for special-purpose tooling (Zhongwei, 2004). Among the better known RP processes are Stereolithography (SL), Layered Object Modeling (LOM), Selective Laser Sintering (SLS) and Fused Deposition Modelling (FDM).

2.5.1 Stereolithography (SL)

For all RP applications, the forming material was in focus, which was developed and designed on specific forming materials. SL for instance, was based on the photopolymerization of liquid photosensitive resins induced by UV radiation. It usually consists of a liquid basin filled with liquid photosensitive resins, a mobile elevated workbench with a porous board, UV laser and a scanning system (Yongnian *et al*., 2009).

2.5.2 Layered Object Modeling (LOM)

LOM applied the “bond-then-cut” principle. A sheet was laminated to the previously laid and bonded layers by a hot roller. The roller applied heat and pressure as it rolled over the sheet which had a thin layer of thermoplastic adhesive on the down-