Title: 3D geometric and haptic modeling of hand-woven textile artifacts

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Year: 2009

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3D Geometric and Haptic Modeling of Hand-Woven Textile Artifacts

by

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B.Sc. Computer Science (Hons.)

This thesis is submitted in fulfillment of the requirements for the award of the Degree of Master of Engineering by Research of the University of Wollongong, Australia

School of Electrical, Computer and Telecommunications Engineering

Faculty of Informatics

March, 2009

" Man is the supreme Talisman. Lack of a proper education hath, however, deprived him of that which he doth inherently possess. Through a word proceeding out of the mouth of God he was called into being; by one word more he was guided to recognize the Source of his education; by yet another word his station and destiny were safeguarded. The Great Being saith: Regard man as a mine rich in gems of inestimable value. Education can, alone, cause it to reveal its treasures, and enable mankind to benefit therefrom."

Baha'u'llah

To my Mum

CERTIFICATION

I, Hooman Shidanshidi, declare that this thesis, submitted in fulfillment of the requirements for the award of Master of Engineering by Research, in the School of Electrical, Computer and Telecommunications Engineering, Faculty of Informatics, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Hooman Shidanshidi

March 2009

Acknowledgments

This thesis could not have been pursued without the undeviating support from Bahá'í Institute for Higher Education (BIHE) University, the National Spiritual Assembly of Bahá'ís of Australia and the sacrifices made by my family and friends. The facilities provided by the University of Wollongong have enabled me to achieve project outcomes using optimal resources.

First and foremost, I would like to thank my supervisor, Professor Fazel Naghdy and my Co-Supervisors, Associate Professor Golshah Naghdy and Professor D. Wood Conroy for their continued support and guidance from the very early stages of this research. They gave me the opportunity to grow and mature as an experienced researcher. I am indebted to my supervisors more they are aware. Fazel's high level of professionalism, Golshah's truly scientist intuition and Diana's unflinching encouragement made this research possible.

I would like to thank Kamran Mortezaei Farid, BIHE University's Vice-chancellor to whom I owe my success in life and to all of my professors during my study as well as my colleagues in BIHE Computer Engineering Department who have sacrificed their lives for education of Bahá'í youth in Iran. The Bahá'í Institute for Higher Education (BIHE) was founded in 1987 in response to the Iranian government's continuing campaign to deny Iranian Bahá'ís access to higher education. As such, the origin of BIHE is rooted in a spirit of purposefulness, dedication, and a belief in the power of true education. The unique circumstances surrounding BIHE, whereby professors taught without compensation, and all staff and students participated in the university at great personal risk, have unwittingly forced university to become a leader in combining on-line learning, traditional classroom instruction and preparation for a successful career.

I would like to thank Bahá'í International community and in particular the Iranian Bahá'í community. This degree would enable me to serve more efficiently my fellow Bahá'í brothers and sisters in Iran who face unrelenting religious persecution involving a wide range of human rights violations, including systematic denial of access to higher education.

I would like to thank my beloved mum for her moral support during my study and her sacrifices in bringing me up, especially after passing of my father. She has sacrificed her life for my education. Also I would like to thank my sister and other family members and friends in Iran and Australia who have always encouraged and supported me. I would also like to acknowledge my appreciation of academic, administrative and general staff in the School of Electrical, Computer and Telecommunication Engineering at the University of Wollongong.

I am truly grateful to be given the opportunity to become involved in this interesting area of research and am ever thankful to those who have helped me achieve it.

Hooman Shidanshidi

August 2009

Wollongong, Australia

Abstract

Haptic Modeling of textile has attracted significant interest over the last decade. In spite of extensive research, no generic system has yet been proposed. The majority of the haptic models developed in the previous work assume a 2D mesh model for the textile which does not represent the real geometric configuration of the textile. In addition, they are based on empirical parameters obtained from textile samples using specialized instruments. The process is often time consuming and elaborate, consisting of manual measurement of physical and mechanical properties of the artifacts. The development of a generic approach for 3D haptic modeling of hand-woven textile artifacts is pursued in this work.

In the proposed approach, the textile pattern and structure are recognized by digital processing of the artifact still image. A fuzzy-rule based expert system is developed to perform the recognition process. The data obtained in this process is employed to automatically generate the 3D geometric model of the artifact in VRML. The mechanical properties of the artifact are estimated by processing the textile geometric characteristics and yarn properties in a neural network system. These mechanical properties are then deployed in the construction of the textile mechanical model. The mechanical model is superimposed over the 3D geometric model to construct the haptic model. The proposed system is validated through both subjective and objective methods using a number of artifact samples.

An extensive review of the published literature on the haptic modeling of textile is provided in the thesis. The benefits of textile haptic modeling are identified. Applications of existing models are reviewed and the significance and unique contribution of the work is presented.

The image processing method and the fuzzy rule based expert system deployed in the construction of the geometric model are described in detail. The outcome is a 3D geometric model of the artifact in VRML which could be explored in a virtual reality world viewer. Similarly, the neural network model designed to estimate the mechanical characteristics of an artifact is presented the results of the training and validation of the model are provided.

Finally, two methods developed for the haptic model based on geometric and mechanical models in the Reachin are explained. The accuracy and effectiveness of the overall approach are validated through a series of experiments.

Overall, the work conduced in this study offers a novel 3D generic haptic modeling for textile artifacts. It can be deployed in museums providing an opportunity for the visitors to touch unique samples of hand-woven textile artifacts. The approach is cost-effective, reliable and reproducible as the haptic modeling of these samples does not need time-consuming and costly laboratory conditions.

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Chapter 1

Introduction

1.1 Overview and problem statement

Exploring the feasibility of creating a haptic rendered 3D model of textile artifacts in a virtual environment is the primary goal of this study. This will enable a user to simultaneously navigate the 3D graphical model wearing 3D glasses and touch the physical constraints of the model using a haptic interface device (Figure 1). The study seeks to develop a generic and systematic approach for both geometrical and haptic modeling of textile.

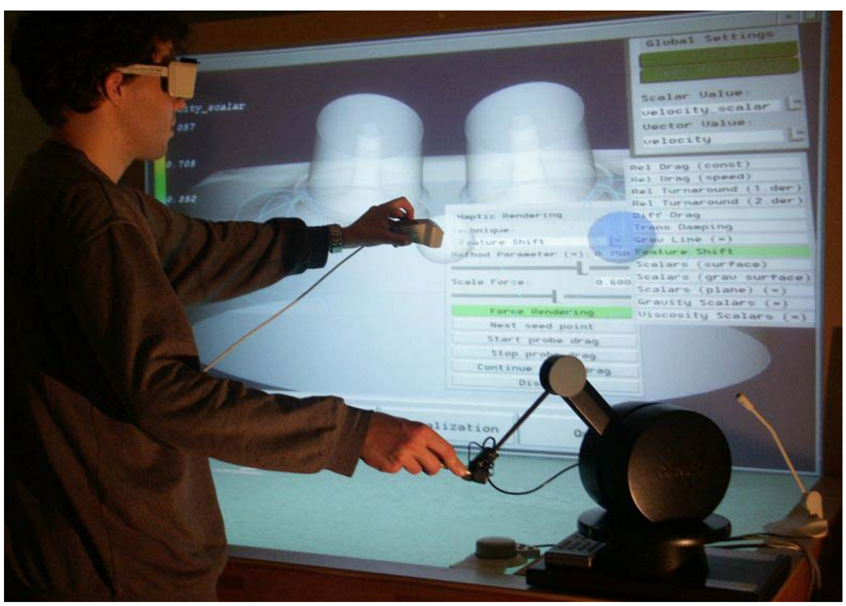


Figure 1. Virtual Reality World with Haptic Capability

Enhancing the virtual reality world by adding tactile perception and haptic modelling has been a popular area of research and has attracted significant interest over the last decade, as evident from the literature. There are more than 50 research centres and laboratories in the world working on haptic fields and about 4 or 5 of them are engaged in haptic modelling of textile. The findings and outcomes produced by these studies [1-4] will be reviewed in chapter 2 of the thesis.

The methodologies developed in the previous studies assume that the fabric has a 2D mesh structure which does not represent the real geometric configuration of the textile, especially in hand-woven textile. Figure 2 shows a typical 2D mesh structure developed widely in modelling the textile artefacts [4]. The draping graphical representation of the 2D mesh model is shown in Figure 3. These two figures are selected specifically from Haptex project [5].

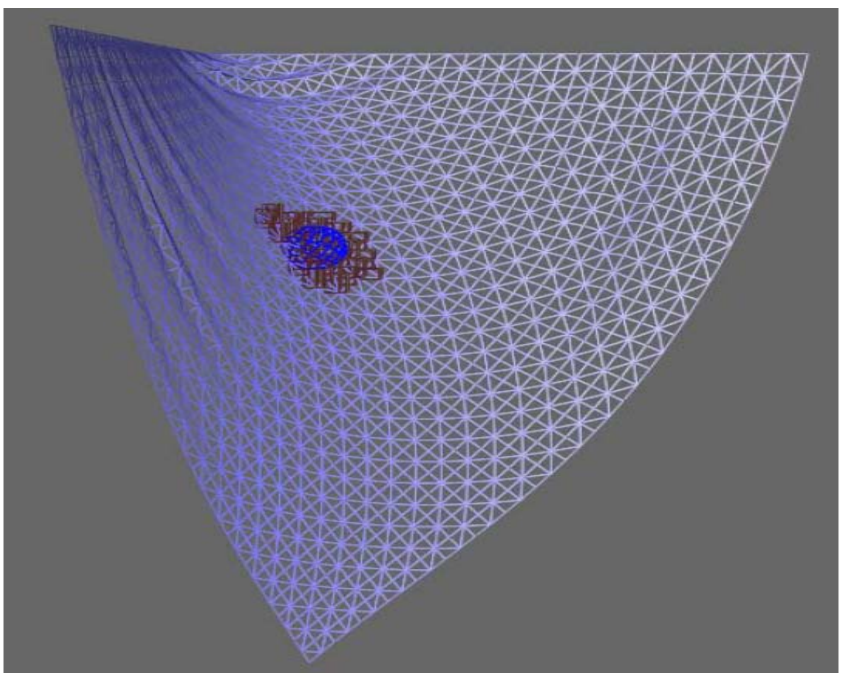


Figure 2. 2D mesh structure for modeling the textile artifact widely used by almost all of the textile representation and haptic systems [5]

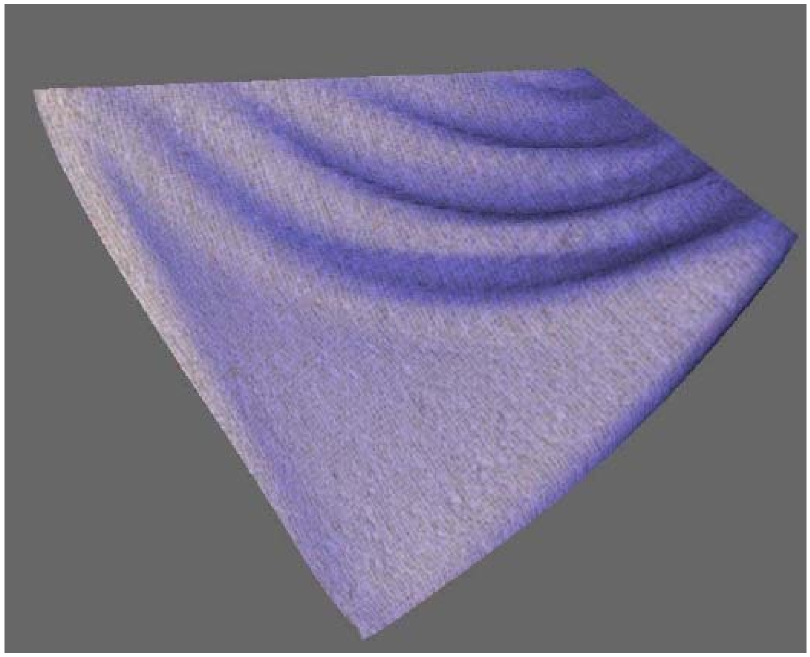


Figure 3. Typical graphic representation of a textile artifact with 2D mesh with physical simulation of draping [5]

In addition, the 2D models are developed based on empirical objective parameters, measured from textile samples. This requires time-consuming manual measurement of physical and mechanical properties of textile samples using specialised machines such as Kawabata system (Figure 4-6) and employing these measurements in building a mechanical model for haptic simulation. The process is costly, time-consuming and non-generic, requiring experts and tight laboratory conditions.

Figure 4. Kawabata Machine- Tensile and Shear tester [5]

Figure 5. Kawabata Machine- Compression tester [5]

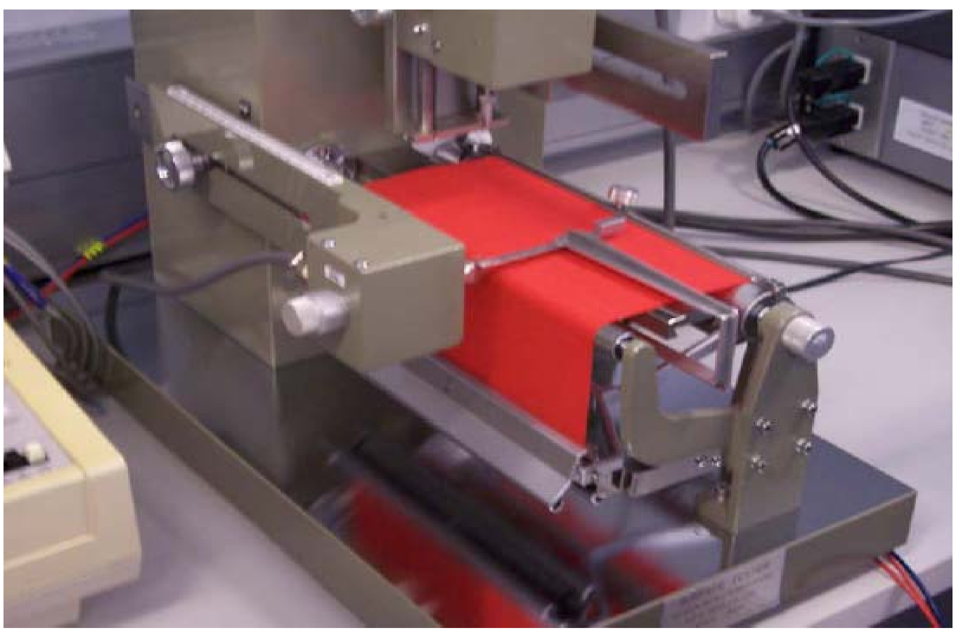


Figure 6. Kawabata Machine-Surface tester [5]

In contrast, a more generic approach based on image processing techniques, computational intelligence and a prior knowledge about the woven fabric is deployed in this work to automatically generate a 3D geometric model of a woven textile. The geometric model is augmented by the physical and mechanical model representing the haptic rendered model of artefacts in an interactive virtual reality environment.

The textile pattern and structure are identified by applying image processing techniques to the digital still image of the artifact. In order to deal with the non-linearities associated with the textile, a fuzzy rule-based expert system is deployed. This information is then used to generate a 3D geometric model of the artifact in VRML.

This information in conjunction with a prior knowledge about the yarn material and structure are fed to a neural network to estimate some of the mechanical and physical properties of the textile. The neural network learning and verification and validation processes are carried out by a sample data set. These properties are used for the construction of mechanical model.

The haptic rendered model is generated by superimposing the physical and mechanical model over the geometric model. This model has been implemented and rendered in Reachin environment. The overall model can be used in an interactive Virtual Reality environment where the user can navigate the graphic 3D presentation of the textile and touch it by a haptic device.

Finally, Different samples have been modeled and the whole approach has been validated. The primary application of the developed system will be in museums providing a tactile interaction between the visitors and textile artifacts. The interface can be provided in both in the physical environment and through the cyberspace.

1.2 Research questions

The research is driven by the following key research questions:

1. Can the key qualities of texture and touch be rendered accurately in a scalable geometric model for textile artefacts based on the weaving patterns of fabric?
2. Can a viable scalable haptic rendered model be developed for modelling the textile artifacts?

3. Can the tactile and haptic knowledge of the textile practitioner be harnessed to enhance and extend the haptic interface? Can the design of the interface be extended through the input of the tactile experts?

4. Is there a new haptic learning that will transfer into the arts and/or is there a loss of touch that will have a negative impact on a wide spectrum of material culture?

5. Can the primary haptic feelings of a woven textile (smooth, hairy, silky, or rough) be represented adequately in mimetic form through a haptic interface? Or is the sense of touch fundamentally different when experienced through magnetic impulses?

6. What possibilities are there for interactive and haptic modes in craft/design installations that may combine actual physical sensations with a computer screen?

7. Is it possible to recognize weaving pattern and yarn dimensions by applying image processing techniques to a still image? And to what extent?

8. How could weave pattern and yarn dimensions be employed for automatic generation of 3D geometric model?

9. Is it possible to estimate the physical and mechanical properties of a textile sample by applying image processing techniques to the still image? And to what extent?

10. How could these physical and mechanical properties be employed for haptic model generation and how this haptic model could be superimposed over geometric model?

1.3 Proposed haptic system architecture

The organization of the work carried out in this study is illustrated in Figure 7. The approach is inspired by the following two studies:

(a) The technique proposed by Thalmann and Bonanni [5] in 2006 and later on by Fontana in 2006 [6] for integrating the haptic model in a Virtual Reality.

(b) The model proposed by Böttcher, Allerkamp and Wolter in 2007, allowing the user to interact with the fabric using two fingers [7]. This model consists of a dual layer and two separate computational threads. The first is a low-frequency thread for dealing with the complex large scale simulation of the whole fabric surface, and an accurate particle system representation integrated with state-of-the-art numerical methods for achieving quantitative accuracy of the nonlinear anisotropic behavior of cloth in real-time. The second is a high-frequency thread for computing the local data necessary for haptic rendering and for accurately sending haptic forces back to mechanical simulation. This model also could be enhanced and employed in this research.

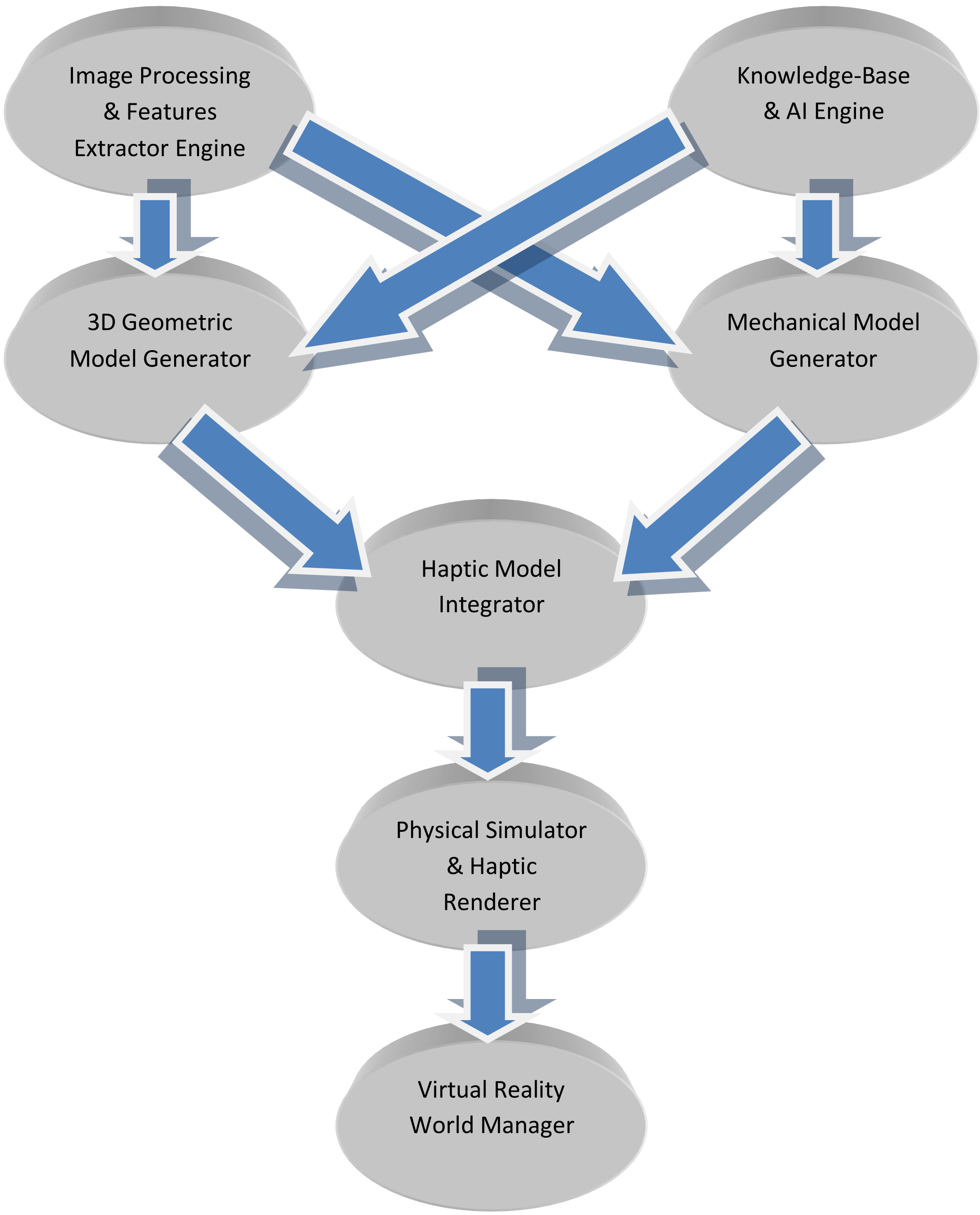


Figure 7. The haptic system architecture

1.3.1 Image Processing & Features Extractor Engine

The image Processing & features Extractor Engine Module itself consists of several parts:

Image Enhancement: This is responsible for noise reduction, filtering, data correction and simplification, and histogram equalization aimed at providing reliable data.

Pattern Recognizer: This is responsible for woven pattern recognition. A woven fabric made of the cross combination of the warp and weft yarns has a two-dimensional lattice structure[8]. The problem of fabric weave pattern recognition consists of two steps; the "crossed-points detection" which is detecting of the areas of the interlacing warp and weft yarns and "crossed-states detection" which is identifying which yarn runs over the other in these areas [9, 10]

Fabric weave pattern recognition has been a popular area of research since the mid-1980's for automatic fabric pattern recognition systems development based on image processing concepts and methods. Many different methods like neural networks [11] ,fuzzy logic [12] and Fourier image analysis techniques [13-15], have been proposed for this purpose.

The methods suggested in the literature for crossed-points detection could be categorized in two groups. The first group focuses on Fourier filtering techniques for finding periodic weave pattern in a woven fabric image by finding the peaks in the power spectrum image like [9, 13, 14] or finding the peak of autocorrelation function of the gray level data in warp and weft directions [11]. The second group obtains the crossed-points by finding the peaks in accumulation gray level values in vertical and horizontal directions pixels [12, 16].

A variety of methods have been suggested for crossed-states detection in the literature. Some examples include employing texture orientation features in each one of the detected cells [10], normalized aspect ratio of an ellipse-shaped image at crossed points of the fabric [17], Fuzzy C-Means Clustering [12, 16] and Fourier image analysis techniques [13-15, 18, 19]. The outcome of this step is a weave pattern diagram illustrating the warp over weft or weft over warp in each cell of cross points.

Nearly all the methods mentioned above can handle geometrically crisply-defined patterns and fail in processing woven fabrics which are naturally with uncertain and fuzzy patterns. The warp and weft shape and cross section can dramatically change especially in hand-woven fabrics due to variable yarn structure and compression and elasticity forces in the fabric structure. The work carried out in this study has resulted in the development of an effective method for flexible modeling of the textile. This novel approach is based on fuzzy rule-based and Fourier image analysis for automatic nondeterministic pattern recognition of the woven fabrics.

Textile Features Extraction: This stage is responsible for extracting textile features from the still image which could be deployed in modeling the physical and mechanical parameters like roughness, friction, compression estimation. Neural Networks, Fuzzy Expert Systems, and other methods will be examined to find the best approach for this step.

1.3.2 Knowledge-base & AI Engine

This module is responsible for utilizing the prior knowledge about textile pattern and its martial, to enhance the features extracted from image processing and building the 3D geometrical and mechanical models more accurately and realistically. Fuzzy rule based-systems and neural networks are employed in this module.

1.3.3 3D Geometric Model Generator

This module is responsible for generating a 3D geometric model of textile sample with data provided by the previous stage. There are various methods proposed in the literature [20, 21] for 3D geometric modeling of textile. The approach pursued in his study is different as it seeks an automatic model generation in the context of haptic rendering and virtual reality world requirement.

1.3.4 Mechanical Model Generator

This module is responsible for generating a mechanical model of textile sample with data during pattern recognition process. As described earlier, current scope of the project covers static representation of the textile and not its dynamic drape behavior. Therefore only the mechanical and physical properties of the textile which are required in static model including friction, roughness and compression are estimated in this stage. Many analytical and hierarchical models are available for prediction of mechanical properties which could be employed for design and implementation of this module. As an example, Shigeru Inui et al. have developed a system based on real textile weave structure rather than point mass or continuous body models [22]. The proposed algorithm estimates the mechanical behavior of the textile. However no physical justification has been provided for the method used to estimate the mechanical properties. The proposed model is static and resembles a CAD model rather than a real textile simulation.

Leaf and Anandjiwala proposed a general mechanical model for plain woven fabric [23] which could be used for estimating textile mechanical properties analytically. Sinoimeri and Dr´ean suggest a more reliable model based on energy methods for mechanical behavior modeling of plain textile in 1997 [24]. More information about textile and its mechanical modeling could be found in [25, 26].

1.3.5 Haptic Model Integrator

This module is responsible for integrating the geometric model and mechanical model in the haptic model. The haptic model will be developed within Reachin [27] environment. The Reachin scene graph has proved to be a more powerful and suitable tool for this stage of the project.

1.3.6 Physical Simulator & Haptic Renderer

This module is responsible for haptic rendering and textile physical simulation. The textile simulation method offers accurate real-time simulation of the nonlinear anisotropic viscoelastic properties of cloth materials. It is used in large-scale simulation of full cloth objects in the context of haptic applications. It combines access to simulation data (particle position, velocity, force and Jacobian) for interfacing with the haptic simulation framework, and collision detection query procedures (detection of cloth mesh elements in proximity of given locations).

The major challenge in the development of this module is to find the best compromise between the high requirement for mechanical accuracy (quantitative accuracy with anisotropic nonlinear strain-stress behavior) and the drastic performance requirements of real-time and interactive applications.

While the visual motion of the global cloth object can be computed with frame rates of about 25 Hz for achieving realistic visual feedback, realistic haptic interaction requires at least 1 kHz for rendering properly the mechanical effect of the user interaction and the force feedback. A complete survey of all the methods is provided in the literature review.

1.3.7 Virtual Reality World Manager

This module is responsible for the management of the entire virtual reality world. It checks the user interactions with the textile and sends them to simulator and haptic renderer. This module also provides the textile graphic representation and allows the user to navigate simultaneously the world graphically and haptically. It makes it also possible to access the world remotely through web.

1.4 Thesis scope

This thesis is structured into 6 chapters. In Chapter 1, an overview is presented, highlighting the motivation behind the work as well as its objectives and scope.

An extensive review of the published literature relating to haptic modeling of textile is undertaken in Chapter 2. The focus of the work is on textile tactile perception in a virtual reality environment. As such, different stages of implementation are reviewed in the context of the previous work. Various approaches deployed in geometric and mechanical modeling of textile artifacts are considered, including haptic simulation of fabric hand, haptic sensing of virtual textiles, sensation simulation through sensory evaluation, subjective assessment of fabrics in haptic modeling, fabric hand modeling in haptic systems, textile physical simulation in haptic systems, haptic model generation with image processing techniques and applied psychological and tactile perception. The advantages of textile haptic modeling are identified. Applications of existing models are reviewed and finally the significance and unique contribution of this work are presented.

Textile geometric modeling is discussed in chapter 3. The basic weave patterns, yarn structure and the geometric modeling of hand-woven artifacts are discussed and the current textile pattern recognition methods reported in literature are reviewed. These methods cover crossed-points detection which deals with interlacing areas between warp and weft yarns and crossed-states detection which is concerned with which yarn is over the other in the interlacing areas. A new generic and non-rigid method for artifact pattern recognition is proposed, implemented and tested. The approach is based on image processing, Fourier image analysis and fuzzy rule-based system. Finally based on the features extracted in the pattern recognition, a generic approach for generating the geometric model is proposed, implemented and validated. This method creates a 3D geometric model of the artifact in VRML which could be explored in a virtual reality world viewer.

Chapter 4 is dedicated to textile mechanical and physical modeling. Fabric hand, subjective and objective methods of its evaluation and factors affecting fabric hand are discussed. Subsequently textile mechanical and physical properties are investigated and a summery of literature review of textile mechanical and physical modeling is given. The design of the neural network model for estimating the physical/mechanical properties of the textile is described. The neural network is trained and validated and the physical/mechanical model is generated according to the output of the neural network.

The development of the textile haptic modeling is addressed in chapter 5. A comparative study of different haptic devices and haptic implementation platforms has been carried out. Reachin programming environment is chosen for this project. Reachin APIs in the framework of this work are discussed and subsequently the haptic model implementation in Reachin is reviewed. Two different methods for textile haptic modeling based on Reachin built-in facilities are developed. The complete model is validated and its efficiency over other two methods is demonstrated through experimental work.

A critical analysis of the strengths and shortcomings of the work and its major contributions is carried out in chapter 6. There are also some recommendations provided for future extension of the work.

Chapter 2

Background

2.1 Introduction

Haptic modeling of textile has attracted significant interest over the last decade. Haptic rendering requires adding the physical and mechanical properties of an object to its geometric representation to make tactile perception of the object possible. In a haptic system, the interacting forces and torques are derived from a computer haptic model. These signals are used to drive a haptic device which in turn generates tactile sensing for the user.

Haptic sensing is the first one among the senses developed in a human embryo. The reproduction of this sense in a virtual reality has, however, been a challenging task and has a long way to go before it reaches maturity [28] . Traditionally two senses are modelled in a Virtual Reality including visual perception and the hearing. The next challenge is to integrate other senses, most notably the haptic and tactile sensing which permits feeling the presence of an object. This is in contrast to more traditional approaches of Virtual Reality in which only visual and acoustic sensations are deployed. This is especially critical when objects such as textile artifacts are manipulated.

Since 2000, many significant research projects have been reported in the field of haptic modelling of textiles. There are more than 50 research centres and laboratories in the world working on haptic fields but only 4 or 5 of them are engaged in haptic modelling of textile. The findings and outcomes produced by these studies have been considered in the literature review carried out in this project to identify state of the art in this area and significance of the project.

Although each project addresses a different problem such as the architecture of haptic devices, the real-time simulation engines, haptic modelling and others, the majority of them are developed based on objective measurement of textile samples characteristics. This requires time-consuming manual measurement of physical and mechanical properties of textile samples using specialised machines such as Kawabata system and employing these measurements in building a mechanical model for haptic simulation. The process is costly, time-consuming and non-generic, requiring experts and tight laboratory conditions.

In addition, most of the graphic systems and fabric physical simulation engines deployed in the current haptic systems, consider textile as a 2D mesh structure which does not represent the real geometric configuration of the textile, especially in hand-woven textile. This simplification may be necessary in some applications such as real time simulation of textile drape. However, in interactive Virtual Reality representation of hand woven textiles the 3D geometric configuration is significantly important.

The findings and outcomes produced by the previous work will be reviewed in this chapter to identify state of the art in this field and the significance of this study.

2.2 Haptic simulation of fabric hand

The *Fabric Hand* of a cloth or garment is defined as the overall fabric quality perceived through operations such as touching, squeezing, or rubbing [29]. Many factors affect the Fabric Hand including flexibility, compressibility, elasticity, resilience, density, surface contour (roughness, smoothness), surface friction and thermal characteristics of the fabric. The properties of the textile raw material, yarn structure, planner structure (woven or knitted pattern) and finishing treatment could be employed in a model for predicting the fabric hand and its factors [30]. In many industrial applications, manual objective assessment methods employing Kawabata machine [31] or subjective assessment are being utilized for fabric hand assessment rather than analytical models.

Haptic rendering of textile is based on simulating the fabric hand of a cloth or garment by adding its physical properties to the geometric visualization of the fabric in a full Virtual Reality world where user can explore a 3D visual model of the textile and touch it by using haptic devices simultaneously.

The feasibility of simulating fabric hand has been studied by a joint research project carried out from 2000 to 2008, by a consortium of universities including Philadelphia University, California State University, University of Pennsylvania, Rutgers University, and the State University of New Jersey with the leadership of Prof. Muthu Govindaray (School of Textiles and Materials Technology, Philadelphia University). The research aims at developing a virtual fabric handling experience using a haptic display. In the current commercial online systems, the drape of a garment can be visualized, but the 'hand' of the fabric can not be experienced. The fabric hand is simulated in this work to provide the user with a feel of the fabric as well as observing its drape [1].

A Kawabata KES-F system is deployed to measure the surface characteristics of fabric which results in a force profile for each sample. The surface and friction properties have been measured as semi-periodic signals and denoised by applying wavelet analysis to them. Different wavelet filters and bi-orthogonal spline three tap wavelet with eight coefficients were selected. The two signals (warp and weft) with noises removed were padded to generate two three-dimensional profiles in either direction. Fourier convolution has been applied to combine the two orthogonal surface profiles to reconstruct the 3D surface profile of the fabric. This 3D profile has been used as their model. A special force feedback haptic device called PhilaU which is a combination force feedback and a tactile display has been also developed. The device consists of a feeler pad at the end of an articulated arm. An array of pins (tactors) is mounted on the feeler pad which provides a virtual textile touch and feel.

As mentioned before, the approach adapted is quite time-consuming and costly, limiting the laboratory validation of the project. The reports provided also do not indicate how the static 3D profile has been used in the haptic model. In addition, the developed approach is only applicable to static modeling and can not handle any dynamic behavior based on Physical simulation using textile mechanical properties. The static model itself is limited to 3D profile of the surface and friction and not other surface properties. The current development of the project has its focus on interface device rather than enhancing the algorithm which is rather primitive and is not suitable for real applications [32].

2.3 Haptic sensing of virtual textiles

HAPTEX (HAPtic sensing of virtual TEXtiles) was funded by the European Commission within the Sixth Framework Programme (2002-2006). The HAPTEX Project Consortium consists of the Organizations shown in Table I.

Table I - Organizations forming HAPTEX

ORGANIZATION	***SHORTNAME***	***ROLE***	***STATE***
MIRALab - University of Geneva	UNIGE	Coordinator	Switzerland
University of Exeter	UNEXE	Partner	United Kingdom
Scuola Superiore Sant'Anna	PERCRO	Partner	Italy
University of Hanover	UHAN	Partner	Germany
Tampere University of Technology	SWL	Partner	Finland

This is a visionary fundamental research project, whose final objective is the analysis and development of a first Virtual Reality platform towards realistic visual-haptic real-time rendering of computer generated textiles [33]. The projects technical reports, published research papers, a movie of the final demonstration, and other documents are available on the project website [5]. The project and its outcomes have been documented in several fundamental reports [4, 33-37].

The textile haptic model architecture deployed in Haptex project has been described by Sasedo et al, in a seminal paper [94]. They have investigated different models for physical simulation and mechanical modeling of textiles in the context of real time computation and high accuracy for effective tactile perception in a haptic system. Non-linearities such as visco-elasticity and hysteresis which are exhibited by the material itself in the stress-strain characteristic cannot be neglected in general in a realistic rendering. This makes it impossible to pre-calculate the stiffness matrix before the simulation. Therefore a multi-resolution approach for achieving the tradeoff between speed and accuracy is proposed. It consists of two models: a coarse model (Large Scale Model) for the whole fabric and a fine model (Small Scale Model) for the portion of the fabric that is close to the fingertips.

The Large Scale Model (LSM) represents the whole simulated piece of fabric. Since it is composed of a large number of nodes, it can achieve a relatively low refresh rate (>20Hz). The Small Scale

Model (SSM) is connected to the Large Scale Model through a Norton Equivalent Impedance. Since it consists of few nodes, it can achieve a high refresh rate (>500Hz). The SSM evaluates the reaction forces that have to be exerted on the user by the Force Feedback Device (FFD) and the operational conditions of the contact (relative velocity and pressure) to be sent to the Tactile Renderer that in turn generates the driving signals for the Tactile Feedback Device (TFD). The large scale model uses a mesh with low number of nodes and simulated by a mass-spring model without exact modeling of all non-linear behavior of the textile. The small scale model uses a particle model with a mesh with high number of nodes and a particle model for estimating the non-linear behavior of the textile [95]. The fundamental research undertaken by the HAPTEX project varies from the real-time physical based simulation of textile to the design and development of novel tactile and force-feedback rendering strategies and interfaces.

A major shortcoming of the study is that a 2D textile surface model is assumed which is not the real case, especially in haptic modeling. In addition, many of the physical and mechanical characteristics of the textile such as non-linear visco-elasticity and hysteresis are ignored to improve the real-time performance of the model. The measurements obtained from the Kawabata machine are modeled using the well-known polynomial fitting. Overall, the approach and the modeling approach are compromised to achieve real-time performance. However this method of textile simulation has not been proved to be the best method for fabric simulation as it will be discussed later in the section on the mechanical modeling literature review.

2.4 Sensing the fabric: to simulate sensation through sensory evaluation

Subjective assessment of fabric hand is the heart of the research which has been carried out by Dillon, Moody et al. in Liverpool John Moores University [2]. This is an initial investigation of textile industry into developing and refining current fabric/textile simulation and interface design triggered by increasingly awareness of the textile industry of the need to enhance sensory experience in virtual reality navigation. The interaction takes place through a Wingman Mouse.

A subjective fabric hand evaluation experiment has been designed. In this experiment a female expert investigates the samples in well-defined conditions with 3 different statuses, visual and touch, without sight (blindfolded) and visual only. Twenty two different parameters such as stiffness, Roughness, and Grainy are estimated and given a score of 1 to 15 (e.g. For roughness 1=smoothest and 15=roughest). The qualitative measurements are then mapped to some physical properties, directly or indirectly. The Immersion application is then calibrated based on the measured parameters to provide realistic feel of the fabric surface. Various experiments have been conducted to get a better understanding of the parameters which affects the measurement and judgment. In later stages of the project, a PHANTOM haptic device is deployed for more accurate haptic navigation.

The study is heavily dependent on subjective evaluations rather than haptic modeling of textile. In addition, there is no explanation presented on how subjective measurements are mapped on physical properties. This probably is the main drawback of the approach. The study is quite focused on static mechanical model based on subjective evaluation and does not contribute much towards the haptic modeling or real time issues.

2.5 Subjective assessment of fabrics in haptic modeling

Subjective evaluation of fabrics for haptic systems has been employed by Luible, Varheenmaa and Thalmann [38] in 2007. They have designed a new subjective evaluation experiment based on AATCC (American Association of Textile Chemist and Colourists) guidelines and standards towards haptic system requirements. The mechanical fabric properties included in the study are Tensile properties, Shear properties, Bending properties, Compression properties, Surface properties and Weight property. They are estimated by subjective evaluation of Bending, Shear, Tensile, Roughness, Friction, Compression and Weight of 10 samples.

The validity of the developed model is not verified through experimental methods. Some explanation is however provided on the process of mapping subjective measurements to mechanical and physical properties.

The last two studies have opened a new direction for subjective evaluation of a textile in haptic systems. Generally, haptic modeling based on subjective assessment requires extensive time and laboratory conditions which are not applicable in real problems. On the other hand, the accuracy of these models has not been completely investigated and there is no comparison between objective and subjective evaluation in the context of haptic modeling of textile. In addition, due to difference in tactile perceptions between different ages, sexes and cultures, these models could not be generalized.

2.6 Fabric hand modeling in haptic systems

There are some studies reported in the literature on the fabric hand and its modeling in the context of haptic systems An example is the HAPTEX project [39] in which a mapping is defined between Kawabata machine output and the fabric hand as a qualitative sensation. However there are many ambiguities in this mapping. The process of sample collection in HAPTEX project and the objective assessment of them show the inefficiency of this costly and time-consuming method.

2.7 Textile physical simulation in haptic systems

Raymaekers et al. have carried out a study on the issue of collision detection in haptic modeling of textile [40]. Based on this study, some effective numerical integration methods are proposed.

Their research has been followed by the work carried out by Volino et. al. [41]. A comparison study on textile simulation engines in haptic domain has been performed by this group. Current methods for fabric simulation such as finite elements, particle models and mass-spring models (as a specific particle model) have been investigated. Subsequently, a new real-time fabric simulation system which offers a compromise between a realistic physically based simulation of fabrics and a haptic application with high requirements in terms of computation speed is proposed. The emphasis is on architecture and algorithmic choices for obtaining the best tradeoff in the framework of haptic applications.

The main challenge of both researches which have been used in HAPTEX project is polynomial fit of Kawabata machine which make their simulation input quite complicated for real time applications. The proposed particle model is also not accurate for most of the data imported from Kawabata machine, making the process incomplete. There are a number of questions unanswered. If the accuracy of haptic modeling of textile requires exact complicated data from

Kawabata machine, why have most of the data been neglected in simulation engine in favour of speed? If the efficiency of the simulation engine and its real-time behavior is important, why have they used the complicated costly Kawabata measurements?

The proposed fast particle mode model cannot produce the exact viscoelastic modeling of textile. In order to achieve real-time performance, some compromises have been made such as ignoring bending stiffness or avoiding self-collision within the fabric which plays a significant role in realistic textile behavior.

In practice, this study shows that the accuracy of Kawabata is too high for simulation in real time. Hence, alternative methods which can provide adequate accuracy, a more realistic model, and less computing intensity are required. The approach pursued in this study is designed in this direction.

The same research group has carried out further work [42] and developed an alternative model [43], combining the accuracy of continuum surface mechanics with the versatility of particle system. The new model has proved to be more efficient as illustrated by the comparison they have carried out against a first order finite elements continuous model of their system.

2.8 Haptic model through image processing

The closest research to the approach proposed in this study is the study conducted by Peinecke, Allerkamp and Wolter at university of Hannover [44]. The focus of that work is on presenting a new method for automatically generating tactile input from optical scans. Standard image processing techniques such as Hough transforms have been applied to the gray scale image of a textile sample. The Tsai and Shah algorithm has been then applied to generate a height map from the 2D texture primitive. The results are used to build a 3D shape model of the textile surface. Finally PHANTOM device is programmed using high level developer's kit to simulate and render the haptic static model of the sample.

The model is validated by comparing it against the result of the same procedure with Kawabata machine carried out by Huang [45]. A subjective evaluation experiment was designed in which 12 individuals initially touched 7 objects with different characteristics with a pen like Phantom device's pen. Then they touched the same samples with Phantom haptic device with the model generated by Kawabata machine. This experiment was repeated using the model obtained automatically from the image. The statistical analysis showed that the automatic model was almost as effective as Huang model.

The main drawback of the approach is that it offers a surface height profile model rather than a real 3D geometric model of the textile. Moreover, no mechanical model of the samples, even the surface physical properties like friction or roughness have been considered. In addition, their modeling algorithm can be only applied to simple textile samples as it cannot analyze textiles with patterns, different colored yarns or complicated weave structure.

2.9 Psychological and tactile perception

The handling of the textiles produces a set of mechanical stimulations acting on our haptic sensory system (constituted by exteroceptive sensors, like the mechanoreceptors located in the skin, and the proprioceptive sensors located in the muscles, tendons and articulations). These stimulations create a corresponding response (sensation) in these sensors that is interpreted by our brain that in turn is able to evaluate the properties of the textile. From the technical point of view, it is central to understand which kind of mechanical stimulation are really relevant for the assessment of a specific textile property. The analysis of the state of art of the available knowledge has been confined to the understanding of the mechanism underlying the perception of only the properties of the textiles most relevant to the assessment of the fabric hand.

Glabrous (smooth) skin contains various populations of mechanoreceptors: pacinian receptors and three types of non-pacinian receptor as demonstrated in Figure 8. These differ in terms of their frequency response. In order to evoke a wide range of “realistic” touch sensations, an array must operate over a significant fraction of the tactile frequency range of, say, 10 to 500 Hz. Vibratory stimulation in the upper part of this frequency range (approximately 100–500 Hz) is expected to stimulate pacinian receptors predominantly. Stimulation at lower frequencies is expected to stimulate nonpacinian receptors predominantly. The proposed design for the stimulator arrays in the HAPTEX project has a nominal bandwidth of 25–400 Hz.

please see print copy for image

Figure 8. Skin mechanoreceptors, (from NEUROSCIENCE [Purves et al., 2001])

Allerkamp et al. in their paper "Tactile Rendering: A Vibrotactile Approach" [28] have suggested a new approach to the problem of haptic modeling of textile which is more in line with the perspective of applied psychology. They have based their model on the function of tactile receptors in human skin i.e., Pacinian and non-Pacinian receptors which can be stimulated by vibrations. To produce appropriate excitation patterns, they used an array of vibrating contactor pins similar to the color model in computer graphics.

They considered the textile as a 2D surface as a property map which for the first try, they assigned the height profile of the textile to it. Then they used the well-known methods in image processing for estimating the height pattern from a grey value image of the textile. Then by applying the movement of the fingerprint over the surface, they generated the function of time. They also calculated the frequency spectrum of the function and decomposing it to two base frequencies 40 and 320 (empirical numbers) which have been considered as the frequencies for stimulating skin Pacinian and non-Pacinian receptors. Then they used synthetically generated Brownian surfaces with varying fractal dimensions generated by the frequency patterns from previous step as their Vibrotactile rendering strategy. They validated their model with constant finger's movement over the surface and with employing PHANTOM haptic device.

In addition, they have proposed a new haptic device array with 24 contactors over the fingertip. Although their approach is innovative, there are some drawbacks as the human skin receptors are sensitive to wide ranges of frequencies rather than 2 base frequencies.

Their model is not real time and needs finger movement over the surface and the time dependent function to be calculated offline. They have not suggested any online real time method for this process. Their proposed haptic device has not been manufactured yet completely and it seems very complicated to be produced for real industrial applications. The modeling is restricted to the surface height and roughness and not other physical and mechanical properties of real textiles.

They have followed this approach and proposed a more complete model with wider frequency rate [46, 47].

2.10 Conclusion

In contrast to the previous studies, this work will bridge the identified gaps. Pattern recognition techniques are applied to a still image of a woven textile sample. The yarn dimensions, woven pattern and structure and the parameters of sample surface are measured. This information is used to generate a 3D geometric model of the sample. A haptic model is then generated and superimposed on the geometric model.

At this stage, the haptic model has been limited to static representation and not dynamic drape modeling. The physical parameters like friction, roughness, compression, etc are estimated through image analysis rather than shear, bending, etc which are not relevant in hand-woven tactile experience.

In summary, the approach proposed in this study explores innovative concepts which have not been deployed in the previous work including:

1. Automatic estimation of textile physical and mechanical parameters and yarn dimensions woven pattern recognition through analysis of still image of the textile and application of computational intelligence methods.

2. Automatic 3D geometric and mechanical model generation for woven textile haptic rendering instead of manual objective assessment.

3. Utilizing hand-woven textile 3D geometric representation instead of 2D mesh which has been widely utilized in physical simulation and graphic presentation of textiles.

Chapter 3

Textile Geometric Modeling

3.1 Introduction

Textile has a complicated structure made of the cross combination of the warp and weft yarns in a two-dimensional lattice configuration. Different yarn material and weave patterns have been used in textile industry resulting in wide textile structures. Such complexity in textile structure, makes textile geometric modeling challenging. The textile geometric modeling and its graphical representation have been studied for more than 2 decades. Different approaches have been developed. Although most of them consider textile as a 2D mesh which the mechanical characteristics of draping is computed with different methods like finite-elements or mass-spring systems. In this work, the textile is modeled as a 3D geometric object which is essential in hand-woven artifacts where the third dimension is naturally significant.

On the other hand, specific data like weft and warp yarn structure and dimensions and the weave pattern are required for each artifact sample to build the 3D geometric model. Manual data acquisition for each sample is a time-consuming process and needs experts and laboratory conditions. The non-deterministic structure of the artifact also makes the manual assessment not accurate with some possible errors in measurement. Therefore pattern recognition methods have been developed for automatic artifact pattern recognition in favour of providing necessary data for 3D geometric model generation stage.

In this chapter, the textile structure, textile pattern recognition methods and textile 3D geometric modeling techniques proposed in this study, are reviewed.

3.2 Textile structure

Textile has a complicated structure made of cross combination of the warp and weft yarns in a two-dimensional lattice configuration. Different yarn material and weave patterns have been used in textile industry resulting in wide textile structures. Such complexity in textile structure makes it challenging to form textile geometric models. The textile perspective of yarn structure and weave patterns is discussed in following sections.

3.2.1 Weave patterns

The textile artifact is woven from two sets of yarns, vertical yarns called warp and horizontal yarn called weft. All the weave patterns are based on three basic weave styles which are the fundamental blocks for other complex styles. However the knitted artifacts structures are not discussed here and these styles are applicable to woven artifacts.

3.2.2 Plain weave

This is the simplest weave and is accordingly inexpensive to make. It is a symmetrical interlace where the warp and weft fibres alternately pass over one another. This style creates a stable cloth which wears well but has very poor drape.

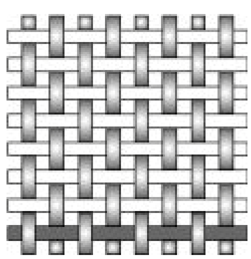


Figure 9. Plain Weave

3.2.3 Twill

Twill is similar to plain weave except the warp and weft fibres repeatedly pass over or under two to four weft fibres. This trend continuously repeats to create a symmetrical pattern. Compared to plain weave twill has superior drape, is slightly less stable than plain weave and is a smoother material.

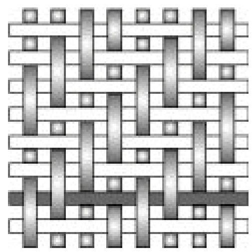


Figure 10. Twill

3.2.4 Satin

Satin is similar to twill weaves in that the warp passes over or under multiple weft. The weft however does not reflect the same pattern. A satin design is described by a 'harness' number which states the number of weft fibres crossed over or under. Satin weaves have very good drape and can be woven tightly.

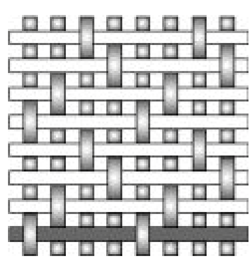


Figure 11. Satin

3.2.5 Yarn structure

Yarn is composed of fibres which are either staple or filament length. All natural fibres except silk are staple length fibres. Silk and manmade fibres could be staple or filament length. Fibre size is specified in terms of diameter or linear density. Finer fibres result in smoother and more flexible yarn and subsequently to more beautiful drape of fabric. On the other hand, the fibre length affects the smoothness of the yarn. Longer the fibre and smaller the fibre length distribution, the smoother will be the spun yarn. The cross-sectional shape of the fibre affects the smoothness of the yarn as well.

Filament yarns are categorized in two classes: monofilament which has one filament and multifilament yarn which has many filaments. In apparel fabrics, the multifilament yarns are usually used. Multifilament yarns with more filaments (finer) are much less stiff than multifilament yarns containing fewer filaments (coarser). Flat multifilament yarns are yarns in which the filaments are straight and well-aligned with the yarn axis and are the smoothest of all types of yarns. Textured yarn is a generic term given to the filament yarns with greater apparent volume which is achieved through physical, chemical or heat treatments or a combination of these and give a fabric more pleasant hand, fabric become warmer and softer.

Properties of yarns and of fabric made from them are influenced by the degree of twist in the yarn. As the twist is inserted, the fibres or filaments come closer to each other. High twist gives greater bending stiffness. In plied yarn, i.e. two or more single yarns twisted together, the stiffness is increased compared to single yarns [35] .

3.2.6 Considerations in hand-woven artifacts geometric modeling

These are two main considerations related to hand-woven artifact geometric model generation:

1) Artifact Weave and yarn structure pattern recognition and dimensions measurement
2) 3D graphic model generation based on artifact patterns and dimensions recognized in first step.

As it has been mentioned before most of the current textile physical simulation and haptic systems consider a textile artifact as a 2D mesh structure which is suitable for real time simulation but not accurate enough for hand woven textile artifact which has 3D structure with apparent yarn waving in horizontal and vertical axis. For more precise model, the real 3D structure of the artifact should be considered.

On the other hand, specific data like weft and warp yarn structure and dimensions and the weave pattern are required for each artifact sample to build the 3D geometric model. Manual data acquisition for each sample is a time-consuming process and needs experts and laboratory conditions. Also the non-deterministic structure of the artifact makes the manual assessment not accurate with some possible errors in measurement. Therefore pattern recognition methods have been developed for automatic artifact pattern recognition in favour of providing necessary data for 3D geometric model generation stage.

In following sections, steps taken in haptic modeling of hand-woven artifacts are explained and the developed algorithms and methods are introduced.

3.3 Textile pattern recognition

A woven fabric made of the cross combination of the warp and weft yarns has a two-dimensional lattice structure. Fabric weave pattern recognition based on computer image processing techniques has attracted many researchers since the middle of 1980's. Many different methods such as neural networks [11], fuzzy logic [12], Fourier image analysis techniques [13-15], etc have been proposed for this purpose which many of them have been successfully employed in research laboratories and small applications.

The problem field could be divided to crossed-points detection which deals with interlacing areas between warp and weft yarns and crossed-states detection which is concerned with which yarn is over the other in the interlacing areas [9, 10].

Different approaches have been proposed to deal with both problems. The developed approaches, however, have proved to be inadequate to deal with the non-rigidity of the hand-woven artifacts.

Different methods suggested in the literature for crossed-points detection can be categorized in two groups:

(a) Employing Fourier filtering techniques to find periodic weave pattern in a woven fabric image by either identification of the peaks in the power spectrum image [9, 13, 14] or finding the peak of autocorrelation function of the gray level data in warp and weft directions [11].

(b) Identifying the peaks in accumulation gray level values in vertical and horizontal directions pixels [12, 16].

A variety of methods have been suggested for crossed-states detection in the literature including employing texture orientation features in each one of the detected cells [10], normalized aspect ratio of an ellipse-shaped image at crossed points of the fabric [17], fuzzy c-means clustering [12, 16], and Fourier image analysis techniques [13-15, 18, 19]. The outcome of this stage is a weave pattern diagram showing the warp over weft or weft over warp in each cell of cross points.

However these methods are rigid and are inadequate to model real woven artifacts which are naturally non-rigid and nondeterministic. This rigidity in previous methods is demonstrated in Figure 12. As it can be seen the recognized pattern is like a table with linear yarn edge which is not the real case in hand-woven artifacts. The warp and weft yarn shape and cross section change dramatically specially in hand-woven fabrics due to variable yarn structure and compression and elasticity forces in the fabric structure. This non-linearity should be considered in pattern recognition.

A new flexible model is developed in this project. This method is based on fuzzy rules and Fourier image analysis for automatic nondeterministic pattern recognition of the woven fabrics. This approach will be discussed later in following sections.

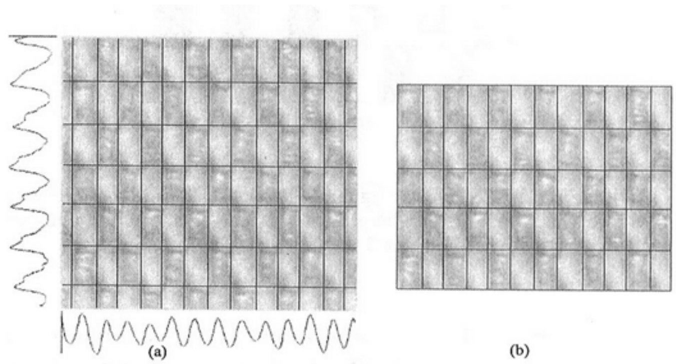


Figure 12. Traditional deterministic methods for Crossed-points detection with fixed and straight shape assumption for warp and weft yarns

3.4. Background and literature review

Kinoshita et al. [8] are among the first who have investigated textile pattern recognition in 1989 and proposed the primitive image processing techniques for woven pattern recognition. These techniques almost employed by other researches as discussed in detail in this literature review.

Ravandi and Toriumi have applied Fourier-Transform for pattern recognition of textile in 1995 [14] Protruding yarns influence a fabric's properties and its end use. This paper discusses a new approach to measuring fabric appearance objectively using image processing techniques by Fourier transform analysis. Characteristics of the fabric surface such as directionality, density of yarns protruding from the fabric body, and periodicity of weft and warp yarns (yarn spacing) for plain-weave cotton fabric are discussed. The protruding yarn density obtained in this study correlates with those from previous work by spectral analysis of dynamic friction in the fabric surface. This new approach is regarded as a useful method for estimating protruding yarn density on fabric surfaces. Through the angular Fourier power spectrum, changes in protruding yarns due to wear are evaluated for yarns spun by different systems such as air-jet, core-spun, opened, carded, and combed.

Xu has suggested FFT for identifying fabric structure [13]. The Fast Fourier Transform (FFT) plays a very important role in image processing and pattern recognition. Since a woven fabric consists of regular repeating units, the FFT is particularly useful for analyzing periodicity, directionality, and spacing of repeating units in the fabric. This paper describes procedures for applying FFT techniques in image processing to identify weave pattern, fabric count, yarn skewness, and other structural characteristics of woven fabrics. A color scanner is used to digitize fabric images (two-dimensional functions in a spatial domain), and a customized software package is used to apply the FFT to the images. A power spectrum image is derived from the FFT of an image, and considered a two-dimensional function in a frequency domain. Peaks in the power spectrum image stand for frequency terms of periodic elements, from which basic weave patterns (e.g., plain, twill, satin, etc,) can be recognized. A radial function and an angular function, derived from the power spectrum, are used to measure the coarseness and directionality of the periodic elements. By selecting power peaks in a certain direction to reconstruct the image, warp or weft elements can be extracted to facilitate fabric count and skewness measurements. Fourier filtering, that is, image filtering in the frequency domain, is used to suppress noise and to select features that have a certain range of frequencies. Fabrics with various weave patterns and yarn counts are tested using the FFT techniques.

Campbell and Murtagh suggest a two-stage defect detector [15] and refer to automatic inspection of woven textile fabric. A two-stage detection process is adopted, with the second stage involving a set of novel contextual decision fusion techniques. Three significant problems are addressed:

a) Texture feature extraction: Fourier transform features are found to be well matched to the spatially periodic nature of the woven pattern
b) Detection of localized flaw patterns: since it is impossible to estimate prior probabilities and to enumerate all defect classes, a Neyman-Pearson approach is adopted. This is a flaw detection via measured deviation from nominal
c) Detection of extended flaw patterns: the most common flaws are characterized by linear or other cluster shaped patterns. Although these are weakly detectable by local detectors, they may be ignored when local detector sensitivity is set to achieve tolerably low false-alarm rates. A local-extended contextual decision fusion technique using morphological filtering will produce very low composite false-alarm rate.

The performance of the system is evaluated on samples of denim fabric containing real defects. The predicted composite false-alarm rate is of the order 1 in 10 (13), or equivalent to 1 per 100 km of fabric roll. Experimental results demonstrate the compatibility of this favorable false-alarm rate with the reliable detection of flaws, which have been chosen for their subtlety and detection difficulty.

Jeong and Phillips have done a study on predicting fabric-drape behavior with image [48] which shows how image processing techniques could be employed for estimating the physical and mechanical properties of the textile.

Kang, Kim and Oh have proposed a method [17] to utilize computer image processing and analysis for designing a system to detect both weave patterns and yarn color. The image of a woven fabric is captured by a Hitachi color CCD camera and converted into digital data by a Targa+32 board. Two images-transmitted and reflected-are used to detect weave patterns. From the transmitted images, warp and weft cross points and the sizes of the yarns are determined by analyzing gray value changes in both horizontal and vertical directions. Then the warp and weft crossed states are determined by analyzing the normalized aspect ratio of an ellipse-shaped image at crossed points of the fabric. Furthermore, from reflected images, the total number of yarn colors and their arrangements in the fabric are determined. An HSV color model differentiates or groups similar yarn colors. Consequently, the system allows the weave pattern, either colored or solid, and the color design of a fabric to be correctly recognized.

Huang, Liu and Yu carried out another research in 2000 for the same purpose [49] . Their image processing method could be employed for woven fabric analysis and identification of weave patterns. An image processing approach was proposed for identifying weave patterns of woven fabrics and automatically displaying harness drafts and chain drafts. Fabric counts are also measured. Based on the maximum and minimum gray-level sums of the horizontal and vertical pixel lines over an entire image, yarns and their crossover points were located. The decision rules for recognizing warp and weft floats are developed on the basis of geometric features of yarn distribution. The experimental materials include plain, twill, and satin weaves, each with twenty samples. They have also conducted some experiments to demonstrate that the three basic weave patterns can be distinguished from each other. The computer measurements of fabric counts show good agreement with manual measurements

Lin has proposed a method of applying a co-occurrence matrix to automatic inspection of weaving density for woven fabrics [50] The efficiency and accuracy of an approach to detect a fabric's weaving density using a co-occurrence-based method is described. Three basic fabrics weave structures-plain, twill, and satin-are evaluated by this method. Based on the co-occurrence matrix algorithm, the weaving density of a plain weave structure is accurately computed. The method used to process image feature extraction; the co-occurrence-based method, is one in which a feature parameter (the contrast parameter or CON) is obtained. It consists of contrast measurements involving sixty-four spatial displacements (i.e., 1-64) and two directions (0 and 90 degrees) of fabric images used for calculation. The results show that the calculation precision for the plain weave is far better than that for the twill and satin weaves.

Rallo, Escofet and Millan have suggested a new method to extract information about the fabric structure by image analysis [19]. Two descriptions of the image of a web structure including a convolution model and an additive model, in both the spatial and frequency domains, are combined in the design process. The method allows the extraction of the conventional and also the minimal weave repeats, their size in terms of number of threads, their interlacing patterns, and their patterns of repetition. The method can be applied to fabrics with square and non-square conventional weave repeat. Experimental results with images of real samples are presented and discussed.

Joen et al. [11] have suggested a neural network system for automatic pattern recognition of textiles. A neural network and image processing technique are introduced for classifying woven fabric patterns. An autocorrelation function is used to determine one weave repeat of the fabric. The reflected fabric image is captured and digitized by the computer system. The learning vector quantization algorithm as a learning rule of the artificial neural network enables recognition of woven fabric types more effectively. The results demonstrate that three fundamental weave types can be classified accurately, and structural parameters such as yarn spacing, its variance, and the ratio of warp spacing to weft spacing can also be obtained.

Kuo et al. [12] suggest fuzzy C-clustering for the same purpose. A new robust recognition algorithm is proposed for fabric weave pattern recognition. The gray-level images of solid woven fabrics a. re captured by a color scanner and converted into digital files, then enhanced images are obtained by a gray-level morphological operation. Based on the interstices of yarns, warp and weft crossed areas are located, and four texture features of these areas are obtained by first-order and second-order statistics. Unsupervised decision rules for recognizing. warp and weft floats are developed using a fuzzy c-means clustering method. The experimental materials include plain, twill, and satin woven fabrics. Experimental results demonstrate that three basic weave patterns can be clearly identified.

Celik, Ucar and Ertugrul carried out a study to determine spirality in knitted fabrics by image analysis [51] which shows the efficiency of image processing techniques in this area.

Jeong and Jang applied some image analysis to automatic inspection of fabric density for woven fabric [52] The gray line-profile method has been introduced to find fabric density. Some patterned fabrics like stripe design as well as solid fabrics of basic weave structures have been used to verify the efficiency and accuracy of the method. The approach was compared with Fourier transform method. Although the gray line-profile method is concise, it shows good results in both solid and patterned fabrics. In addition, it does not require a pre-processing or filtering technique in space or frequency domain to enhance the image suitable for the analysis. However, the approach is slightly influenced by the filter size for finding the local minimums of profile graph.

Lachkar et al. have proposed a pattern recognition method for crossed-section and crossed-states detection in 2003 and 2005 [9, 10].

Kuo and Tsai have proposed an approach to texture analysis which could be used to recognize the fabric nature and type of the main weaving texture [18]. First, the color scanner captures the fabric image and saves it as a digital image and then the wavelet transformation is used to display the image texture. The co-occurrence matrix is then be applied to calculate the texture characteristics, such as angular second moment, entropy, homogeneity, and contrast, The learning vector quantization networks (LVQN) are finally adopted as a classifier to categorize the fabric nature and the type of weaving texture. The experimental result shows that this approach could automatically and accurately classify the fabric nature, including woven fabric, knitted fabric and non-woven fabric, and the type of its main weaving texture, such as plain, twill or satin weave, single or double knitted and non-woven fabric.

Kuo and Kao have proposed a neural network system for automatic recognition of color texture fabric nature [53]. The method of recognizing color texture proposed in this study employs unsupervised learning network to automatically recognize the fabric type and the main texture types. Firstly, the color scanner is adopted to extract fabric image which is afterwards saved as the digital image. Secondly, CIE-Lab color model is taken to obtain the feature value and wavelet transform is utilized to display the texture of the fabric image. Thirdly, co-occurrence matrix is employed to figure out the feature values of the texture structure such as angular second moment, entropy, homogeneity, contrast. Finally, self-organizing map (SOM) network is used as the classifier. The experimental results show that the study can automatically and accurately classify the fabric types (including shuttle-woven fabric, jersey fabric and non-woven fabric) and main texture type of the fabric (such as plain weave, twill weave, satin weave, single jersey, double jersey and non-woven fabric).

3.5 Proposed method for textile pattern recognition

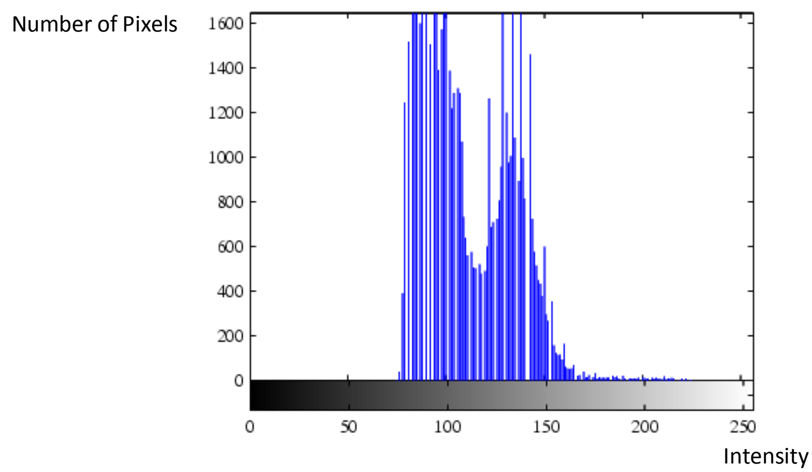
As it has been mentioned the current pattern recognition algorithms are not suitable for hand-woven artifacts. Therefore, a new method based on a fuzzy rule based expert system is developed to overcome these shortcomings. The whole process could be divided to three phases: Image Enhancement, Crossed-points detection and Crossed-states detection. Following sections summarize each one of the phases.

The artefact samples are scanned with a scanner at 300 DPI and 24 bits colour depth. The digital images are used in the consequent steps.

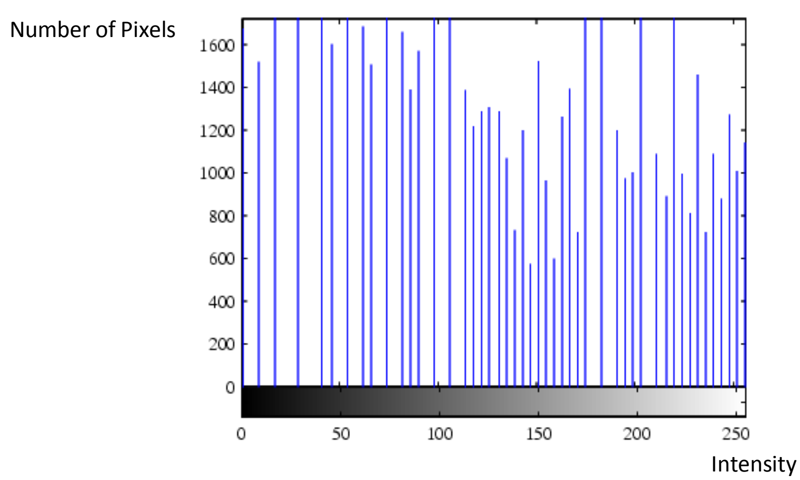
3.5.1 Image enhancement

The colour image is converted to gray-scale for process. Median and low-pass filters are then applied to the image to reduce noise and enhance the image quality. The median filter determines the value of an output pixel by the median of the neighborhood pixels. This filter reduces sample noises without reducing the sharpness of the image which is necessary for edge detection in next steps. The low-pass filter removes the high frequency noise which generally occurs in artifact sampling. The parameters of the filters were tuned manually for the best result.

The histogram equalization was then applied to the filtered image to enhance the image contrast. Figure 13 shows a sample histogram after and before equalization. As it is demonstrated the intensity range in first histogram is narrow and just covers a fraction of the potential range [0, 255]. The histogram equalization method spread the intensity values over the full range as it could be seen in second histogram after operation.



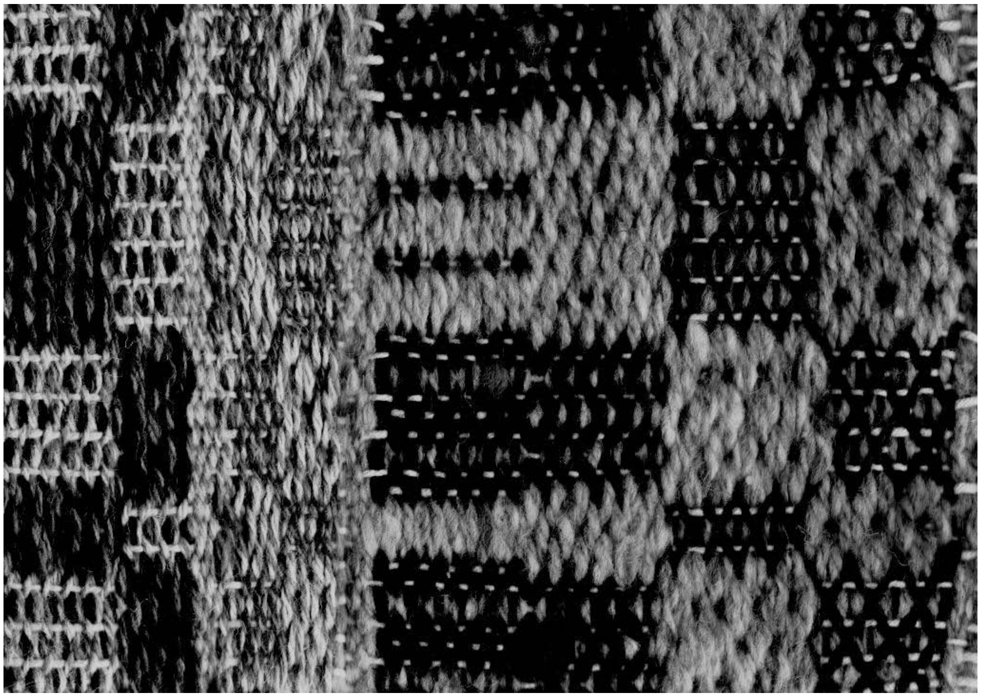
a)



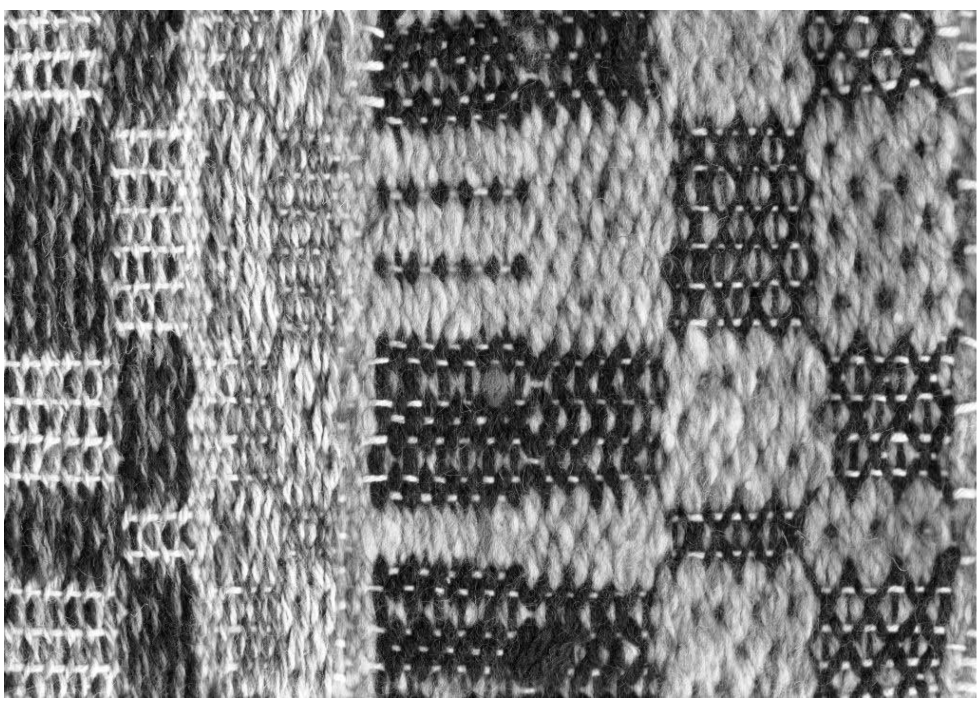
b)

Figure 13. Image histogram a) before and b) after equalization

Figure 14 shows a sample before and after enhancement phase.



a)

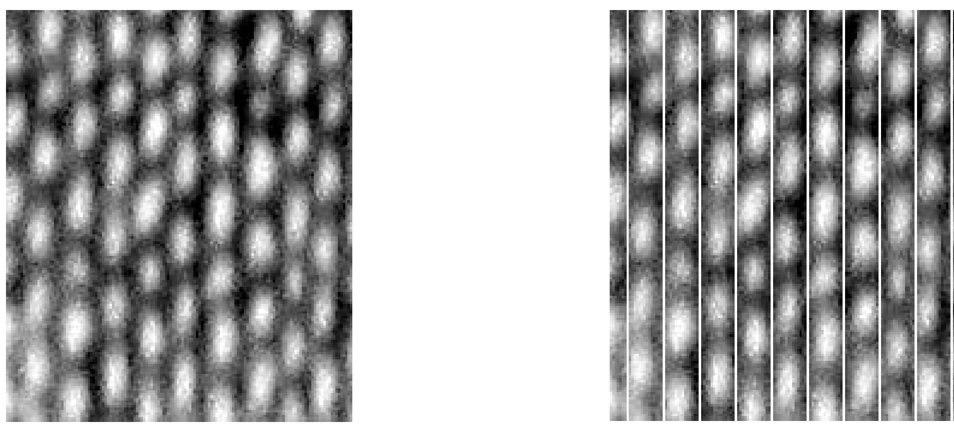


b)

Figure 14. a) Original gray-scale image b) Image enhancement output

3.5.2 Crossed-points detection

As it was mentioned earlier the conventional methods of crossed-points detection are too rigid to recognize the hand-woven artifacts patterns. The main method which used in this phase is based on finding the peaks of autocorrelation function of the gray level data in warp and weft directions. The autocorrelation function is the accumulation of gray level values of pixels for each column and row of the image. Due to darkness of valleys between two neighboring yarns, the minimum peaks of the autocorrelation function is expected to be located on the yarns edge. This method would work if the yarns are straight and the shapes of the patterns do not vary across the artifact. An example of such case is shown in Figure 15. This hypothesis, however, does not hold for hand-woven artifacts as the warp and weft yarns shape changes dramatically. An example of such case is illustrated in Figure 16.



a) b)

Figure 15. a) A textile sample with almost straight and fixed-shape yarns b) Result of yarn edge detection by finding the peaks of autocorrelation function which is successful in this case

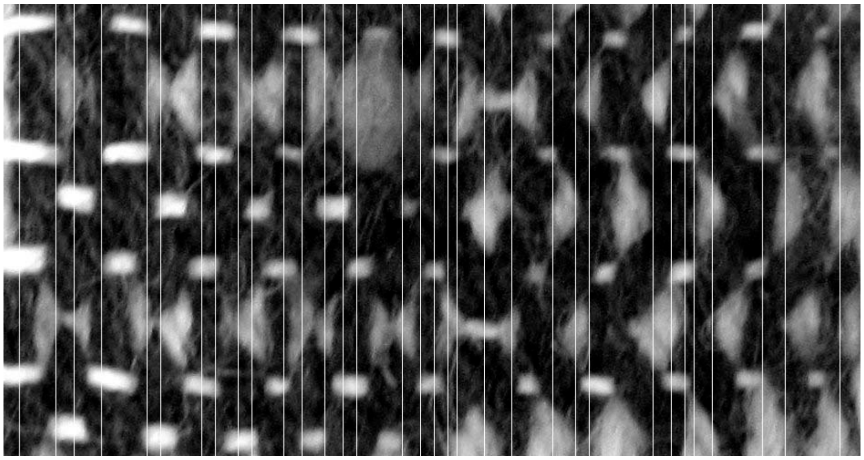


Figure 16. Inefficiency and rigidness of finding the peaks of autocorrelation function in a complicated hand-woven artifact

In order to overcome this problem, a novel flexible piecewise-linear method is introduced to cater for the non-linearities present in the variable structure of the fabric. In this approach, the image is sliced horizontally and vertically. The width of the slice is determined empirically. It is assumed that the yarn shape is almost fixed in each slice, the same assumption in calculus when the derivation is calculated for a specific point on a curve. Then the autocorrelation function is calculated for each vertical and horizontal slice. The minimum peaks in each slice shows the yarn-sections edges.

Figure 17 demonstrates the way the horizontal and vertical slicing is done. The first slice and its autocorrelation curve are shown.

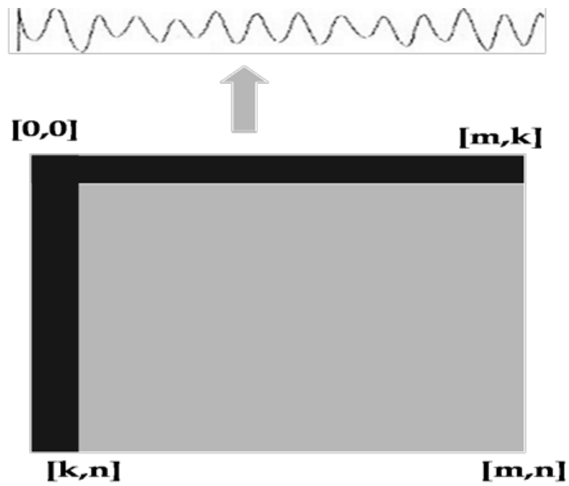


Figure 17. The horizontal and vertical slicing and the corresponding horizontal autocorrelation curve

While ideally, the minimum peaks of the autocorrelation show the yarn border in that section, variation in artifact pattern sometimes results in false peaks. Hence, a special filter is developed to identify real peaks in the yarn boarder. Figure 18 illustrates this filtering mechanism.

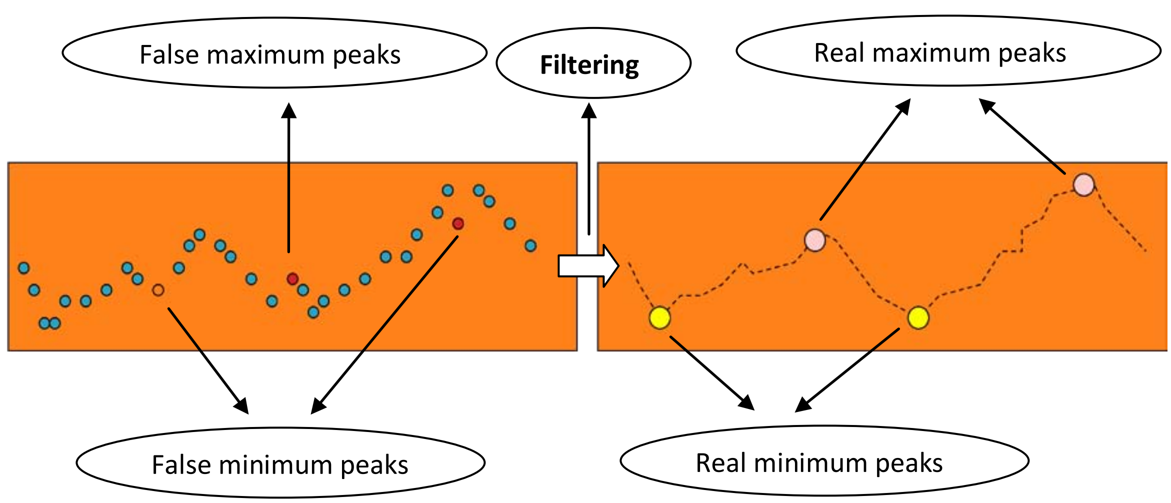


Figure 18. Intelligent filtering mechanism for removing the false peaks and picking the real peaks

In addition, a mechanism is also required to locate the corresponding points in different slices belonging to one specific yarn boarder. At this stage, some peak points might be merged as one point or some might be identified as false peaks.

Accordingly, a fuzzy rule based algorithm is developed to perform the following actions:

1) Local Filtering: filtering the false maximum and minimum peaks and pick up real peaks in each slice.

2) Global Combination: Merging some close points as one point and removing false points based on the global knowledge of the whole artifact rather than only a slice.

3) Edge Detection: locating corresponding points in different slices which belong to a specific yarn boarder.

For this algorithm to work effectively, the maximum peaks of the autocorrelation function should be also calculated. It is expected that a max peak should be seen between two sequential minimum peaks which presents somewhere on top of the yarn where the light is maximum due to yarn convexity.

Figure 19 demonstrates the Global Combination mechanism. The distance is described by a distance fuzzy variable and merging of the points is carried out by the algorithm.

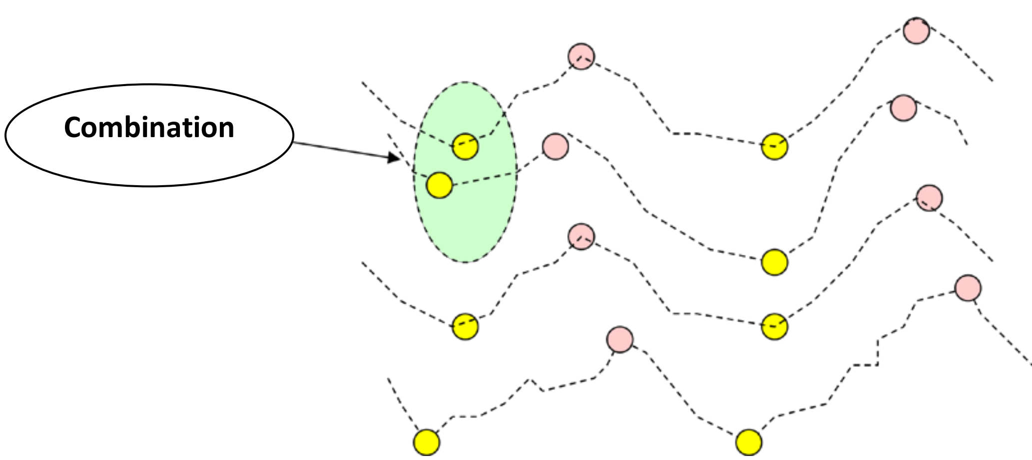


Figure 19. Global combination mechanism

Figure 20 shows the edge detection mechanism which locates corresponding points in different slices belonging to a specific yarn boarder. This mechanism searches for the points as a backtracking algorithm in a tree structure. It starts from the bottom left minimum peak in the artifact and finds different paths of closest points based on their fuzzy distance. The mechanism continues by considering next points recursively. This process creates a virtual tree. The fuzzy algorithm selects a path in the tree from root to leaves with the best estimation as a yarn boarder. The selected points are removed from the feature point set and the mechanism continues from next bottom left point. The algorithm ensures that a maximum peak point curve is located between two neighboring yarn boarders.

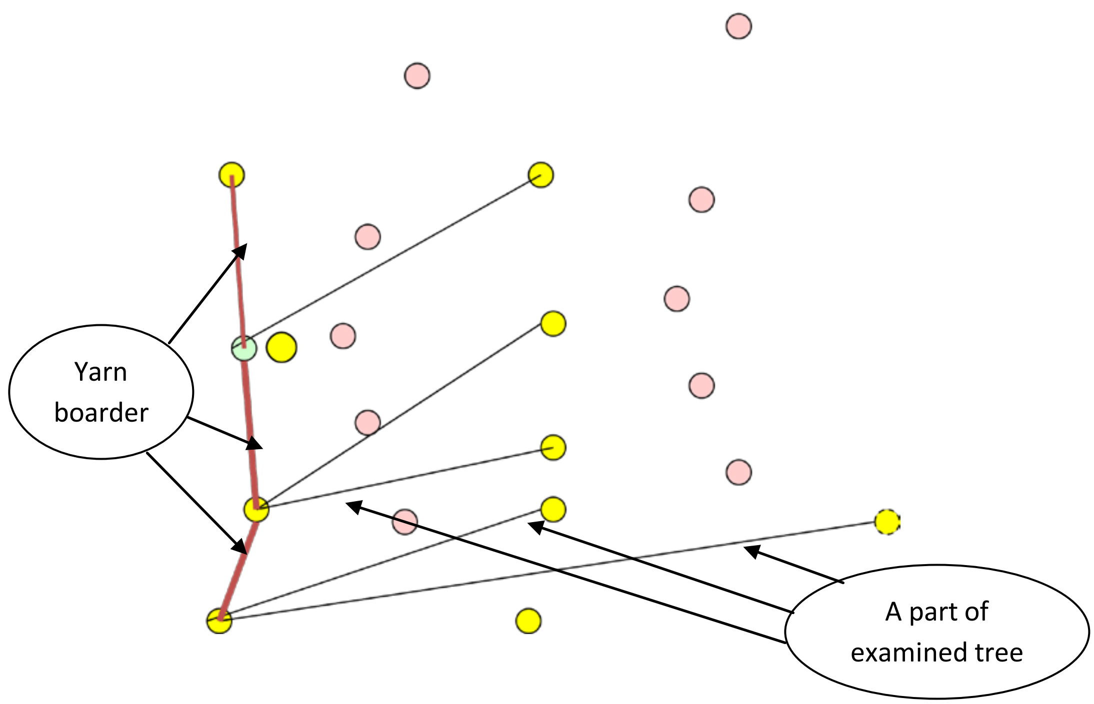


Figure 20. Edge detection mechanism

The following mathematical model is used to find the peak points. The image matrix ω_{m*n} is sliced horizontally and vertically. The image slices SV_i in vertical and SH_i in horizontal directions are defined as elements of ω matrix which is represented by a '_' operator in following equations, where k is the thickness of the image slice:

$SV_i = \omega_{i*k,0} \_\omega_{i*k,n}\_ \omega_{(i+1)*k,0} \_\omega_{(i+1)*k,n}$ (1)

where $0 \leq i \leq \left\lceil \frac{m}{k} \right\rceil - 1$

$SH_i = \omega_{0,i*k} \_\omega_{m,i*k}\_ \omega_{0,(i+1)*k} \_\omega_{m,(i+1)*k}$ (2)

where $0 \leq i \leq \left\lceil \frac{n}{k} \right\rceil - 1$

By considering the $\Omega_{x,y}$ the gray level conversion function of the pixel in position x and y, α_i a vector with m elements as the accumulating gray level values for vertical slice i, SV_i could be calculated as:

$$\alpha_{i,j} = \sum_{z=0}^{k} \Omega(SV_i^{z,j}) \quad (3)$$

For $1 \leq j \leq n$

And the same for β_i a vector with n elements as the accumulating gray level values for horizontal slice i, SH_i:

$$\beta_{i,j} = \sum_{z=0}^{k} \Omega(SH_i^{j,z}) \quad (4)$$

For $1 \leq j \leq m$

Finally, Feature point set μ_{vi} for vertical slice *i* and μ_{hi} for horizontal slice *i* are calculated as below:

$$\mu_{vi} = \{ p | p \in \min(\alpha_i) \} \tag{5}$$

For $1 \leq i \leq m$

$$\mu_{hi} = \{ p | p \in \min(\beta_i) \} \tag{6}$$

For $1 \leq i \leq n$

The recursive backtracking procedure to find yarn edge sets *warp*$_i$ and *weft*$_i$ by employing the following Fuzzy Rule-Based Engine:

Select the point p with minimum x from μ_{h0}

Find_edge(p,warp$_i$*)*

{

For each i $\in$ *{ 1,…n}*

{

Find the distance of p with the feature points in μ_{hi}

Fuzzify the distances based on ***distance*** *fuzzy set degree of membership*

Calculate the gradients of each connection lines between p and feature points set μ_{hi}

Choose ***f;*** *the feasible feature points set in slice i based on fuzzy rules and edge gradient paradigm*

For each ***p, a*** *member of* ***f;*** *call the find_edge (p, warp*$_i$*) procedure for slice i+1*

}

}

The yarn boarder gradient pattern is known and could be used for predicting the yarn edge path in tree structure (Figure 20). This gradient prediction is illustrated in Figure 21. The short lines indicate the gradients of the edge curve. The narrow cross sections show the locations where weft and warp are floating over each other. The shape is changing due to friction forces and compression in these areas. Finding the next point in the path has to satisfy the gradient pattern and the fuzzy rules.

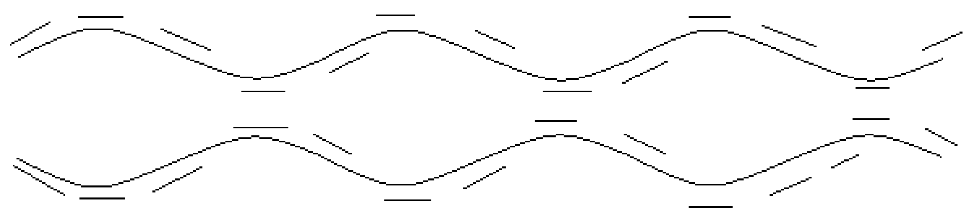


Figure 21. Gradient pattern for yarn boarder

The *distance* fuzzy variable membership function is shown in Figure 22. The Fuzzification of the distance is carried out by calculating the distance of point *p* relative to all the points in slice i+1 and normalizing the distances between 0 to 1. The fuzzy set consists of very small, small, small-medium, large-medium, large and very large values.

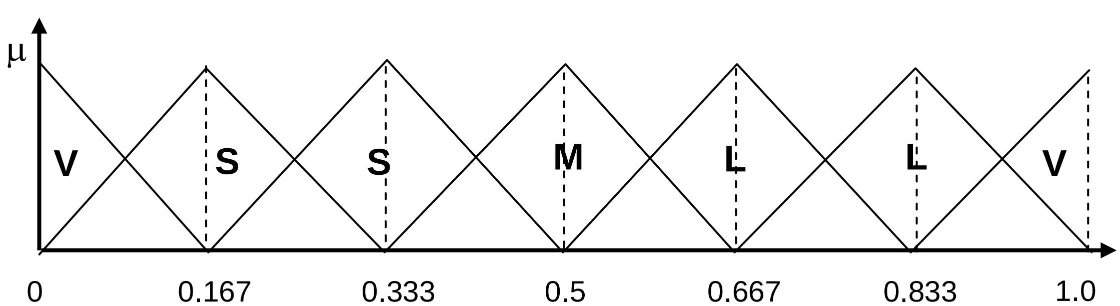


Figure 22. The distance fuzzy variable membership function using for fuzzification

The fuzzy rules for the system categorize in three groups. The following is the detail of these groups and some sample rules of the expert system in each one.

Local Filtering rules filter the false maximum and minimum peaks and pick up real peaks in each slice. The feature extractor engine calculates the peaks, evaluates their fuzzy distance and then feed them to fuzzy expert system. The local filtering rules in expert system are as follow:

1) If minimum peaks distance is VS then combine them

2) If minimum peaks distance is S then combine them

3) If minimum peaks distance is SM and the distance of maximum peak between them to the mean point of minimum peaks is VS then combine them

4) If minimum peaks distance is SM and the distance of maximum peak between them to the mean point of minimum peaks is S then combine them

5) If maximum peaks distance is VS then combine them

6) If maximum peaks distance is S then combine them

7) If maximum peaks distance is SM and the distance of minimum peak between them to the mean point of maximum peaks is VS then combine them

8) If maximum peaks distance is SM and the distance of minimum peak between them to the mean point of maximum peaks is S then combine them

Global Combination rules combine some close points as one point and filtering some noise points based on the global knowledge of the whole artifact rather than only a slice. The global combination rules in expert system are as follow. These rules are applied to each point (minimum and maximum peaks).

1) For all points in VS distance of the point combine them as one in the center of gravity.

2) For all points in S distance of the point combine them as one in the center of gravity.

3) If the gradient difference of connection line between the point and the last point in SM distance in bottom and the next point in SM distance in top is more than S then tune up the position of these three points in gradient direction VS units

Edge Detection rules locate corresponding points in different slices which belong to a specific yarn boarder. These rules are applied to the feature points to create the tree structure for backtracking search and also finding the edge path from root to the leaf. The tree generation and backtracking mechanism has been addressed before. Some sample rules for value HIGH for probability fuzzy variable are described follow. There are similar rules for other fuzzy values.

1) If the gradient difference of connection line to the next point in the path and current path is VS and both of them are positive and the distance of these points is S, add the new point to the path with HIGH probability

2) If the gradient difference of connection line to the next point in the path and current path is S and both of them are positive and the distance of these points is S, add the new point to the path with HIGH probability

3) If the gradient difference of connection line to next point in the path and current path is VS and both of them are negative and the distance of these points is S add the new point to the path with HIGH probability

4) If the gradient difference of connection line to the next point in the path and current path is S and both of them are negative and the distance of these points is S, add the new point to the path with HIGH probability

5) If the gradient difference of connection line to the next point in the path and the current path is S and the current path gradient is negative and the connection line gradient is positive and the there is a choice for next path with positive gradient in tree, add the new point to the path with HIGH probability

6) If the gradient difference of connection line to next point in the path and current path is S and the current path gradient is positive and the connection line gradient is negative and there is a choice for next path with negative gradient in tree, add the new point to the path with HIGH probability

The engine then finds the highest probability for the yarn edge and remove the selected points from the point set. Finally for all the points in each $warp_i$ or $weft_i$ a quadratic spline interpolation is applied which formulates a curve for yarn edge rather than a fixed line in conventional methods.

After finding all the yarn edges in vertical and horizontal axis, the space between two neighboring yarns should be recognized. The space is determined by finding the pixels surrounded the yarn edge with intensity less than a threshold which is calculated empirically and based on the average intensity of the artifact sample.

The whole model and algorithms are developed in Matlab and tested for 21 samples. Figure 23 shows the whole process applied to two small pieces of hand woven fabrics referred to by a and b. Indexes 1 to 4 represent the following stages, respectively:

1. The original scanned images of textiles

2. Textile image with its vertical and horizontal feature points after local filtering and global combination

3. First iteration of fuzzy rules implication for yarn edge detection

4. Final step of fuzzy rules implication for yarn edge detection. The white color shows the space between two neighboring yarns. The non-linear nature of the algorithm is well represented. The yarn's edge is produced by quadratic spline interpolation.

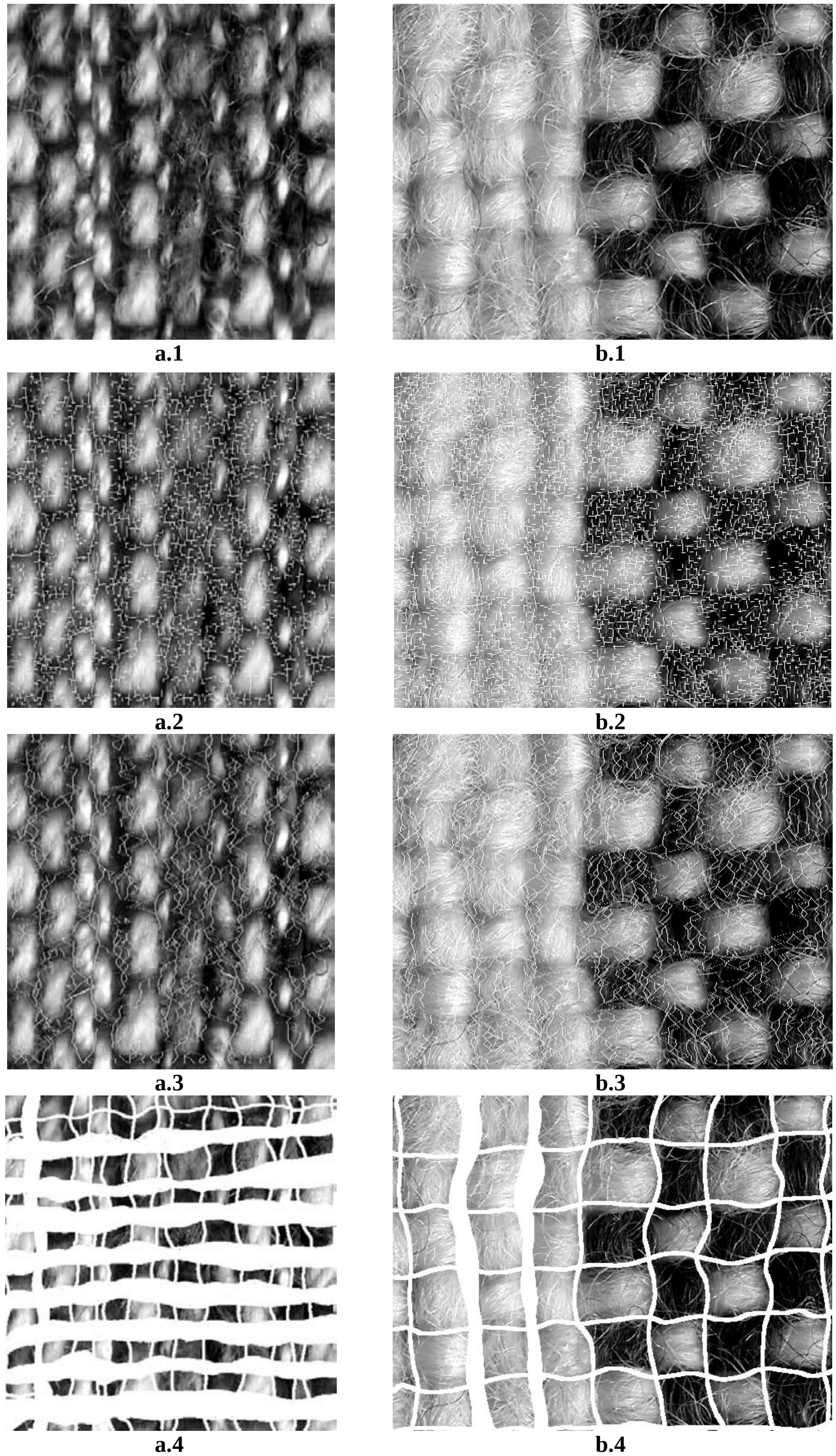


Figure 23. Crossed-points detection for two samples a and b

A close up of the feature points of Figure 23.2 is illustrated in Figure 24. Vertical and horizontal dashes show the minimum peaks in both directions. Figure 25 illustrates points of Figure 23.3 at another scale.

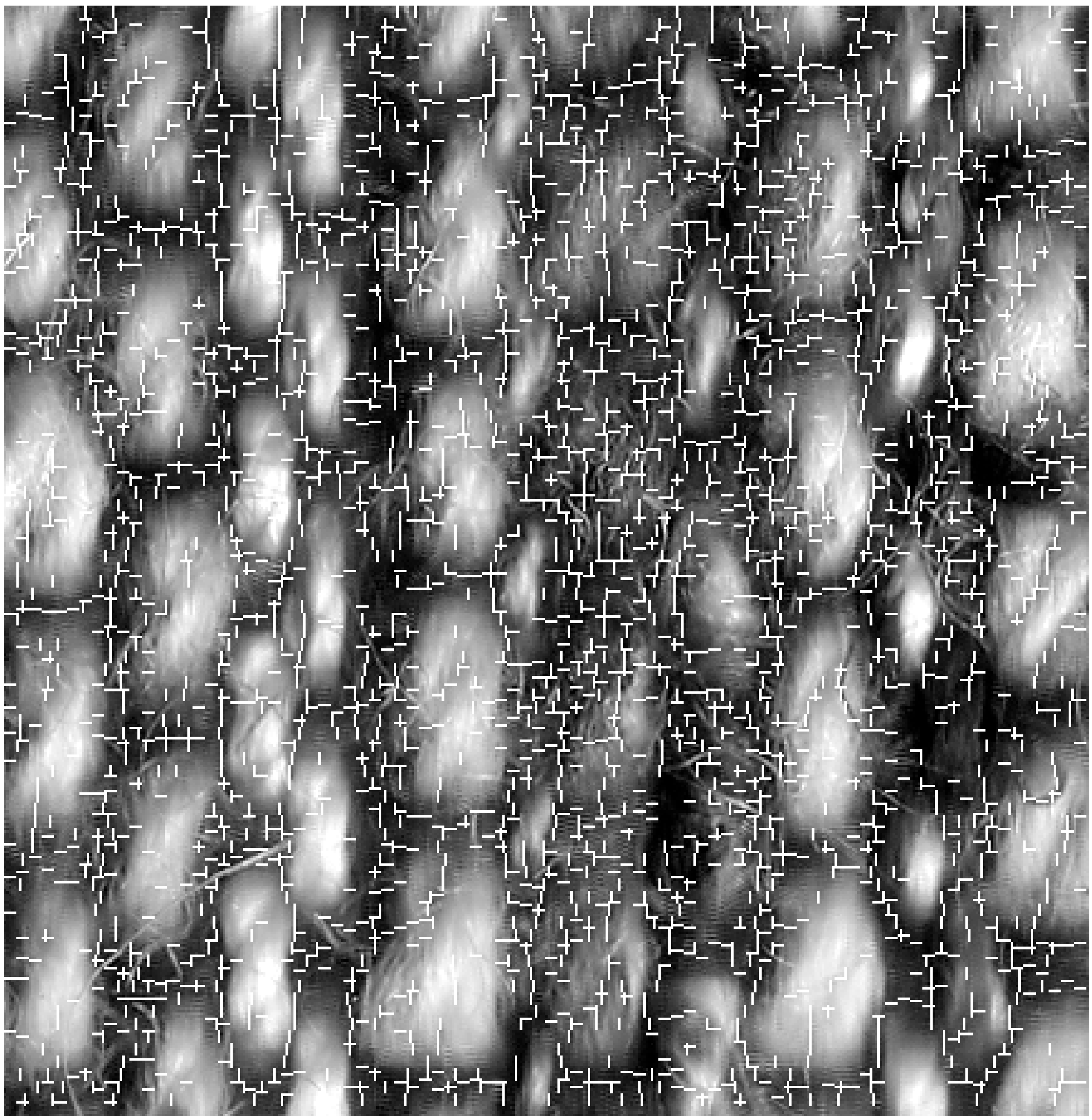


Figure 24. Vertical and horizontal feature points

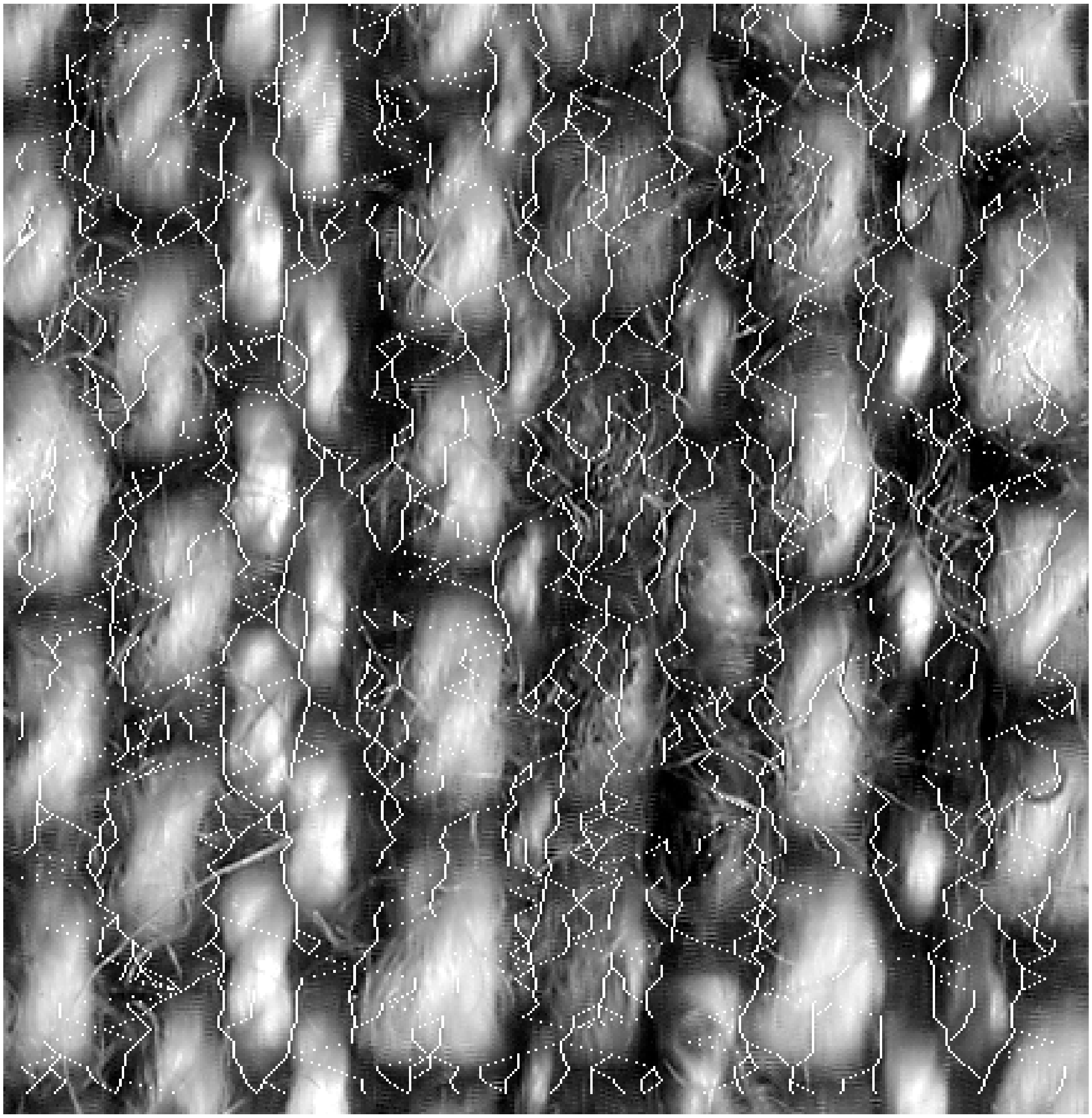
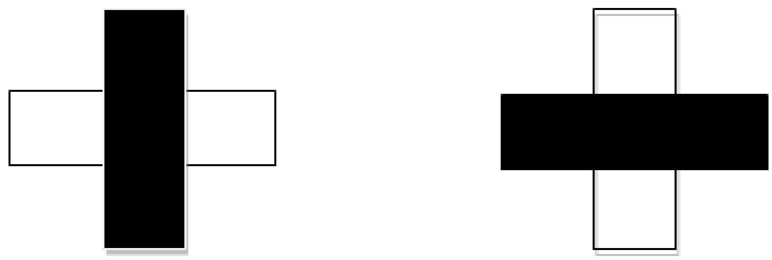


Figure 25. First iteration of fuzzy rules implication for yarn edge detection

After tuning the rules, fuzzication & defuzzication, and parameters estimation, the system is validated for 21 samples and has proved to be quite effective. Validation has shown 85% accuracy for the model. The model errors are found in artifacts with patterns or complicated woven structures.

3.5.3 Crossed-states detection

The last step in textile pattern recognition is crossed-states detection. In each detected cell in crossed-points detection, two states are possible, warp yarn floating over weft yarn or weft yarn floating over warp yarn. Figure 26 shows these two states.



a) b)

Figure 26. a) Warp yarn floating over weft yarn, b) Weft yarn floating over warp yarn

As it has been mentioned, a variety of methods have been suggested for crossed-states detection in the literature including employing texture orientation features in each one of the detected cells [10], normalized aspect ratio of an ellipse-shaped image at crossed points of the fabric [17], fuzzy c-means clustering [12, 16], and Fourier image analysis techniques [13-15, 18, 19]. The outcome of this stage is a weave pattern diagram showing the warp over weft or weft over warp in each cell of cross points.

In the proposed system, the texture orientation is found to be the most appropriate method for crossed-states detection. Some attempt has been made in the literature to solve this problem with texture orientation features [10]. In this research, the texture orientation features, called 'covariabilities' are calculated in each detected cells. These features measure gray level average difference between two pixels according to their distance d and orientation. The main problem with this approach is its sensitivity to small changes in gray level due to the noisy nature of the hand-woven textile.

Due to the sensitivity and inaccuracy of this method, a novel approach for finding the texture orientation in frequency domain is proposed. This method has not been explored in textile industry.

The first step is to find a rectangle inside each detected cell by identifying 4 points in each 4 sides of the cell with maximum x in left boundary, minimum x in right boundary, maximum y in bottom boundary and minimum y in top boundary. Figure 27 shows the rectangular inside one sample cell.

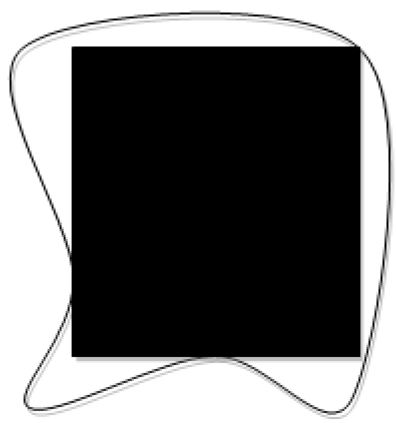
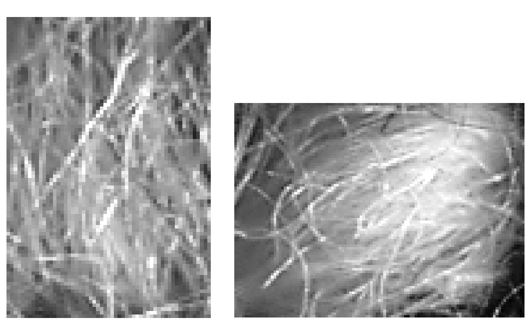


Figure 27. A detected cell and rectangular inside the boundary

Figure 28 shows two rectangular for warp yarn floating over weft yarn and weft yarn floating over warp yarn.



a) b)

Figure 28. Rectangular of a) Warp yarn floating over weft yarn, b) Weft yarn floating over warp yarn

The next step is to convert the gray level images to black and white by calculating the threshold as the average intensity of the image sample and assigning 1 to each pixel with an intensity higher than threshold and 0 to pixels with intensity less than threshold. Figure 29 shows the binary transformation of the same rectangular samples.

Figure 29. Black and white image of the rectangular cells

Figure 29 shows that the texture orientation is almost obvious and could be recognized by applying various methods for texture orientation recognition [10]. In this study, a frequency domain approach based on discrete Fourier transform (DFT) is applied. Figure 30 shows the discrete Fourier transform for the binary images of Figure 29. As it can be seen, the first DFT image is more symmetric about y axis and oriented vertically while the second image is more symmetric about x axis and oriented horizontally.

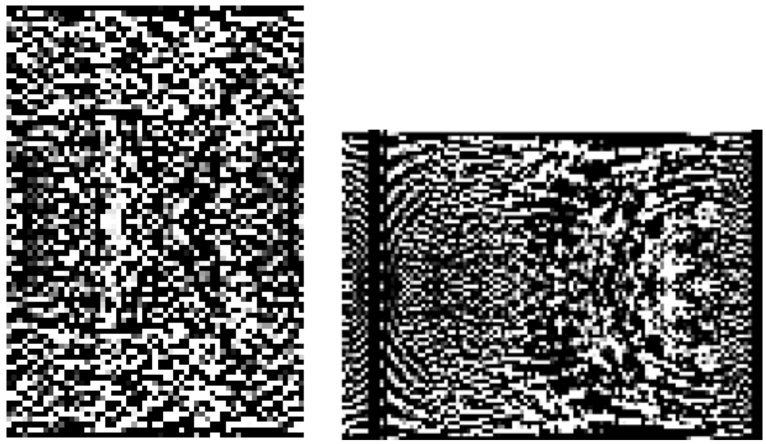
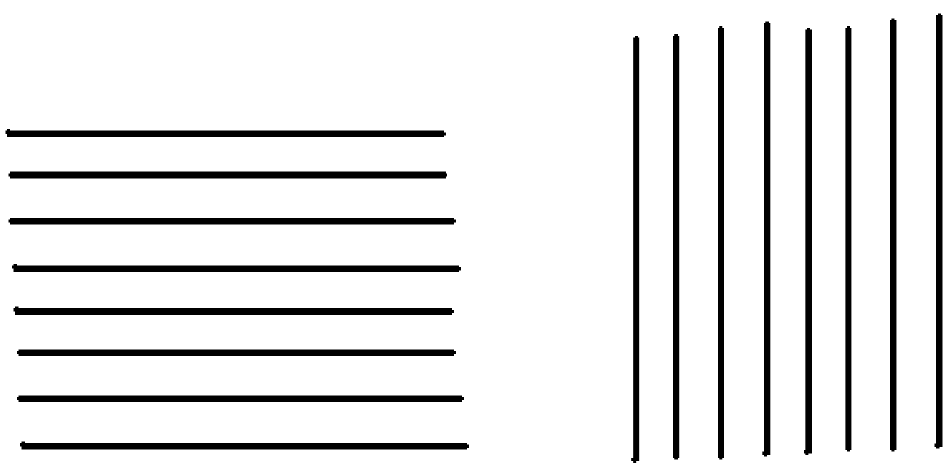


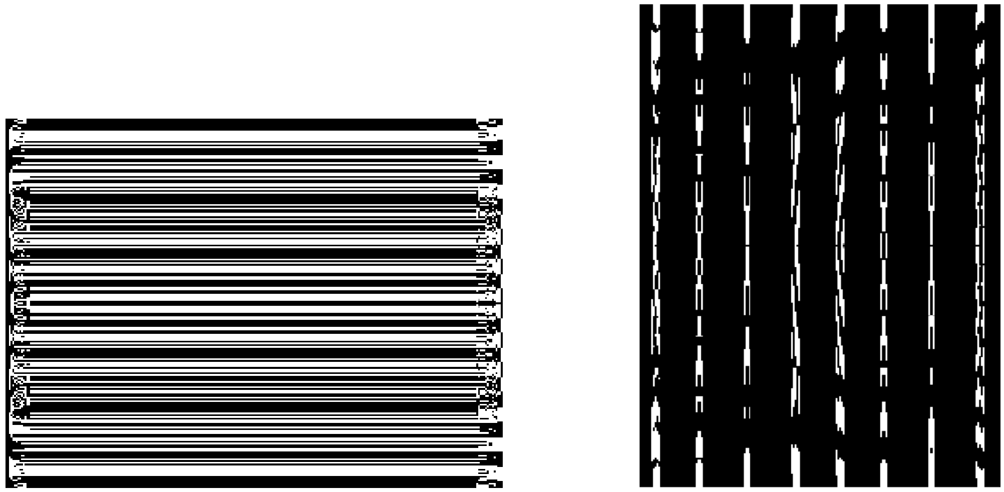
Figure 30. Discrete Fourier Transform of rectangular cells

In order to verify the relationship between texture orientation and the orientation of corresponding Discrete Fourier Transformation, a sample is considered. Figure 31 shows two images with apparent vertical and horizontal orientation. Figure 32 illustrates the corresponding DFT images. Similar orientation could be observed. Identifying texture orientation in frequency domain is less sensitive to noise and unimportant data in the original image.



a) b)

Figure 31. a) A horizontal pattern b) A vertical pattern



a) b)

Figure 32. Discrete Fourier Transform of a) Horizontal pattern, b) Vertical pattern

The customized formula for calculating the normal texture orientation [10] is applied to the DFT images. Equation 7 and 8 show the formula for horizontal and vertical covariabilities in a cell of size N*M.

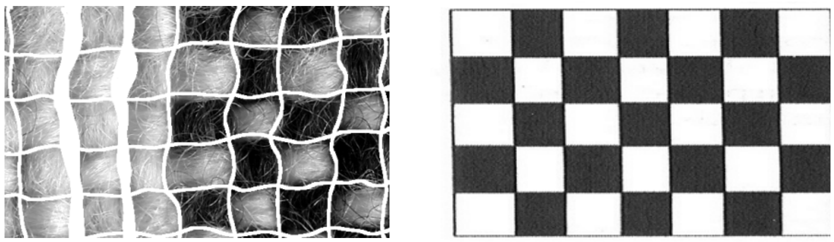
$$Cover_{H(d)} = \frac{1}{M.(N-d)} \sum_{j=0}^{M-1} \sum_{i=0}^{N-1-d} | I(i,j) - I(i+d,j) | \qquad (7)$$

$$Cover_{V(d)} = \frac{1}{N.(M-d)} \sum_{i=0}^{N-1} \sum_{j=0}^{M-1-d} | I(i,j) - I(i,j+d) | \qquad (8)$$

Where d is the physical distance between two pixels which is known due to specific DPI for scanned images. After calculating $Cover_{H(d)}$ and $Cover_{V(d)}$ for any specific rectangular cell in frequency domain, the following condition could determine the weft over warp or warp over weft status in the cell:

IF ($Cover_{H(d)}$ > $Cover_{V(d)}$) THEN _weft yarn flow over warp yarn_ ELSE _warp yarn flow over weft yarn_

Figure 33 illustrates the result of crossed-states detection for an artifact sample. The output is a weave pattern diagram. The black cells in the diagram shows the warp float areas and white ones shows weft float areas.



(a) (b)

Figure 33. Weave pattern diagram produced in crossed state detection

The proposed method is verified by applying it to 21 artifact samples. The texture orientation method in frequency domain is evaluated with 87% accuracy compared to conventional methods with less than 70% accuracy.

As the final step in the process, the structure of the artifact is determined and the yarn thickness is measured from the scanned image with determined DPI. This step completes the range of data required for building the 3D geometric model.

3.6 Textile 3D geometric model generation

3.6.1 Background

The textile geometric modeling and graphic representation has been studied for more than 2 decades. Different approaches have been developed. But almost all of them consider textile as a 2D mesh which the mechanical characteristics of draping is computed with different methods like finite-elements or mass-spring systems. In this work, the main contrast is modeling the textile as a 3D geometric object which is essential in hand-woven artifacts where the third dimension is significant. Before explaining the methodology which developed in this work, a short literature review of textile geometric modeling and graphic representation is discussed to show the contrast of proposed method.

The first major work on modeling fabric drape in the computer graphics field was carried out by Weil [54]. The proposed model was purely geometric and provided only static representation. This new branch of knowledge and its application in fashion and cloth industry was followed up by Nisselson [55].

Since then, a large number of particle models have been proposed in the computer graphics literature for dynamic simulation and presentation of the textile. One of the well-known research group in this area are N.Magnenat Thalmann and D. Thalmann who have progressively developed a linear elastic model for cloth simulation in the period between 1992 to 1998 [56-62].

Another significant work has been led by Breen and House in the period of 1992-1998 [63-65] who proposed a particle model based on energy potential functions resulted from Kawabata Evaluation System [31]. However, no physical justification given for the energy potential equations and only the loading portion of the KES data has been used in their work.

Eberhardt used the same approach but by including both the loading and unloading KES data [66-68]. Anyway he has not suggested a solution for transition from loading to unloading.

Another significant methodology was developed by Baraff and Witkin [69] in 1998 which has been utilized in Alias-Wavefront Maya Cloth software and developed in Pixar's cloth model used in Monsters Inc. two industrial cloth simulation software. However their particle model has the same weakness in not presenting the physical reasoning for the energy functions between neighboring particles.

During the 90’s, many other particle models have been suggested in literature including [70-76] using different approaches to particle interactions. They all consider textile as a 2D mesh, though use different relationships for interaction among particles.

In addition to the studies conducted in the field of computer, there are some works on computer aided design for garment design. Hindds and McCartney in 1990 [77] and Okabe in 1992 [21] introduced models for 3D geometric modeling of textiles with woven patterns, but their models were 2D geometric and different as the textile mechanical properties have not been taken into account.

Aono offered a framework for mapping fabric on to curved surfaces [78, 79] and handling darts in fabric [80] but still without any mechanical modeling and just pure 2D geometric.

The majority of these studies have focused on drape modeling which is important in real-time computer simulation and graphic representation. Most of the haptic systems also use the same methods for graphic representation of the textile, superimposed by a more accurate mechanical model for tactile interaction. In this work, the focus is on automatic 3D geometric model generation from a still image and then superimposing the mechanical model to generate a full integrated haptic model.

A new approach is proposed in this research for 3D geometric model generation of textile by developing the data obtained at pattern recognition step.

3.6.2 Yarn flow formulation

The weft or warp yarn flow is modeled in two sections:

1) The sinusoidal section used in transition flow when a weft or a warp flows over or below the corresponding yarn

2) The linear section used in constant flow

The weft and warp yarn cross-section has been modeled as a variable ellipsoid shape which varies based on pattern recognition provided data. This variable shape occurs due to internal friction and compression forces between the warp and weft yarns in fabric structure.

Figure 34 illustrates the linear flow section, sinusoidal flow section and yarn cross sections in both warp and weft directions.

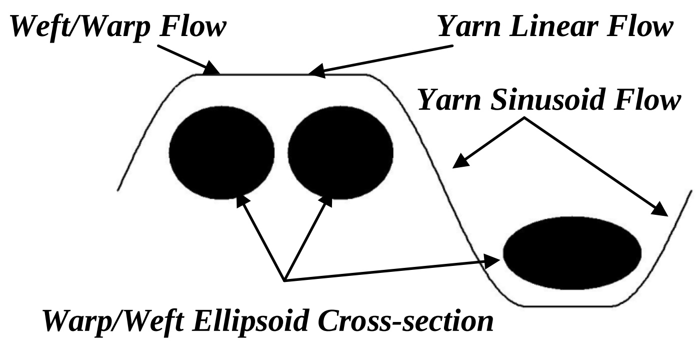


Figure 34. Weft/Warp yarn flow in textile 3D geometric model

Following sections describe the modeling of these two parts in detail.

3.6.2.1 Yarn sinusoidal flow

By considering d_{weft} and d_{warp}, weft and warp yarn diameters respectively, sinusoidal amplitude of weft and warp sinusoidal flow, A_{weft} and A_{warp} should satisfy (9):

$$A_{weft} + A_{warp} = \frac{d_{weft} + d_{warp}}{2} \qquad (9)$$

A_{weft}/A_{warp} ratio is dependent on the weft and warp yarns raw material, composition and dimension which determines the tension and compressibility of yarns and could be estimated empirically.

The higher value for A_{weft} or A_{warp} means the corresponding yarn is not firm and easily floats over and below the other yarn. On the other hand less value for them means a firm yarn which resists against floating. The zero value means the yarn is straight and never floats but the other yarn floats over and below it.

The simplest way to model the yarn floating over and below the other one is interpolating it with a sinusoidal function. Although the real curve is complicated and varies in different artifacts, this abstraction is accurate and valid and at the same time easy to model.

The weft and warp sinusoidal flow curve in 3D Cartesian coordinate space could be formulated as follows:

$$z = \pm A_{weft} Sin(\frac{2\Pi x}{d_{weft} + d_{warp}}) \qquad (10)$$

$$z = \mp A_{warp} Sin(\frac{2\Pi y}{d_{weft} + d_{warp}}) \qquad (11)$$

The positive and negative values mean the yarn floating over and below the other respectively. It is obvious that in any specific float transaction, one of the weft or warp yarns uses the positive and the other one uses negative value.

The flow of the center of weft and warp yarns in x and y directions are shown by (10) and (11). By adding the ellipsoid cross-section for each specific point in curves, the textile 3D geometric model is generated.

3.6.2.2 Yarn linear flow

Another assumption in yarn flow formulation is the linearity of yarn flow in non-transition parts. It means yarn direction does not change when there is no transition. Yarn floats over or below the other with sinusoidal curve and then stays as a parallel line within XY plane. Hence, the linear part could be easily modeled with **y=a** for weft and **x=b** for warp lines.

3.6.3 Weft/Warp yarn set modeling

Based on the textile pattern recognition the length and width of a woven artifact as well as its weft/warp yarn thickness and shape change, pattern and structure are determined which could be employed in this step. In the first iteration of geometric model generation, the yarns are conceptualized as curves in 3D Cartesian coordinate space. These curves are considered to be the center of yarns in weft/warp directions. Therefore there are n weft yarns located parallel with x axis and m warp yarns parallel with y axis. The distance between each two neighboring yarns could be determined by the data produced at pattern recognition phase.

Figure 35 illustrates 3 warp yarns in a plain weave sample. It is obvious that the whole structure has more warp and weft yarns, though omitted in this figure to show the procedure more clearly.

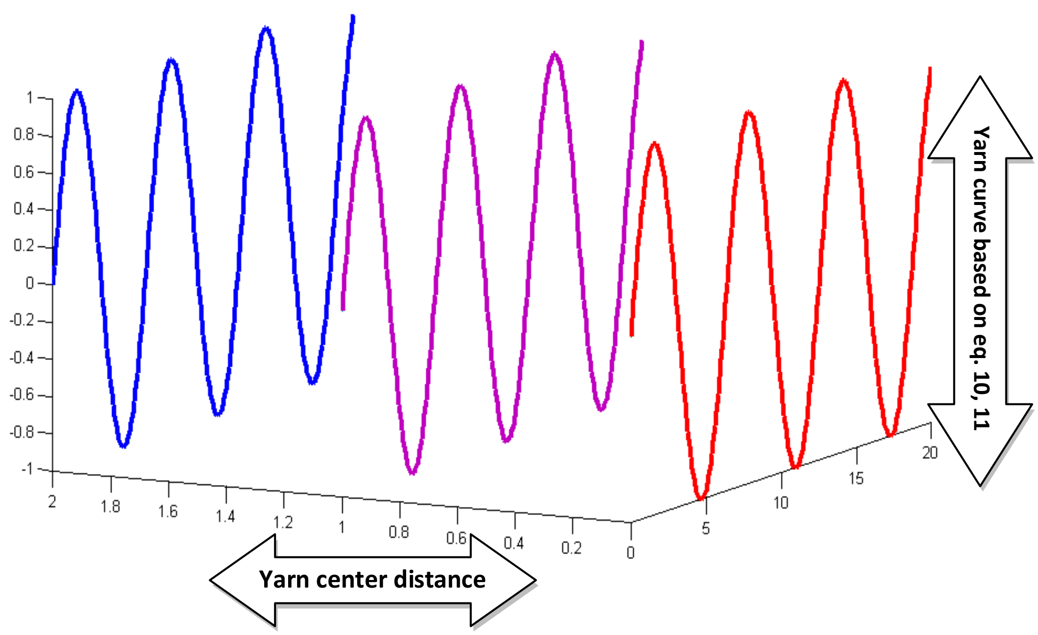


Figure 35. 3 warp yarn curves in a plain weave sample

Figure 36 illustrates the procedure by which yarn curve is produced from a weave pattern diagram. Any transition from white to black or black to white cells causes sinusoidal change in the curve based on equations 10 and 11. Alternatively, the curve remains fixed as discussed before in sinusoidal and linear yarn flow. The same procedure repeats for all yarns in vertical and horizontal directions of the diagram.

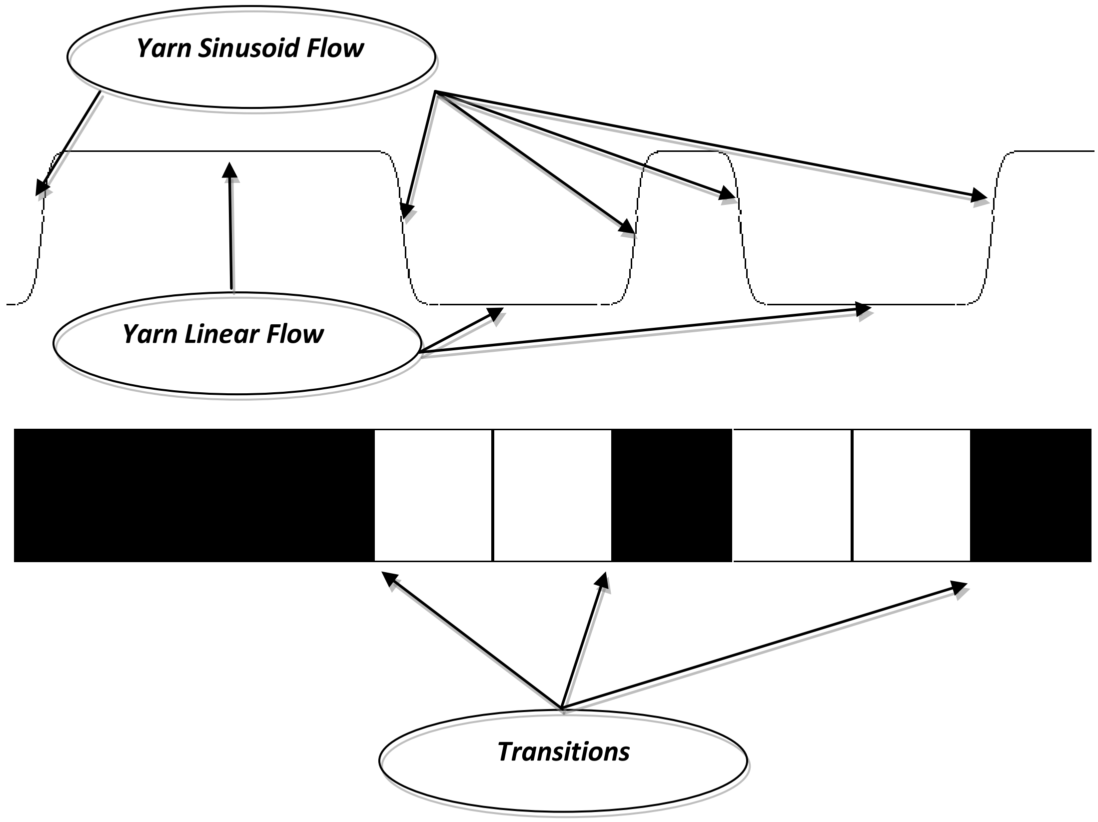


Figure 36. Yarn curve produced from a weave pattern diagram

3.6.4 Applying yarn cross-section to yarn curve

The weft and warp yarn cross-section has been modeled as a variable ellipsoid shape which varies based on pattern recognition provided data. This variable shape is occurred due to internal, friction and compression forces between the warp and weft yarns in fabric structure.

At this stage, the yarn cross-section is covered around the yarn curve for complete 3D geometric model. It is like covering the skeleton with muscles. The real yarn cross-section is not ellipsoid but for abstraction this assumption is made. The pattern recognition could provide one diameter of the yarn ellipsoid; the other one could be calculated with this assumption that the ellipse surface area is almost fixed. There are different methods in the literature to calculate the yarn cross-section by applying the forces at each point. In this work a straight forward method is applied. The yarn diameter is assigned by the average yarn width (based on pattern recognition). The area of the cross-section is then calculated analytically, $radius_X$ and $radius_y$ are estimated from still image and ellipse surface.

Generally, the yarn cross-section area is assumed fixed but for more accurate modeling in sinusoidal flow, this area is reduced by a fraction (such as 20%) to model the compression in floating areas. This constant could be estimated based on the yarn raw material and structure and the woven pattern.

For any specific point in weft and warp yarn curve, the cross-section is applied and some points in 3D space are calculated based on ellipse curve formula. The number of these points and the sampling rate in curve determine the accuracy and complexity of 3D geometric model. Figure 37 shows an example of cross-section calculation.

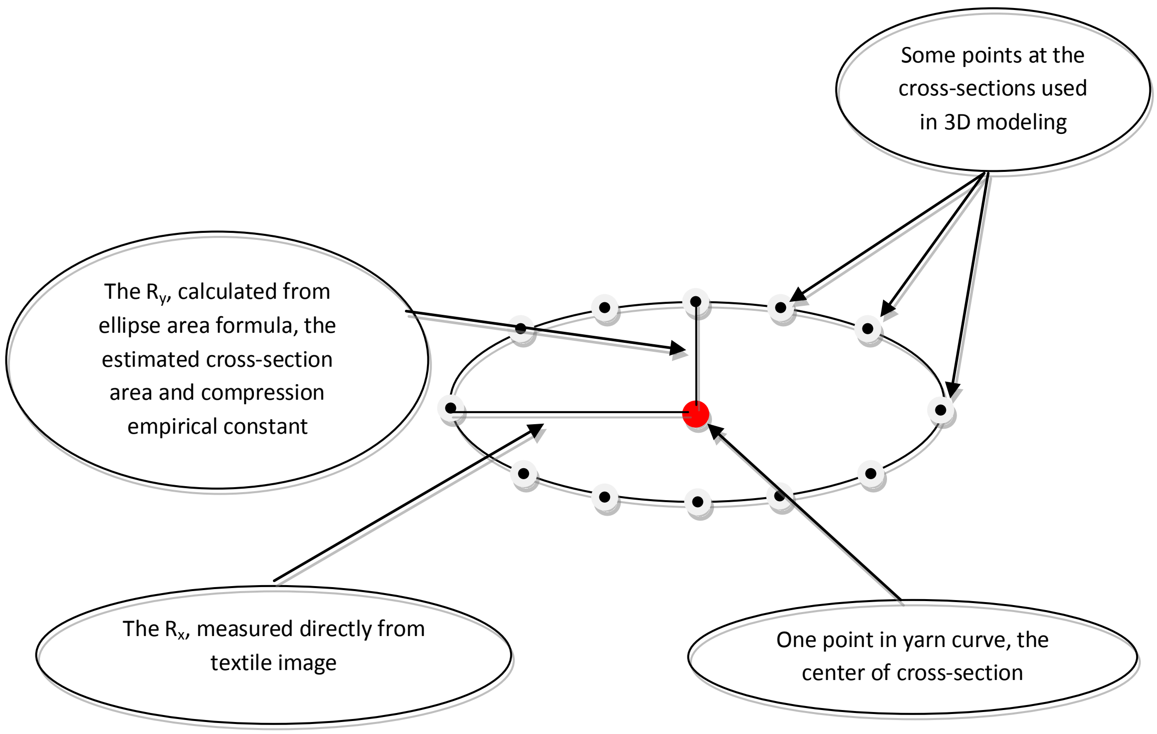


Figure 37. Yarn ellipsoid cross-section

3.7 3D geometric model generation

The points on the cross-sections of all the yarns in the artifact could be calculated as mentioned in the last part. The points in each cross-section are used to build a polygon. The higher the number of points, the closer will be the polygon to an ellipsoid. At the same time, higher the sampling rate in yarn curve, larger will be the number of polygons used to estimate the cylindrical yarn and therefore the more accurate will be the 3D geometric model.

The VRML (Virtual Reality Modeling Language) version 2 is used to generate the 3D geometric model. It is generic, platform independent, fast and compatible with Reachin environment which is used for haptic modeling of textile.

The main idea behind the VRML is scene graph. The VRML uses standard tags for describing a 3D virtual world. The main geometry tag, employed in our model is *IndexedFaceSet* which has a list of coordinates (the points in two neighbor cross-sections) and some triangles as primitive polygons for connecting these points together to create a 3D object. The template of textile artifact 3D geometric model in VRML is as follow:

```
#VRML V2.0 utf8
Group {
    children [
        Shape {   # each disk of the yarn modeled with one shape object bounded by two cross-sections
            appearance Appearance {
            material Material {}
            texture ImageTexture {
            url " "  # could be the part of artifact image
            }
            }
```

geometry IndexedFaceSet {

coord Coordinate {

point [# each cross-section demonstrates by 13 points and there are two cross-section for each disk so 26 points are located here

x0, y0, z0

x2, y2, z2

…

X25, y25, z25

]

}

coordIndex [# the triangles as primitive polygons for creating the 3D object

0 1 2 -1,

3 2 1 -1,

2 3 4 -1,

5 4 3 -1,

4 5 6 -1,

7 6 5 -1,

6 7 8 -1,

9 8 7 -1,

8 9 10 -1,

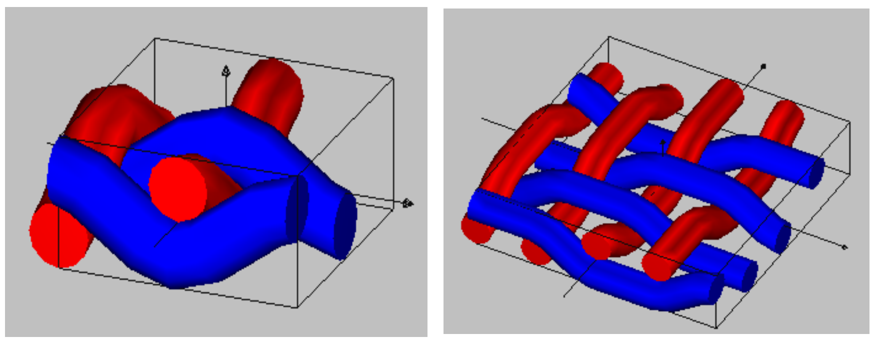
11 10 9 -1,

10 11 12 -1,

```
                    13 12 11 -1,
                    12 13 14 -1,
                    15 14 13 -1,
                    14 15 16 -1,
                    17 16 15 -1,
                    16 17 18 -1,
                    19 18 17 -1,
                    18 19 20 -1,
                    21 20 19 -1,
                    20 21 22 -1,
                    23 22 21 -1,
                    22 23 24 -1,
                    25 24 23 -1]
            solid TRUE
            }
    },
    Shape { # the next disk and so on
        …
        }
        …
    ]
}
```

A 3D geometric model generator is implemented to automatically generate a VRML file by finding all the points in cross-sections based on the data from pattern recognition engine and then to create the 3D VRML model derived from the given template.

The 3D geometric model generator can easily generate VRML models for any artifacts within few seconds. Figure 38 illustrates a partial 3D geometric model for a plain artifact and a twill artifact samples.



(a) (b)

Figure 38. Partial 3D geometric model for: a) A plain artifact sample b) A twill artifact sample

The VRML 3D geometric model of an artifact in Virtual Reality Viewer is shown in Figure 39. Virtual Reality Viewer is a plug-in which is installed in a normal Internet browser and gives the browser the capability to browse VRML virtual 3D world.

The textile texture also could be added to the model for a real presentation of the sample in virtual reality world. The only requirement is putting the yarn section image as texture in VRML file as highlighted in the file template.

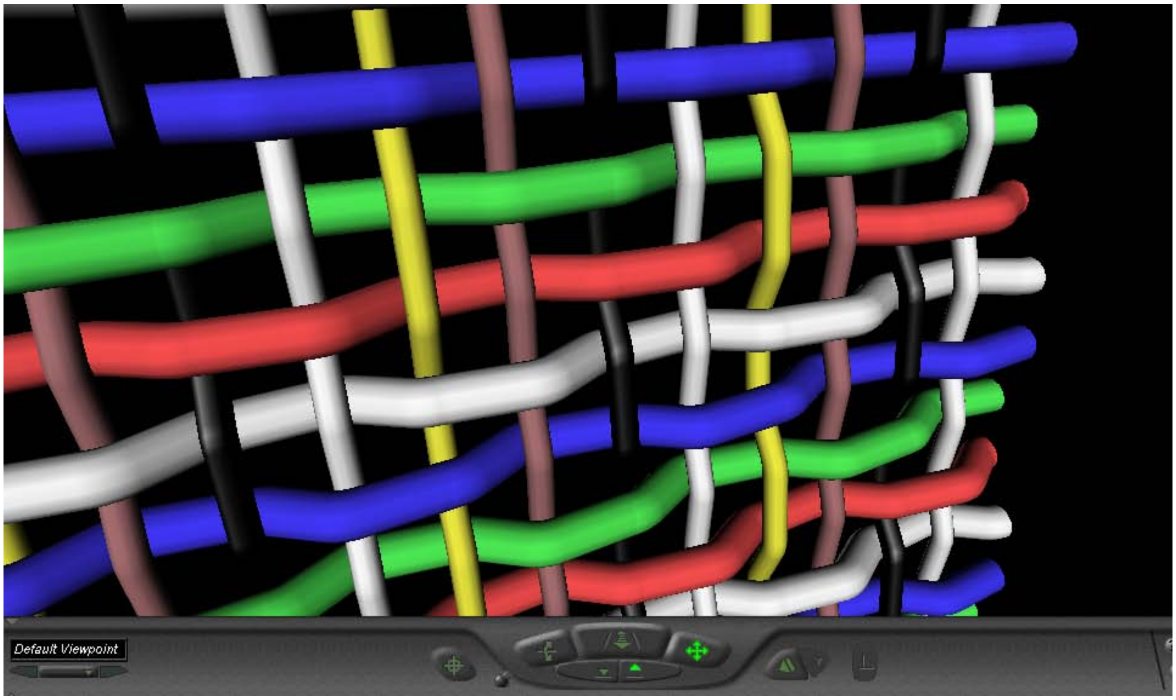


Figure 39. An artifact VRML 3D geometric model in Virtual Reality Viewer

The artifact 3D geometric model is ready and could be superimposed by mechanical model for haptic rendering of textile in a tactile perception of hand-woven artifacts. The 3D geometric models are generated for all 21 artifact samples.

Chapter 4

Textile Mechanical/Physical Modeling

4.1 Introduction

A haptic model is produced by superimposing mechanical and physical model over geometric model of an object. The 3D geometric model of the textile was discussed in the last chapter. In this chapter, textile mechanical and physical properties are investigated and the current approaches to mechanical modeling of textile is explored. The novel generic approach developed in this work for building textile mechanical/physical model is finally introduced and validated.

4.2 Fabric hand

Fabric hand is a term in textile industry to explain tactile sensations associated with fabrics which determines consumer preference. It is a reflection of overall quality which could be quantitatively defined by some physical properties. The *Fabric Hand* of a cloth or garment is defined as the overall fabric quality perceived through operations such as touching, squeezing, or rubbing [29]. Many factors affect the Fabric Hand including flexibility, compressibility, elasticity, resilience, density, surface contour (roughness, smoothness), surface friction and thermal characteristics of the fabric. Two different methods suggested in the literature for fabric hand evaluation, subjective and objective methods.

4.3 Subjective methods for fabric hand evaluation

Subjective assessments treat fabric hand as a psychological reaction obtained by the sense of touch [4]. It is a descriptive method based on the experience and sensitivity of human beings[29]. This method is traditionally used for fabric classification according to their sensory description by experts who sort out the fabric qualities by touching, bending and stretching them. The main problems with this method have been defined by Hui [29] and Dent [81] as:

1) The assessment process is very time consuming and costly

2) There are different fabric sensory perceptions for different people, depending on their background and experience.

3) There are communication problems between experts and consumers (for instance the same adjective can be used with a different meaning by different individuals)

One of the critical researches in subjective assessment has been carried out by Bishop, et al [82]. They asked 25 laboratory assistants with no special experience in textile industry to evaluate 27 samples of fabric subjectively. Then they categorized the terms and their frequency which could be seen in Table II. Subsequently these terms and indicators have been ranked and categorized in seven descriptors:

• Smoothness

• Softness

• Coarseness

• Thickness

• Weight

• Warmth

• Stiffness

Table II - Usage Frequencies of Descriptors in Bishop Research

Term Used	Frequency	Frequency (%)
Smoothness	82	28
Softness	64	22
Firmness	23	8
Coarseness	22	7
Thickness	16	5
Weight	15	5
Warmth	12	4
Harshness	12	4
Stiffness	9	3
Body	8	3
Liveliness	6	2
Fullness	4	1.3
“Wood-like”	4	1.3
“Quality”	4	1.3
Crispness	3	1.0
Paperiness	3	1.0
Greasiness	3	1.0
Weave	3	1.0
Boardy	2	0.7
Creasability	1	0.3
Drape	1	0.3
Total	**297**	**100 %**

4.4 Objective assessment for fabric hand evaluation

Objective assessments try to predict fabric hand by measuring some physical properties by an instrument or a machine. Several sets of standards and machines have been developed for objective assessment like Kawabata, FAST and some hand tester like Ring test and Slot test. Behery in his book investigates the relationship between fabric hand and the textile mechanical and physical properties in depth [83]. These tests are still costly and time consuming which make them industrially unviable.

Shishoo [84] has carried out a critical investigation about objective assessment and its real application in realizing fabric hand. He asks some several philosophical questions about objective assessment and its efficiency in real applications.

Some new methods for fabric hand assessment are being developed. For instance, Strazdiene method [85] is a new method for objective assessment.

Grineviciute has carried out a comparison study between subjective and objective evaluation and has identified advantages and disadvantages of each method [86] .

4.4.1 Kawabata Evaluation System for Fabrics, KES-F

The KES-F system (Kawabata's hand evaluation system for fabrics) was developed in Japan by the Hand Evaluation and Standardization Committee (HESC, established in 1972) organized by Professor Kawabata.

In this fabric objective measurement method, scientific principles are applied to the instrumental measurement and interpretation of fabric low stress mechanical and surface properties such as fabric extension, shear, bending, compression, surface friction and roughness. The fabric handle is calculated from measurements of these properties. Empirical equations for calculating Primary Hand values and Total Hand Values were put forward by Kawabata and Niwa .

The characteristic values (Table III) are calculated from recorded data obtained by each tester. Tensile properties (force-strain curve) and shear properties (force-angle curve) are measured by the same device (Figure 40). Bending properties (torque-angle curve) are measured by bending reverse sides against each other and after that the face sides against each other (Figure 41). Pressure-thickness curves are obtained by compression tester (Figure 42). The measurements of surface friction (friction coefficient variation curve) and surface roughness (thickness variation curve) are made with the same apparatus (Figure 43) using different detectors. All measurements (except compression) are performed both in machine (warp) and in cross (weft) direction [35, 36].

Figure 40. Kawabata Tensile and shear tester

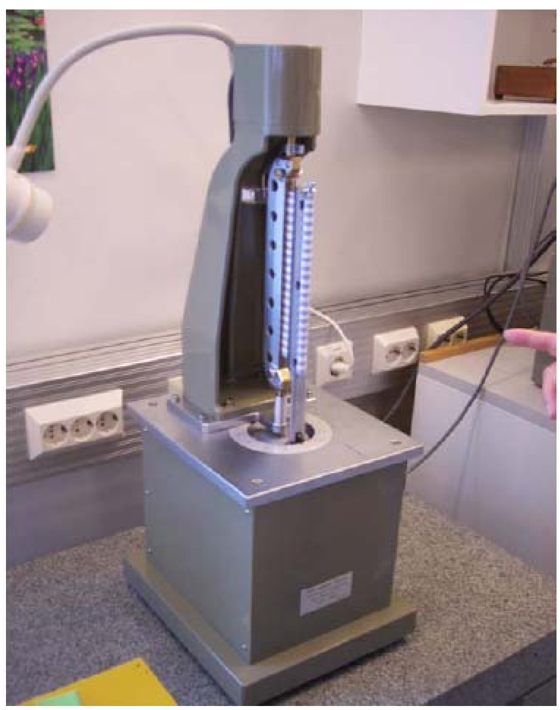


Figure 41. Kawabata Bending tester

Figure 42. Kawabata Compression tester

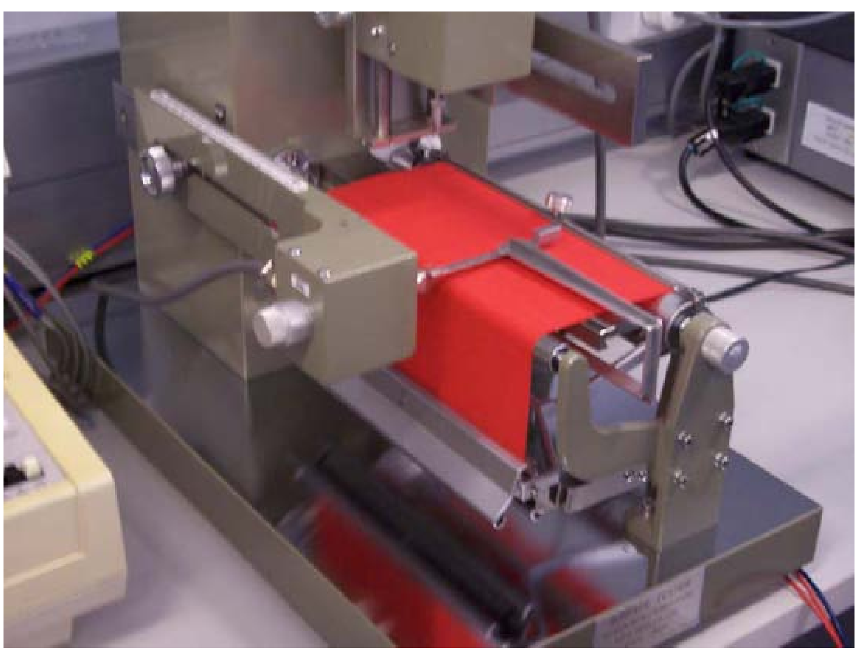


Figure 43. Kawabata Surface tester

Table III - Mechanical properties of textile in objective assessment of the Fabric Hand

Group of Variables	Variables	Symbol	Unit
Tensile	Linearity of load-extension curve	LT	-
	Tensile energy	WT	$g.cm/cm^2$
	Tensile resilience	RT	%
	Elongation at max. load (500 gf/cm)	EMT	%
Shearing	Shear rigidity	G	$g.cm/^o$
	Hysteresis of shear force at 0.5^o shear angle	2HG	g/cm
	Hysteresis of shear force at 5^o shear angle	2HG5	g/cm
Bending	Bending rigidity	B	$g.cm^2/cm$
	Hysteresis of bending moment	2HB	g.cm/cm
Compression	Linearity of pressure-thickness curve	LC	-
	Compressional energy	WC	$g.cm/cm^2$
	Compressional resilience	RC	%
Fabric thickness	Thickness at 0.5 gf/cm^2	T_0	mm
	Thickness at 50 gf/cm^2	T_m	mm
Surface	Coefficient of friction	MIU	-
	Mean deviation of MIU, frictional roughness	MMD	-
	Geometrical roughness	SMD	µm
Weight	Weight pre unit area	W	g/m^2

The textile mechanical and physical properties which are measured in objective assessment and specifically in Kawabata assessment could be categorized in following groups (Group 3 and 6 are more physical rather than mechanical):

- Group 1: Tensile property
- Group 2: Bending property

- Group 3: Surface property
- Group 4: Shearing property
- Group 5: Compression property
- Group 6: Weight and thickness

Bishop has done a research and proposed sensory and mechanical properties of the textile [82] which could be used to understand the effects of each one of these properties in textile behavior and so in its mechanical modeling. On the other hand there are many methods for analytical or empirically prediction of these properties which have been investigated in the following sections.

However, although objective assessments are precise from a mechanical point of view, these methods have not been commonly used in the textile and clothing industry. Even today, many companies still use subjective evaluation to assess fabric properties. The main reason for this situation is the repetitious and lengthy process of measurement and the lack of knowledge for a good interpretation of the test results.

In many industrial applications, objective assessment methods by employing Kawabata machine are being deployed for fabric hand assessment rather than analytical or empirical models for textile physical and mechanical properties estimation.

4.5 Factors affecting fabric hand

The properties of the textile raw material, yarn structure, planner structure (woven or knitted pattern) and finishing treatment affect the fabric hand and could be employed in a mechanical/mathematical model for predicting the fabric hand and its factors including textile mechanical properties [30].

Yarn is created of fibres. Fibres are staple or filament length. All natural fibres excluding silk are staple length fibres. Silk and manmade fibres may be staple or filament length. Fibre size is indicated in terms of diameter or linear density. Better fibres make the yarn more flexible and as the result fabric drapes well. On the other hand the fibre length determines the smoothness of the yarn. The cross-sectional shape of the fibre affects the yarn quality, too. Filament yarns composed of one filament are called monofilament yarns and those with many filaments are called multifilament yarns. In clothing fabrics, multifilament yarns are usually used. Evaluating multifilament yarns of the same size and fibre composition, yarns containing more filaments (finer) are much less stiff than multifilament yarns containing less filaments (coarser). Flat multifilament yarns are yarns in which the filaments are straight and aligned with the yarn axis. They tend to be the smoothest of all types of yarns. Textured yarn is a generic term given to the filament yarns with greater apparent volume, which is produced through physical, chemical or heat treatments or a combination of them. The feel of textured-yarn fabrics against the skin is significantly different from flat-yarn fabric. Textured yarns give fabric a more pleasant hand. Yarn properties and the fabric are affected by the degree of twist in the yarn. As the twist is inserted, the fibres or filaments come closer to each other. High twist gives greater bending stiffness. In plied yarns in which two or more single yarns twisted together, the stiffness is increased compared to single yarns [35].

In woven fabrics, the weave and the yarn densities affect the fabric hand. Variations in warp and weft densities and in warp and weft numbers have a considerable effect on the hand. Feeling depends also on the weaves in woven structures (cf. terry fabric, velvet, velveteen, corduroy, satin, twill, rib weave, plain) [35]. Figure 44 [39], demonstrates different factors affecting fabric hand.

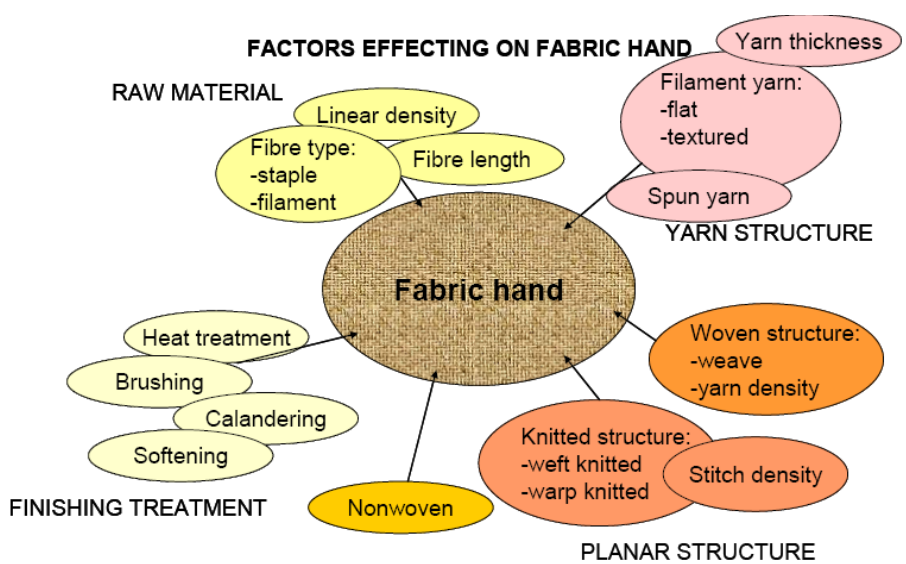


Figure 44. Factors affecting the fabric hand [39]

Fibre raw material which affect fabric hand and could be used for mechanical and physical parameters prediction include:

1. Natural fibres (Plant fibres (cotton, linen, etc), animal fibres (wool, silk, etc)
2. Man-made fibres (Natural polymers (viscose, cupro, acetate, etc), Synthetic polymers (polyester, elastane, polyacryl, etc)
3. Type : (Staple, Filament)
4. Length
5. Fibre size (In term of diameter or linear density)

Yarn structure which affect fabric hand and could be used for mechanical and physical parameters prediction include:

1. One filament or Multifilament
2. Degree of twist
3. Flat or Textured
4. Thickness

Fabric structure (Planner structure) which affect fabric hand and could be used for mechanical and physical parameters prediction include:

1. Weaving (Plain, Twill, Stain/Sateen, combination of these 3 main types)
2. Knitted (Weft knitted, Warp knitted)
3. Nonwoven (like leather)

Physical aspect and dimension of the fabric which affect fabric hand and could be used for mechanical and physical parameters prediction include:

1. Thickness
2. Density (yarn density (warp and weft densities and numbers), loop density)
3. Weight

Finishing treatment which affect fabric hand and could be used for mechanical and physical parameters prediction include:

1. Heat treatment
2. Brushing

3. Calandering
4. Softening

4.6 Textile mechanical properties

Textile industry has worked on the analysis of fabric evaluation methods and its quantitative measurement for decades. Early studies on this topic go back to 1930 [87] when Pierce et al. worked on handling cloth and its measurement with some quantitative indicators. Many other researchers followed this idea and advanced it during fifties and sixties [88-95] which resulted in a theoretical framework for fabric evaluation.

Fabrics vary in type, fibre, geometric structure and their basic mechanical properties. The geometric structure of woven fabric plays a significant role in determining the mechanical properties of the fabric. A series of studies was conducted by P. Grosberg in 1960's to investigate different mechanical and physical parameters required for mechanical modeling of textile:

1. The Initial Load Extension Modulus of Woven Fabrics has been investigated in [91].
2. The Bending of Woven Fabrics has been investigated in [92].
3. Shearing and Buckling of Various Commercial Fabrics has been investigated in [93].
4. The Determination of the Bending Rigidity and Frictional Restraint in Woven Fabrics has been investigated in [94].
5. The Initial Modulus and the Frictional Restraint in Shearing of Plain Weave Fabrics has been investigated in [95].

In the seventies, a committee organized by Professor Kawabata developed a standard evaluation system for the handling of fabrics [31] They also developed specific machines for the measurement of these quantitative mechanical properties which resulted in the development of KES-F system, which has become the main standard in this area.

In the field of haptics, there have been some attempts to combine studies on the physical properties of fabrics with garment simulation [1, 45]. The simulations could not be carried out in real time.

Since then, many studies have been carried out to measure these mechanical and physical properties through different tests and assessments methods and deploy them in a realistic textile mechanical model.

The complexity of the structure and scale levels of 10-5 m fibres, 10-3 m yarns, 10-1 m fabrics and 100 m composite parts lead to complexity of the predictive models. High levels of approximation and uncertainty in the development of analytical models, when the errors are accumulated in model progress from one hierarchy level to another, result in complicated and inaccurate models.

Shigeru Inui et al. developed a system based on real textile weave structure rather than point mass or continuous body models [22]. The proposed algorithm estimates the mechanical behavior of the textile through a static model. There is no physical justification provided for the estimation of the mechanical properties.

Mitsuo et al. have carried out one of the latest research in objective evaluation of textile mechanical properties by Kawabata machine and the mapping between these mechanical properties and subjective evaluation of the textile [96].

J. V. Desa and his colleagues developed a neural network-based algorithm for textile recognition using the mechanical properties measured by Kawabata machine [97] . The result of the research was encouraging as through similar methods, the mechanical properties could be estimated in a reverse process. This method will be applied in this study.

Lomov and his colleagues proposed a hierarchical model based on composite structure of textile for mechanical behavior prediction. This model combines two primary models of fibre to yarn and yarn to textile based on Minimum Energy Principle for predicting the mechanical properties and behavior of a textile. An Object Oriented approach has been developed in the development of the model which could be effectively utilized in simulation.

Textiles as hierarchically structured fibrous material has been studied in the work conducted by Hearle [98, 99]. He developed an affective approach for the construction of the mathematical and analytical models of the geometry and the mechanical behavior of the textile structure, widely used by others.

During 60 years of research in creating textile structure models, many different models have been suggested. During the 30s, the first studies on mechanical treatment of the structure of textile material were published by peirce [100]. This was followed by a stream of papers dedicated to mechanical description of textile structures was constant and publication of a book called "Mechanics of Flexible Fibre Assemblies" by Hearle [101]. The generic models proposed in the book and the papers published afterwards included models of the internal geometry of the basic textile structures, such as continuous-filament and staple yarns, random fibre mats, and woven and knitted structures [102].

Later on, Lomov et al. developed a software package called WISETEX for 3D geometric modeling of textile [20]. In this model, the inner forces like friction and compression for a real model of weft and warp shape calculation in a woven or knitted textile are developed. The deformability of textile fabric is included in the model by superimposing the mechanical characteristics on the geometric model.

4.7 Mechanical/Physical modeling of textile literature review

Continuum mechanics provide a solid base for deformable objects and theoretically could be deployed in textile simulation if certain constrains are addressed. The computer animation in a Virtual Reality world requires simple and intuitive models for fast simulation. At the same time the exact accuracy is not the case in computer graphics. Linear elasticity is not always applicable in animation. Highly flexible objects like textile need to be modeled by non-linear models which are computationally very expensive in real time applications. Finally materials like textiles are not continuous materials but assemblies or structures of treads. Donald House and David Breen state textile in their book as "a mechanism not a continuous material" [103]

Some researchers in computer graphic and geometric modeling of textile like [64, 66] have used particle systems. Unfortunately the model cannot include adequate details to model each thread of the textile or simulate the exact draping. Therefore in mechanical modeling more accurate models are required.

Many fabric mechanical models for simulation have been proposed in textile engineering literature. Majority of these models are based on standard engineering approximation methods like finite elements or finite volumes, utilizing continuous mechanics principles and formulation.

However there are few models proposed in the literature which use the linear elastic or even nonlinear elastics partial differential equations (PDE) which are solved analytically or numerically. Such models though more accurate, are computationally too expensive to be used in real time applications.

One of these models is Postle model [104] which uses non-linear dynamics with analytical solution. Internal friction is not included in the fabric model, with the exception of the model developed by Chen [105] which utilizes a multi grid techniques in minimizing the energy. This model neglects bending rigidity but adds a new property called wrinkling energy.

The first attempt to model the fabrics behavior was carried out by Moskowitz in 1966 [106] which considered uniform lateral loads acting on two sets of plane, parallel elements superimposed at 90 degree to each other which used to represent the weave of the textile. A finite difference approximation was used to solve the equations derived through the theory of minimum potential energy.

Most of the proposed models in literature like [107, 108] use an orthotropic, linear elastic assumption for material behavior which is not the real case in textile modeling. A comparative study of these linear models has been carried out in [109] and a nonlinear model is proposed.

There are other non-linear models suggested in literature. Bias-Singh in 1998 [110] developed a non-linear finite element model for non-woven fabrics that includes a bi-linear tension model.

Shigan Deng and Eischen [111-113] developed a non-linear, orthotropic shell model which includes a polynomial fit to the KES data. The model does not include bending hysteresis.

Jong and postle have conducted Energy Analysis of Fabric Mechanics Using Optimal Control Theory which could be used in mechanical modeling of textile[114]. Leaf and Anandjiwala proposed a general mechanical model for plain woven fabric in 1985 [23] which could be used for analytical estimation of textile mechanical properties. Sinoimeri and Dr´ean suggested a more reliable model based on energy methods for mechanical behavior modeling of plain textile [24].

Hu and Cahn have proposed a model to define the relationship between draping and mechanical properties of textile [115] which shows how a mechanical model could consider mechanical modeling for a realistic drape of textile.

Chen et al. worked on customizing continuum mechanics for textile modeling. They proposed a discretized linear elastic model for cloth buckling and drape in [105]. Later, Dias, Gamito and Rebord˜ao completed the development of the model [116].

Shi, Hu and Yu proposed a model for modeling the creasing properties of woven fabrics [117] which could be employed for exact mechanical modeling of textile. Toriumi [118] proposed a mechanical model at fibre level which consists of Fibre assembly and structure, fibre mechanical properties and its effect in yarn mechanical behavior.

More information on mechanical modeling of textile could be found in [25, 26].

4.8 Textile mechanical model generation

At this stage of the project, a static approach is used in the mechanical modeling of textile. The model provides the following characteristics during computer simulation:

1. The user can touch the artifact and move fingers on the surface in any direction at different velocities, feeling the friction and toughness of the artifact, as well the peaks and valleys of the weft and warps as a 3D object
2. The user can apply pressure at any point of the artifact and feel the textile resistance against compression

The dynamic behavior of the artifact against shearing, bending, etc require further work in the further stages of the project.

As it has been discussed, the systems developed in previous work use time-consuming objective assessment of fabric hand for estimating the physical and mechanical properties of the textile artifact in laboratory conditions which is not suitable for industrial applications. It has also been noticed that there are mathematical models for calculation of these parameters based on some factors like textile raw material, yarn structure, planner structure and finishing treatment. However these mathematical models are usually complicated and are applicable only in specific domains.

In this research, neural network is employed to estimate the mechanical/physical parameters of the textile. This approach has many advantages over other methods. It is faster, cheaper, more accessible than objective assessment and more straightforward compared with analytical models. On the other hand, the learning capability on neural networks allows the system to be more flexible. This approach could be widely utilized as a substitute in haptic modeling of textiles.

Based on requirements of textile static mechanical modeling, average static and dynamic friction in weft and warp directions and average compressibility are selected to be estimated by the system for model verification and validation. For each fundamental weave patterns (plain, twill, satin, basket and leno) a three-layer Perceptron neural network system is developed. Subsequently, the hidden layer size, learning ratio and primitive weights are estimated by conducting experiments on the training data. The system is then trained by back-propagation and validated by comparing the system output and with objective assessment results which proves the system efficiency and accuracy based on the requirements.

The system input includes weft/warp yarn raw materials, weft and warp/weft yarn structure. Correspondingly the system output includes average static friction, dynamic friction and compressibility.

To setup a framework for the experiment, the raw materials are limited to natural materials – wool, linen, cotton and silk. Next section investigates the input and output parameters in more depth. Figure 45 demonstrates the neural network architecture. The same system developed for each specific weave pattern.

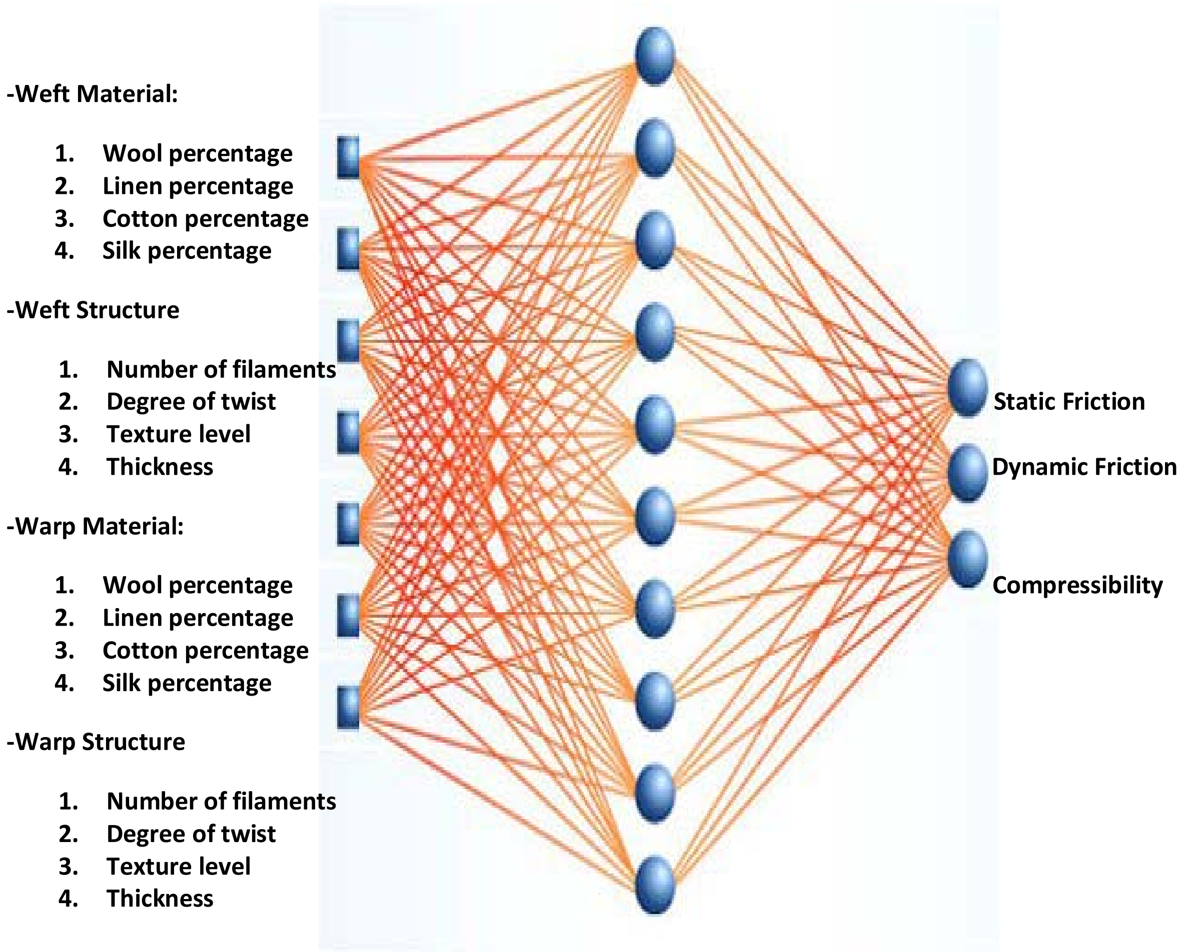


Figure 45. Neural Network system for textile mechanical & physical properties prediction

4.8.1 Neural Network input parameters

The neural network has 16 inputs consisting of two sets of 8 inputs for weft and warp yarns. As it has mentioned, the textile raw material is limited to natural fibres at this stage. Following is the inputs for weft yarn inputs. Warp yarns input is the same:

Weft material- Wool percentage: The normalized percentage of wool in weft yarn material. It is a number between 0 and 1.

Weft material- Linen percentage: The normalized percentage of linen in weft yarn material. It is a number between 0 and 1.

Weft material- Cotton percentage: The normalized percentage of cotton in weft yarn material. It is a number between 0 and 1.

Weft material- Silk percentage: The normalized percentage of silk in weft yarn material. It is a number between 0 and 1.

The yarn structure is a combination of 4 factors: One filament or Multifilament, Degree of twist, Flat or Textured and Thickness. The yarn structure exclusive of yarn thickness is not directly determined with pattern recognition in the work conducted so far, but the level of yarn texture and its hairiness is determined with frequency analysis.

Weft Structure- Number of filaments: The average number of filaments is estimated by supervisor. In one filament yarns (just silk in natural material) it is straightforward, but in multifilament yarns the exact number of filaments is not accurate and vary in different cross-sections of the yarn. Therefore the average is estimated and used as system input.

Weft Structure- Degree of twist: The degree of twist is defined in this project as *the number of twist per cm*. The degree of twist is not measured with pattern recognition techniques and is fed in to the system manually.

Weft Structure- Texture level: the yarn texture level spectrum varies from fully flat yarn to fully textured yarn. Level of yarn texture and its hairiness is determined with frequency analysis in pattern recognition. As it was discussed in crossed state detection, for each detected cell the Discrete Fourier Transform is applied to convert the cell data to frequency domain. If the power spectrum of the cell has many peaks with more than 10% of the maximum peak, the cell is too textured and hairy. If the power spectrum has just few peaks with more than 10% of the maximum peak, the cell is less textured and more flat. The average of the number of peaks for weft yarn is calculated by averaging the number of peaks in all the weft cells. Then a number between 0 and 1 is assigned to texture level based on this number. The value 0 means completely flat when the average is less than 3 (experimental value) and 1 means completely textured and hairy when the average is more than 1000 (experimental value).

Weft Structure- Thickness: The weft yarn diameter for each cross-section is known from pattern recognition phase. The average of this diameter in metric system is used as an input for neural network structure.

4.8.2 Neural Network output parameters

In this stage of the project, the static and dynamic friction and textile compressibility are selected for static modeling of the textile. This approach could be generalized in future for other physical and mechanical properties. In textile objective assessment, a curve for each parameter is calculated which shows the nonlinearity of textile behavior and also non-homogenous structure of the artifact. The artifact samples selected homogenous and just an average value of each parameter is used. In other words, the textile behavior is considered linear for these physical parameters. The output parameters are discussed in more depth below:

Static Friction: when the user put his/her finger in one artifact and start to move the finger, the static friction between the finger and the textile resists against the movement. This static friction changes in weft and warp directions and varies in different positions of the textile. The objective assessment measures two curves for both directions. For simplicity, the neural network just estimates an average static friction coefficient for the whole artifact. System verification shows that simplification does not significantly affect the user tactile perception that much. Realistically the haptic device accuracy is less sensitive than the error produced due to this assumption.

Dynamic Friction: when the user moves his/her finger over the textile artifact, a dynamic friction resists against the movement. The same conditions of static friction are applied here. In an ideal situation, the dynamic friction coefficient varies according to different velocities and forces. In this work, an average coefficient is used in order to simplify the model.

Compressibility: When the user applies a pressure on the textile artifact, the artifact resists against this pressure by exerting a force against the pressure. A rigid textile shows higher resistance and has a smaller compressibility factor. The compressibility is defined as force generated per compressed distance and is non-linear in a physical system. In this work, however, the textile compressibility is assumed linear as an ideal spring which resists against the applied force and represented by $F=-K.X$, where K is the coefficient of compressibility. The neural network algorithm estimates the average of the compressibility for the textile to minimize the linearization error.

4.8.3 Neural Network architecture

The neural network system developed in this study to recognize the textile physical properties is a three layer Perceptron. The unsupervised back-propagation learning method is used for tuning the system weights for any specific problem. The training and validation steps are discussed later. The first layer has 16 neurons for 16 inputs. The output layer has 3 neurons for 3 outputs. The hidden layer size is different for any specific problem. There are different ways available to estimate the hidden layer size. One of the famous empirical rules is the mean of input and output layer size. In this approach, different hidden layer sizes from 5 to 15 neurons are examined to find the minimum error in back-propagation training. The average of input and output layer size is 10 and so a boundary around this point is selected. Figure 46 illustrates variation of error against various hidden layer for plain weaving pattern.

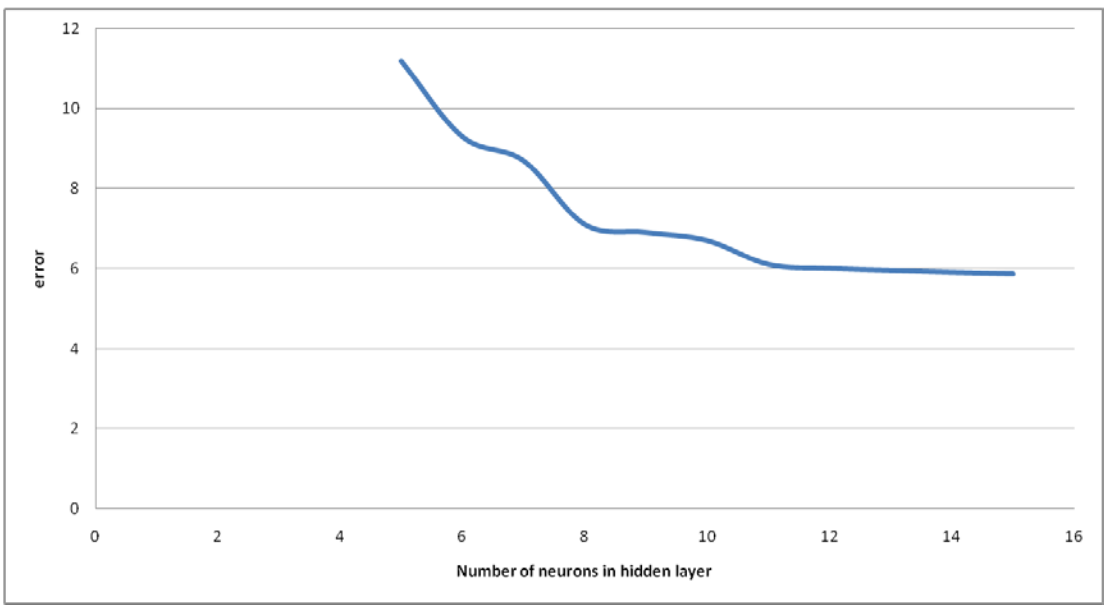


Figure 46. Number of neurons in hidden layer and the error in back-propagation

The variation of execution time against the size of the hidden layer for plain weaving pattern is shown in Figure 47.

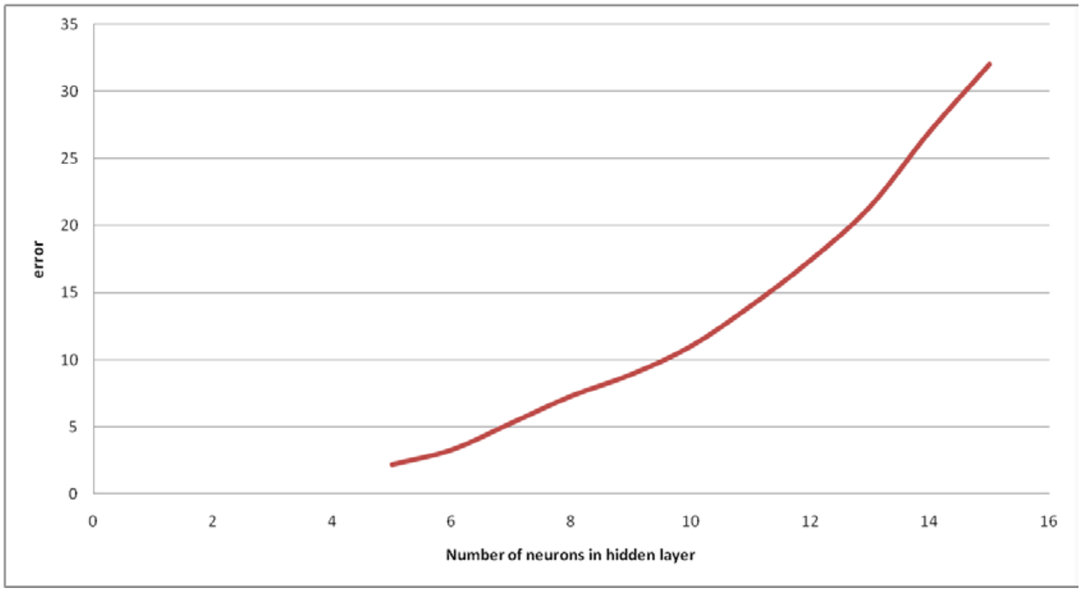


Figure 47. Number of neurons in hidden layer and the execution time

As illustrated by these two diagrams, the system error decreases with an increase in the number of neurons in the hidden layer while the execution time is increased. The change in system error for hidden layers sizes more than 11 is not significant. However, the execution time for hidden layer of size 16 is almost twice of 11. For that reason, the hidden layer size is assumed 11 as the best threshold for less error and faster execution time. The same method is applied for other weaving patterns (Currently just plain and twill have been experimented.)

Learning ratio and primitive weights are estimated with the same type of experiments before back-propagation training. As a result, the learning ratio and weights have been assigned with some experimental values for better performance.

4.8.4 Neural Network training and validation

For back-propagation learning algorithm to work, the input and measured output for a set of samples are required, and then the back-propagation method can tune the weights and minimize error between the estimated output and the real measured ones. In order to train the neural network and validate it in this work, the database produced by Gider [119] was used. This data was generated empirically by testing 185 fabric samples on a Kawabata system.

A rule of thumb in artificial intelligence in design of neural networks is to use 20% to 30% of the available data for training and the remaining for the validation of the algorithm. Due to small size of samples, 50% of them were used for training. As it was mentioned before, for each primitive weaving pattern a separate neural network instance is used. In this stage, the study is limited to plain and twill weaving patterns. A total of 32 plain and 41 twill samples from the database were selected. Half of them were used in back-propagation learning and the other half in system validation. The output of the Kawabata machine is the compressibility curve. The average value of the curve is calculated as the system output.

Table IV shows the system error during validation for plain and twill samples (16 plain samples and 21 twill samples are used in validation).

Table IV - Neural Network validation result

	Plain Neural Network System	Twill Neural Network System
System error in validation	13%	17%

This also demonstrates the efficiency of the approach in estimating the physical and mechanical properties of the textile. In order to reduce the error, the whole system is trained again with all the samples (32 plain and 41 twill samples). The back-propagation error was decreased to 10%. Overall, the low number of samples in the training can be considered as a deficiency of the approach.

4.8.5 Mechanical/ physical model generation with neural network

From 21 hand-woven samples which have been investigated in the geometric model generation, 7 plain and 6 twill samples were selected. The data associated with these samples were applied to the tuned neural network to estimate the physical/mechanical properties of the samples. These properties were then superimposed over geometric model for creating the haptic model of the textile artifacts.

Chapter 5

Textile Haptic Modelling

5.1 Introduction

By superimposing the artifact mechanical model over 3D geometric model, the haptic model is generated and implemented in Reachin environment.

Several hand-woven artifacts have been modeled with the proposed methodology and the corresponding haptic models. These models have been rendered in Virtual Manipulation Laboratory and implemented on a Phantom haptic device. The whole validation process shows the efficiency and reliability of the system and the possibility of further industrial applications in museums, both in the physical environment and through the cyberspace.

The issues and the process of haptic modeling with integrating the 3D geometric and mechanical models and implementation of the model in Reachin environment is addressed in this chapter.

5.2 Haptic devices and controlling

The force feedback device (FFD), one of the most popular haptic devices, replicates the normal and tangential forces generated during the contact of the user's fingers with the fabric in the virtual environment [37]. The most popular commercial haptic device, Phantom, is manufactured by Sensable Technologies. The 6DOF PHANTOM employed in this research is illustrated in Figure 48. It is a pen-based device through which the user can touch a virtual object. The pen can reach all the points in its workspace.

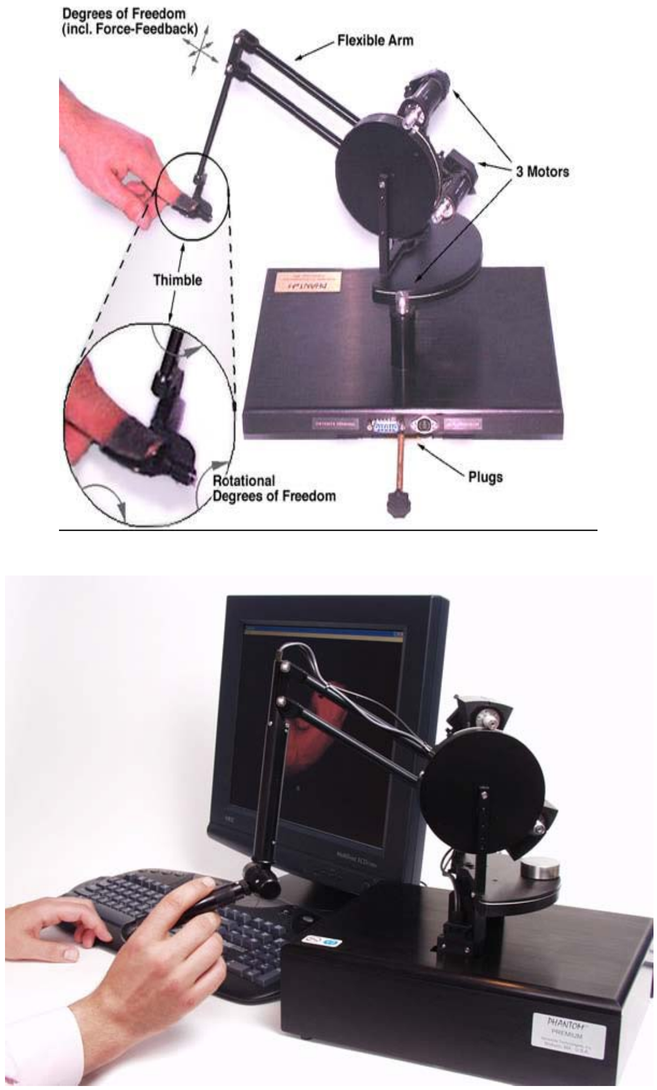


Figure 48. The PHANTOM 6DOF haptic device

The HAPTEX project proposes a specific device for textile haptic interface which is illustrated in Figure 49. This device has mountings for two fingers of the user which can create a better sense of touch in textile field.

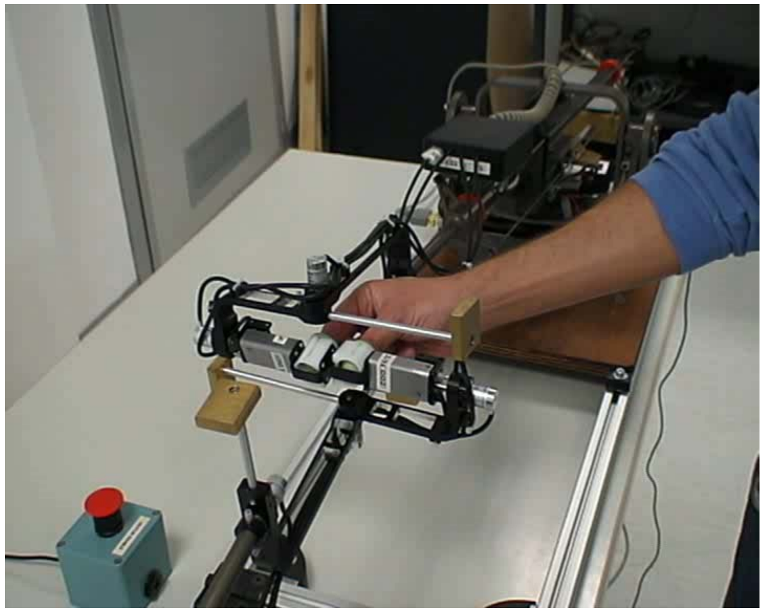


Figure 49. The HAPTEX haptic device

Bergamasco et al. suggest new haptic devices for textile haptic rendering [120] with focus on design of a high performance multi-point haptic interface. They have proposed a haptic device design and shown that the demanding requirements can be met by integrating a high performing force sensor in the closed loop control. A methodology to achieve motion based explicit force control on the basis of the dynamic parameters has been discussed and the details of implementing the HAPTEX system are provided.

The recent developments show that haptic device is moving fast from academic and industrial applications to home users. Such a simple device for home user is shown in Figure 50.

Figure 50. A haptic device for home user

Some new mobile phones with built in haptic interface are shown in Figure 51.

Figure 51. Haptic interface on new mobile phones

Figure 52 shows an advanced haptic device which is like a glove. The user can wear the device and touch the virtual objects. This device is not a force feedback system. It is based on the function of tactile receptors in human skin including Pacinian and non-Pacinian receptors which can be stimulated through vibrations. This already has been discussed before in “**Applied psychological and tactile perception”** section**.**

Figure 52. An advanced glove haptic device

5.3 Haptic implementation platforms

These are different platforms used for implementing a haptic model. A comparison study based on [4] is carried out in this section.

To develop applications with the Phantom series, Sensable provides two toolkits; G*host* and *OpenHaptic*. Both toolkits can be used to program the haptic rendering environments through the Phantom by specifying the geometry and the physical/mechanical properties of the objects.

The graphic rendering is employed in OpenGL. Both toolkits handle two loops including a haptic loop called servo loop running at 1 kHz and a graphic one running at 30 Hz. *Ghost* uses a scene graph structure to deal with the Virtual World and hence is efficient to manage large scenes. It is feasible to load a static scene directly from a VRML file. In this case, the user can feel the geometric objects using the default physical/mechanical properties. An optional library GhostGL can be used for the graphic rendering. The GhostGL parse the scene graph and then uses OpenGL for the graphic rendering.

OpenHaptic comes with two APIs at low level (HDAPI) and high level (HLAPI). With HLAPI, the geometry of the object is specified to the haptic renderer with calls patterned after OpenGL. HLAPI enables the integration of haptics into OpenGL applications. It uses three loops; the graphic, the servo loop and an additional collision loop that runs at 100 Hz responsible for detecting the collision between the haptic end cursor and virtual objects.

HDAPI allows direct communication with the haptic device by reading positions and sending forces and torques. It also handles threading issues and safety cut-offs such as maximum force or exceeded temperature. The low level API allows the developer to control the force feedback without any limitation and in low level. It gives a specific scheduler for managing the threads through. The API provides an interface for Phantom Device Drivers (PDD) at the lowest level and derives the position and force data.

SenseGraphics, author of *H3D*, utilizes the X3D and openGL open standards to build a scene graph-based API based on OpenHaptic toolkit to add the management capability of a scene graph application. It is built on the top of HLAPI, and it only supports the Sensable haptic devices.

Boeing proposes the *Voxmap PointShell* Software that specifies the haptic rendering using voxel. It is organized into three modules:

1. A voxelisation engine that also computes basic collision detection
2. A swept volume module that extracts the exact touched volume
3. A force generation module that computes the forces to be sent

This software uses ghost to communicate with device.

One of the well-known platforms in haptics community is Reachin implemented by Reachin Technologies. *Reachin API 4.0* provides support for developing haptic applications. This API supports different devices such as the phantom form Sensable or the delta and Omega form Force Dimension or the laparoscopic surgical workstation from immersion. Also in this case, the program sources are not publicly available.

The Reachin API is a programming interface for multi-sensory interactive applications development. It is designed to give the programmer a fully extensible programming framework for building interactive applications and prototypes. It combines haptic and graphic rendering capabilities into one straightforward API. The Reachin API is a C++ API based on the VRML scene graph model. It can be easily programmed using VRML and Python as a scripting language or directly with C++.

CHAI 3D is an open source solution proposed by researchers from the Stanford University. It can be used in high level or low level programming. One of the limitations is that it only supports 3 degrees of freedom.

Finally, a new open source solution was presented recently by researchers from the Sirslab - University of Siena: the *Haptik library.* The Haptik library is a component-based open-source library which offers a hardware abstraction layer to access haptic devices. It is built using loadable plug-ins that allow an extensible layout. The disadvantage is that it only supports haptic device access and not graphical display.

Reachin is deployed in this study due to its advantages compared to other platforms. It is VRML based and could be easily extended from 3D geometric model in VRML. It is also system and haptic device independent which make it suitable for future applications with other haptic devices.

5.4 Reachin environment for haptic modeling and programming

Reachin API is based on the concept of the scene graph. A scene graph is a hierarchical data structure that describes a 3D scene. It holds the geometry of all objects in the scene and their relative positions, appearance attributes such as color, transparency, textures and surfaces and also light sources, viewing position and information about the scene. A scene graph provides a framework for managing objects in a scene, and makes it easy to express the relationship between those objects [27].

The Reachin API is a multi-sensory rendering engine that integrates visual and haptic rendering through the use of one single scene graph. It parses the graph and presents the 3D presentation of the objects as well as providing tactile perception for the world [27].

The main node in Reachin graph scene is shape. Each shape encapsulates a shape object in virtual world. Each shape node has two fields: geometry and appearance. Table V shows the geometry nodes in Reachin which is similar to VRML. The appearance node itself has four fields: material, texture, texture transform and surface. The first three are common between Reachin and VRML, but surface is Reachin specific which abstracts the physical and mechanical properties of the object. Table VI demonstrates the surface nodes (These tables cited from Reachin programming guide [27]).

Table V - Some of the Reachin API geometry nodes

Geometry Nodes	Description
Box	A three dimensional box
Cone	A three dimensional cone
Cylinder	A three dimensional cylinder
Sphere	A three dimensional sphere
IndexedLineSet	Arbitrary 3D geometry formed by polylines between 3D vertices
IndexedFaceSet	Arbitrary 3D shape formed by polygonal faces between vertices
IndexedTriangleSet	Arbitrary 3D shape formed by triangles between vertices
Membrane	Deformable IndexedFaceSet
ImageTextFace	A geometry that renders text

Table VI - Some of the Reachin API surface nodes

Surface Nodes	Description
SimpleSurface	A simple surface implementation only surface repulsion
FrictionalSurface	***FrictionalSurface*** extends the ***SimpleSurface***, adding static and dynamic friction
ImageSurface	A surface texture based on an image
FrictionImageSurface	A ***FrictionalSurface*** whose starting_friction and the dynamic_friction are determined by the grayscale component of an image
RoughSurface	***RoughSurface*** implements an algorithmically textured surface
BumpmapSurface	A ***BumpmapSurface*** uses a grey-scale image as a height-map over the surface, from texture coordinates to height
MagneticSurface	***MagneticSurface*** is a template for modifying surface types sp the surface appears to be magnetic. Current magnetic surfaces available are ***MagneticSimpleSurface***, ***MagneticBumpmapSurface*** and ***MagneticFrictionalSurface***
ButtonSurface	***ButtonSurface*** is a template for modifying surface types so that they behave like a push-button, for instance ***ButtonSimpleSurface***, ***ButtonFrictionalSurface*** and ***ButtonBumpmapSurface***

Following is the hello world example of a haptic model. It is just a box with default values for static and dynamic frictions:

```
#VRML V2.0 utf8
Group {
    children [
        Shape {
            appearance Appearance {
                surface FrictionalSurface{}
                }
            geometry Box { size 0.1 0.1 0.1 }
            }
        ]
    }
```

Surfaces make the creation of solid objects tremendously easy. By specifying geometry with the same VRML structure and then describing a surface, VRML files can be made solid and have different haptic properties. Some default surfaces are API built-in and more can easily be added. Following is the short description for each one.

5.4.1 SimpleSurface

SimpleSurface is the base class for all the other surfaces which adds two properties of surfaces including stiffness and damping. Stiffness is measured in Newton per meter and damping in Newton seconds / meter. Stiffness shows how much the surface pushes against the user's haptic interface, the higher the stiffness the harder the surface feels. It can be considered similar to a spring from the tip of the haptic interaction device to the surface. Damping is the retardation force that is offered when entering a surface. In real surfaces it is extremely large and rapidly applied. Following shows a sample surface block:

```
…
surface SimpleSurface {
        stiffness 100      # 0-1100 Changes around these values
        damping 1.5        # 0-1.5 ( Keep lower ( ~0.5 )  if stiffness > 200
        }
…
```

5.4.2 FrictionalSurface

FrictionalSurface adds friction to the model for haptic interaction. Friction is added in the same way as it is modeled in Newtonian Mechanics, by having friction coefficients. The starting friction is another name for static friction and is relative to the amount of resistance that is needed before the tip of the haptic device can move on the surface. The dynamic friction is the friction in movement and the stopping friction is the friction met before static friction becomes the friction mode. The stiffnessT is the same as stiffness except that it is along the plane of the surface instead of normal to it. It can be considered as a spring that goes from a theoretical interaction point on the surface to the actual tip of the haptic interaction device. Following shows a sample surface block:

. . .

surface FrictionalSurface {

startingFriction 0.8

dynamicFriction 0.4

stoppingFriction 0.2

stiffness 900

stiffnessT 700

damping 0

}

. . .

5.4.3 RoughSurface

RoughSurface is a child of FrictionalSurface. It simulates a surface like a sand paper. The haptic device's motion is constantly stopped and a new starting friction value is randomly calculated using a Gaussian probability distribution with a mean and standard deviation supplied by the user.

. . .

mean 0.5

deviation 0.1

. . .

5.4.4 BumpmapSurface

The BumpmapSurface uses a texture to estimate the surface depth at any point. The grey values for a texture are used to generate heights below the surface, with the maximum value being the full bumpHeight below the surface. Following example shows a sample textile used for generating the 3D surface 3D:

```
. . .
surface BumpmapSurface {
        texture ImageTexture { url “urn:inet:reachin.se:/test.png”
       }
        bumpHeight 0.001
        . . .
        }
. . .
```

5.4.5 FrictionImageSurface

While BumpmapSurface uses a texture to set the values for the height value from a surface, FrictionImageSurface uses a texture to modulate the starting and dynamic friction for a surface:

```
…
surface FrictionImageSurface {
            texture ImageTexture { url "urn:inet:reachin.se:/test.png"
                        }
                        startingFriction 0.8
                        stoppingFriction 0.3
                        dynamicFriction 0.5
                        stiffness 900
                        stiffnessT 700
            }
}
…
```

5.4.6 Button Surfaces

ButtonSurface can be used to create surfaces that create an event when they are activated. Two events are activated, the armed event, when the surface is touched and the activate event when the surface is released. It is the last primitive surface node.

5.4.7 Dynamic objects

In physical simulations of an object or rigid-body dynamics simulation, some API functionality in Dynamic node allows solid objects to be manipulated using forces in a realistic manner. The Dynamic node is a derived class of the Transform node and so inherits its fields. In addition it allows physical properties to be specified. It runs a rigid-body mechanics simulation to define the rotation and translation of the coordinate space. As it has been declared before, in this stage of the project, static modeling is applied and hence this node is not used, however more information about this node could be find in the programming reference [27].

5.4.8 PythonScript and C++

In order to carry out more complicated tasks, an event generated is deployed to synchronize different activities. This is achieved by creating a new type of **Node** sub-class in C++, with interface to VRML and executed within VRML scene as a processing object. Another approach is to use a node called PythonScript which contains a URL field that references a python script or defines python code directly prefixed by python. More information could be found in the programming reference [27].

5.5 Haptic model implementation in Reachin

The 3D geometric model is generated as a VRML file as it is discussed in chapter 2. The primitive physical properties of the textile artifacts are estimated by employing neural network. A haptic model generator is developed to convert the VRML pure geometric model to a full haptic Reachin code. A FrictionalSurface node is added to each shape in VRML code. The FrictionalSurface fields are calculated from artifact physical parameters. The following Reachin code shows the haptic model. The changes in VRML file are highlighted:

```
#VRML V2.0 utf8
 Group {
      children [
           Shape {   # each disk of the yarn modeled with one shape object bounded by two cross-sections
                appearance Appearance {
                material Material {}
                texture ImageTexture {
                url " "  # could be the part of artifact image
                }
                surface FrictionalSurface{
                     startingFriction 0.8  #Directly from artifact static friction estimated in textile mechanical/physical model
                     dynamicFriction 0.4  #Directly from artifact dynamic friction estimated in textile mechanical/physical model
                     stoppingFriction 0.2  # an empirical friction of startingFriction, like %50
                     stiffness 900  #Directly from artifact compressibility estimated in textile mechanical/physical model
                     stiffnessT 720  # an empirical friction of stiffness, like %80
                     damping 0.9 # zero or an empirical friction of stiffness, like %0.1
                }
                }
                geometry IndexedFaceSet {
                     coord Coordinate {
```

point [# each cross-section demonstrates by 13 points and there are two cross-section for each disk so 26 points are located here

x0, y0, z0

x2, y2, z2

…

X25, y25, z25

]

}

coordIndex [# the triangles as primitive polygons for creating the 3D object

0 1 2 -1,

3 2 1 -1,

2 3 4 -1,

5 4 3 -1,

4 5 6 -1,

7 6 5 -1,

6 7 8 -1,

9 8 7 -1,

8 9 10 -1,

11 10 9 -1,

10 11 12 -1,

13 12 11 -1,

12 13 14 -1,

```
                                15 14 13 -1,
                                14 15 16 -1,
                                17 16 15 -1,
                                16 17 18 -1,
                                19 18 17 -1,
                                18 19 20 -1,
                                21 20 19 -1,
                                20 21 22 -1,
                                23 22 21 -1,
                                22 23 24 -1,
                                25 24 23 -1]
                      solid TRUE
                      }
          },
          Shape { # the next disk and so on
               ...
               }
               ...
          ]
}
```

The Reachin file is then loaded with ReachinLoad program. The artifact is displayed as a 3D object in virtual reality world and can be touched by the haptic device. The virtual artefact now is ready to be explored.

5.6 Alternative methods for textile haptic modelling with Reachin built-in facilities

These are two built-in facilities in Reachin which could be employed for fast haptic modelling of textile. Although they are not as accurate and reliable as the method developed in this work, they could be used for checking the model validity and efficiency.

In one method BumpmapSurface node is used to create a 3D surface from the textile still image. It is straightforward by creating a box with small height and then putting a textile image as its texture and Bumpmapsurface. The validity of this model will be examined later in the validation section.

The other method uses FrictionImageSurface node for estimating the frictions from textile still image. This method is also straightforward and is used as the first method.

5.7 Model validation

The 3D geometric model has been generated for 21 samples. From them, 13 twill and plain samples have been selected for mechanical/physical model generation. The haptic model generation method developed in this work is applied to all the samples. In addition, other haptic models using Bumpmapsurface and FrictionImageSurface have been generated for comparison and validation.

Several subjective experiments were designed and implemented to examine the model validity and performance of the methodology. The experiments are described blow.

In the first experiment, 5 observers were selected. Each one was instructed to touch the 13 hand-woven artifact samples and the haptic models developed for them by using the Phantom haptic device. The observers were given 3-5 minutes to examine each real artifact and the corresponding haptic model. For accurate comparison, a pen with the same shape as haptic device pen was given to each. The observers were asked to touch the real artifact with the pen and the haptic model with Phantom device. They would then give a score of 0 to 10 for each sample, with 0 indicating no similarity and 10 means complete similarity. The candidates were told to pause for 2-3 minutes between samples. The experiment took about 1.5 to 2 hours for each observer. They were then asked to repeat the experiment for Bumpmapsurface and FrictionImageSurface methods in the following day. The sequence of samples was changed in each set of experiments, eliminating the previous judgment on the result.

The average of similarity scorers gathered from five candidates for 13 samples are provided in Table VII for each method.

Table VII - The subjective experiment result for 13 samples and 3 different methods

Sample number	1	2	3	4	5	6	7	8	9	10	11	12	13	The Method Average
FrictionImageSurface	3.6	4.2	2.6	6	5.2	4.8	6.2	4.4	3.2	3.6	4.2	5.4	6.4	4.6
BumpmapSurface	4.2	3.8	3.4	5.2	6.4	5.6	5.8	4.2	5.6	3.2	5.8	7.4	6.8	5.2
Proposed method	4.4	7.2	6.8	8.2	7	8.8	7.8	6.6	7.8	6.8	8.4	8.8	7.2	7.4

As shown in the table, the subjective assessment of the three methods has identified the highest similarity score for the method proposed in this work using the developed 3D geometric and physical models. The FrictionImageSurface method is the worst one. The proposed method shows an average similarity score of 74% which is about 60% lead over FrictionImageSurface method and around 40% improvement over BumpmapSurface.

In the second experiment, each observer was exposed to 3 artifact samples and the haptic model of one of the samples. The model was randomly chosen and the observers were not informed of the corresponding sample. The observers were then expected to identify the sample by examining both the model and the samples. Each candidate was given three minutes for each model. The experiment was repeated for FrictionImageSurface and BumpmapSurface haptic models as well as the model developed in this work. Fifteen haptic models were observed by each candidate, 5 in each group. Therefore 25 tests were carried out for each haptic group.

The overall results are provided in Table VIII, illustrating the number and percentage of true identification for each haptic model.

Table VIII - Number of True identification in 25 tests for each haptic group

	Number of True Identification(25 total)	**True Identification Percentage**
FrictionImageSurface	12	48%
BumpmapSurface	16	64%
Our method	21	84%

As highlighted in the table, identification based on the proposed method has again score the highest with true identification percentage of 84%. The true identification rates for FrictionImageSurface and BumpmapSurface are only 48% and 64% respectively. The result shows almost 75% and 31% improvements over FrictionImageSurface and BumpmapSurface respectively.

Both experiments prove the validity and efficiency of the proposed model with acceptable success rates.

Chapter 6

Conclusions and further work

6.1 Overview

The primary focus of the thesis was to explore the feasibility of developing a generic approach for 3D haptic-rendered modeling of hand-woven textile artifacts. The methodology developed relies on processing of the still images of the artifact using computational intelligence as well as the knowledge of the artifact material and yarn structure. Effort was made to ensure that the developed mechanism was a faster and more reliable alternative for textile modeling compared to the costly and time consuming manual fabric hand assessment. The approach was also designed to build the haptic model of the textile based on an accurate 3D geometric model of the artifact rather than conventional 2D mesh structure used for graphical representation.

The work carried out towards this goal has been presented in this thesis as a series of chapters in an order corresponding to the successive stages of the research. The major features of the work includes the development of a non-rigid pattern recognition method for textile artifacts, a 3D geometric model generation system, a neural network system for artifact mechanical and physical properties estimation and an automatic haptic model generator.

Haptic Modeling of textile has attracted significant interest over the last decade. In spite of extensive research, no generic system has yet been proposed. The available systems require time-consuming manual textile objective assessment in laboratory conditions. The development of a generic approach for haptic modeling of hand-woven textile artifacts is the main contribution of this work.

Textile pattern and structure are recognized by digital processing of the still image of the textile artifact. A fuzzy rule-based expert system is developed to perform the recognition process. The data obtained in this process is employed to automatically generate the 3D geometric model of the artifact in VRML. Selected mechanical properties of the object are estimated by applying textile geometric characteristics and yarn properties to a neural network system. These mechanical properties are then deployed in the construction of the textile mechanical model. The mechanical model is superimposed over the 3D geometric model for an integrated haptic model. The system has been validated by modeling different textile samples. The primary application of this system is in museums to provide tactile interaction between the visitors and textile artifacts.

Overall, the work conduced in this study offers a novel 3D generic haptic modeling for textile artifacts. It can be deployed in museums providing an opportunity for the visitors to touch unique samples of hand-woven textile artifacts. The approach is cost-effective, reliable and reproducible as the haptic modeling of these samples does not need time-consuming and costly laboratory conditions.

6.2 Setting the scene

In the first chapter of the thesis, the overall concept of the project was introduced with an emphasis on its unique contribution. The principles of textile artifact geometric, and mechanical and haptic modeling were discussed and the shortcomings of the available systems were addressed. The gap in the current knowledge was identified and the research questions were defined. The methodology proposed to carry out the work was introduced and the architecture envisaged for the system was described. The significance of the work was highlighted and its advantages compared to the previous work were identified. The chapter was concluded by elaborating on the overall objectives of the work and a description of the thesis structure.

6.3 Evolution in textile haptic modeling

In Chapter 2, a thorough review of the previous work on haptic modeling of textile was carried out. The review further highlighted the uniqueness of this work and the potential benefits that an automatic generic haptic model generator could offer to industry and the research community.

Hence, the focus of the work was concentrated on filling the gaps in 2D mesh structures for textile graphic representation and objective assessment of fabric hand which were the main weaknesses of the available systems. The previous works applying image processing techniques in haptic modeling were reviewed and their differences and similarities with this work were identified.

6.4 Textile geometric modeling

Textile geometric modeling was discussed in chapter 3. The basic weave patterns, yarn structure and other aspects of the hand-woven artifacts geometric modeling were addressed. The available textile pattern recognition methods in the literature were then reviewed. These methods cover crossed-points detection which deals with interlacing areas between warp and weft yarns and crossed-states detection which is concerned with which yarn is over the other in the interlacing areas. A novel generic and flexible method for recognizing the structure of an artifact was proposed, implemented and validated. This method was based on image processing concepts and Fourier image analysis techniques, employing a fuzzy rule based expert system. This represented one of the major contributions of the work. Based on pattern recognition outputs, a textile geometric model generation method was proposed. This method generated a 3D geometric model of the artifact in VRML which could be explored in a virtual reality world viewer.

Some experiments were conducted to validate the model. The experiments and the results were discussed in chapter 3.

6.5 Mechanical/ physical modeling of textile artifacts

Chapter 4 was dedicated to the mechanical and physical modeling of textile. Fabric hand, subjective and objective methods used for evaluation of fabric hand and the factors affecting it were discussed. Textile mechanical and physical properties were reviewed and a summery of literature review of textile mechanical and physical modeling was provided. Some of the physical/mechanical properties of the textile were chosen and deployed in a proposed neural network system to estimate the physical properties of the textile. The outputs of the neural network were used in generating the physical/mechanical model. This is another major contribution of the work.

6.6 Haptic modeling of textile

Chapter 5 discussed the generation of the textile haptic model by superimposing the physical model on the 3D geometric model. A comparison study of various haptic devices and haptic platforms was carried out based on which Reachin programming environment was chosen for this project. Reachin fundamentals in the framework of this work was discussed and the haptic model implementation in Reachin was reviewed. Two different methods for textile haptic modeling techniques based on Reachin built-in facilities were proposed. Validation of the methods demonstrated a superior performance compared to two others methods used in industry.

6.7 Current constraints and further work

Further research can concentrate on different aspects of the proposed approach to improve the performance of the system. These improvements could be categorized as follow:

6.7.1 Improvement of image processing techniques and the fuzzy rule based system

The image processing techniques and the fuzzy rule based system currently have an accuracy of 85% for detection of crossed-points and 87% for crossed states in homogenous artefacts. Further work is required to improve these detection rates, particularly for non-homogenous artifacts.

6.7.2 Improvement of 3D geometric model generation

Also, in the current algorithm, the yarn floating is modeled as sinusoidal curve and the yarn cross-section as ellipsoid. Further work is required to explore more effective mathematical models. The new model should also include changes in the yarn cross-section in different parts of the artifact due to friction, compression and internal forces to produce a more accurate representation of the artifact.

6.7.3 Improvement of the neural network

The current system is designed based on a limited number of training data. The effectiveness of the algorithm can be improved by increasing the size of the training data generated through objective assessment of samples. The future study can also examine other neural network architectures and learning methods to identify the most effective algorithm for this application.

Other physical and mechanical properties of the textile artifact could be considered in the study to provide a dynamic model of textile using finite elements to provide shearing and bending capabilities compared to current static model.

6.7.4 Improvement of the haptic model

The current haptic model is static. Further work is required to create a dynamic model by incorporating an improved 3D geometric model and mechanical model. The work can also examine more effective computing and developing platforms for faster and more accurate haptic model.

6.7.5 Improvement of the haptic device

The pen-shape Phantom device was adequate for model validation. In real applications, however, a more appropriate haptic device such as glove haptic interface is required. The future work will be required to either identify a device from the available systems such as HAPTEX or develop a new device to create more natural sense of textile touch for user.

Appendix I The image processing Matlab code

```
clear;
check=5;
lenght=5;
check2=0;
counter_temp=1;
data=imread('c:\sample3.bmp');

data1=histeq(data);
data1_size=size(data1);
data1_size=data1_size(1);
for( num=1:data1_size/lenght)
  col=sum(data1((num-1)*lenght+1:num*lenght,:));
  s2=size(col);
  s2=s2(2);
  %plot(col);
  minimums_temp=findminima(col);
  %remove near minimums...(data correction)
  s=size(minimums_temp);
  s=s(1);
  counter_min=1;
  minimums(1)=minimums_temp(1);
  for i=2:s
    if abs(minimums(counter_min)-minimums_temp(i))>10
      counter_min=counter_min+1;
      minimums(counter_min)=minimums_temp(i);
```

```
        else
            %minimums(counter_min)=fix((minimums(counter_min)+minimums_temp(i))/2);
        end
    end

    %data correction for maximums
    maximums_temp=findmaxima(col);
    s=size(maximums_temp);
    s=s(1);
    counter_min=1;
    maximums(1)=maximums_temp(1);
    for i=2:s
        if abs(maximums(counter_min)-maximums_temp(i))>10
            counter_min=counter_min+1;
            maximums(counter_min)=maximums_temp(i);
        else
            %maximums(counter_min)=fix((maximums(counter_min)+maximums_temp(i))/2);
        end
    end

    % work with edited minimum
    mean_min=mean(minimums);
    mean_max=mean(maximums);
    s=size(minimums);
    s=s(2);
    for i=1:s
        k=minimums(i);
        count1=0;
        count2=0;
```

```
    if (k<check+1) | (k>s2-check)
       continue;
    end
    %if (k> (1+check2)*mean_min)
     %   continue;
    %end

    for j=k-check:k-1
       if col(j)<=col(k)
          count1=count1+1;
          break;
       end
    end

    for j=k+1:k+check
       if col(j)<=col(k)
          count2=count2+1;
          break;
       end
    end

    if ((count1==0)&(count2==0))
       data((num-1)*lenght+1:num*lenght,k-1)=255;
       mins(counter_temp,1)=(num-1)*lenght+1;
       mins(counter_temp,2)=k;
       mins(counter_temp,3)=0;% not used flag
       counter_temp=counter_temp+1;
    end
end
```

```
% for maximum

s=size(maximums);
s=s(2);
for i=1:s
  k=maximums(i);
  count1=0;
  count2=0;
  if (k<check+1) | (k>s2-check)
    continue;
  end

  %if (k< (check2)*mean_max)
   %   continue;
  %end

  for j=k-check:k-1
    if col(j)>=col(k)
      count1=count1+1;
      break;
    end
  end

  for j=k+1:k+check
    if col(j)>=col(k)
      count2=count2+1;
      break;
    end
  end
```

```
        if ((count1==0)&(count2==0))
            data((num-1)*lenght+1:num*lenght,k)=0;
        end
    end
end

%figure, imshow(data);
imwrite(data,'c:\output10.bmp');



data2=data1';
data2_size=size(data1);
data2_size=data2_size(2);
for( num=1:data2_size/lenght)
    colc=sum(data2((num-1)*lenght+1:num*lenght,:));
    s2=size(colc);
    s2=s2(2);
    %figure, plot(colc);
    %minimums=findminima(col2);


    minimumsc_temp=findminima(colc);
    %remove near minimums...(data correction)
    s=size(minimumsc_temp);
    s=s(1);
    counter_min=1;
    minimumsc(1)=minimumsc_temp(1);
    for i=2:s
        if abs(minimumsc(counter_min)-minimumsc_temp(i))>10
```

```
        counter_min=counter_min+1;
        minimumsc(counter_min)=minimumsc_temp(i);
    else
        %minimumsc(counter_min)=fix((minimumsc(counter_min)+minimumsc_temp(i))/2);
    end
end

%data correction for maximums
maximumsc_temp=findmaxima(colc);
s=size(maximumsc_temp);
s=s(1);
counter_min=1;
maximumsc(1)=maximumsc_temp(1);
for i=2:s
    if abs(maximumsc(counter_min)-maximumsc_temp(i))>10
        counter_min=counter_min+1;
        maximumsc(counter_min)=maximumsc_temp(i);
    else
        %maximumsc(counter_min)=fix((maximumsc(counter_min)+maximumsc_temp(i))/2);
    end
end

% work with edited minimum
mean_minc=mean(minimumsc);
mean_maxc=mean(maximumsc);
s=size(minimumsc);
s=s(2);
for i=1:s
    k=minimumsc(i);
```

```
    count1=0;

    count2=0;

    if (k<check+1) | (k>s2-check)

        continue;

    end


    %if (k> (1+check2)*mean_minc)

     %   continue;

    %end


    for j=k-check:k-1

        if colc(j)<=colc(k)

            count1=count1+1;

            break;

        end

    end


    for j=k+1:k+check

        if colc(j)<=colc(k)

            count2=count2+1;

            break;

        end

    end


    if ((count1==0)&(count2==0))

        data(k,(num-1)*lenght+1:num*lenght)=255;

    end

end

%maxumums
```

```
s=size(maximumsc);
s=s(2);
for i=1:s
    k=maximumsc(i);
    count1=0;
    count2=0;
    if (k<check+1) | (k>s2-check)
        continue;
    end

    %if (k<(check2)*mean_maxc)
     %   continue;
    %end

    for j=k-check:k-1
        if colc(j)>=colc(k)
            count1=count1+1;
            break;
        end
    end

    for j=k+1:k+check
        if colc(j)>=colc(k)
            count2=count2+1;
            break;
        end
    end

    if ((count1==0)&(count2==0))
```

```
            data(k,(num-1)*lenght+1:num*lenght)=0;
        end
    end
end

imwrite(data,'c:\output11.bmp');

% add for finding the yarn cross section

counter_col=1;
while(1==1)
    [minsr,indr]=sortrows(mins,2);
    size1=size(minsr);
    size1=size1(1);
    for temp=1:size1
        if minsr(temp,3)== 0
            break;
        end
    end
    if temp>=size1
        break;
    end
    first_k=minsr(temp,2);
    first_r=minsr(temp,1);
    yarn(counter_col,fix(first_r/lenght+1),2)=first_k;
    yarn(counter_col,fix(first_r/lenght+1),1)=first_r;
    mins(indr(temp),3)=1;
    %k_min=first_k;
    %k_max=first_k;
```

```
temp_dis=0;
for ( i=first_r-lenght:-lenght:1)
  find_r=find(mins(:,1)==i);
  [c,ind]=min(abs(mins(find_r,2)-first_k));
  if abs(mins(find_r(ind(1)),2)-first_k)<200
    first_k=mins(find_r(ind(1)),2);
    mins(find_r(ind(1)),3)=1;
    temp_dis=0;
    %if first_k<k_min
     %   k_min=first_k;
    %end
    %if first_k>k_max
     %   k_max=first_k;
    %end
  else
    temp_dis=temp_dis+1;
  end
  if temp_dis>5
    break;
  end
  yarn(counter_col,fix(i/lenght+1),2)=first_k;
  yarn(counter_col,fix(i/lenght+1),1)=i;
end
if temp_dis>5
  continue;
end
first_k=minsr(temp,2);
first_r=minsr(temp,1);
temp_dis=0;
```

```
for ( i=first_r+lenght:lenght:data1_size-lenght)
   find_r=find(mins(:,1)==i);
   [c,ind]=min(abs(mins(find_r,2)-first_k));
   if abs(mins(find_r(ind(1)),2)-first_k)<200
      first_k=mins(find_r(ind(1)),2);
      mins(find_r(ind(1)),3)=1;
      temp_dis=0;
     % if first_k<k_min
      %    k_min=first_k;
      %end
      %if first_k>k_max
      %    k_max=first_k;
      %end
   else
      temp_dis=temp_dis+1;
   end
   if temp_dis>5
      break;
   end
   yarn(counter_col,fix(i/lenght+1),2)=first_k;
   yarn(counter_col,fix(i/lenght+1),1)=i;
end
if temp_dis>5
   continue;
end
%for temp=k_min:k_max
%    v=find(mins(:,2)==temp);
 %   mins(v,2)=100000;
%end
```

```
    counter_col=counter_col+1
end

% adding yarn lines to data

for i=1:counter_col-1
    for j=1:data1_size/lenght-1
        x1=yarn(i,j,1);
        y1=yarn(i,j,2);
        x2=yarn(i,j+1,1);
        y2=yarn(i,j+1,2);
        m=(y2-y1)/(x2-x1);
        for x=x1:x2
                data(x,fix(m*(x-x1))+y1)=255;
        end
    end
end

%figure, imshow(data);
imwrite(data,'c:\output13.bmp');
```

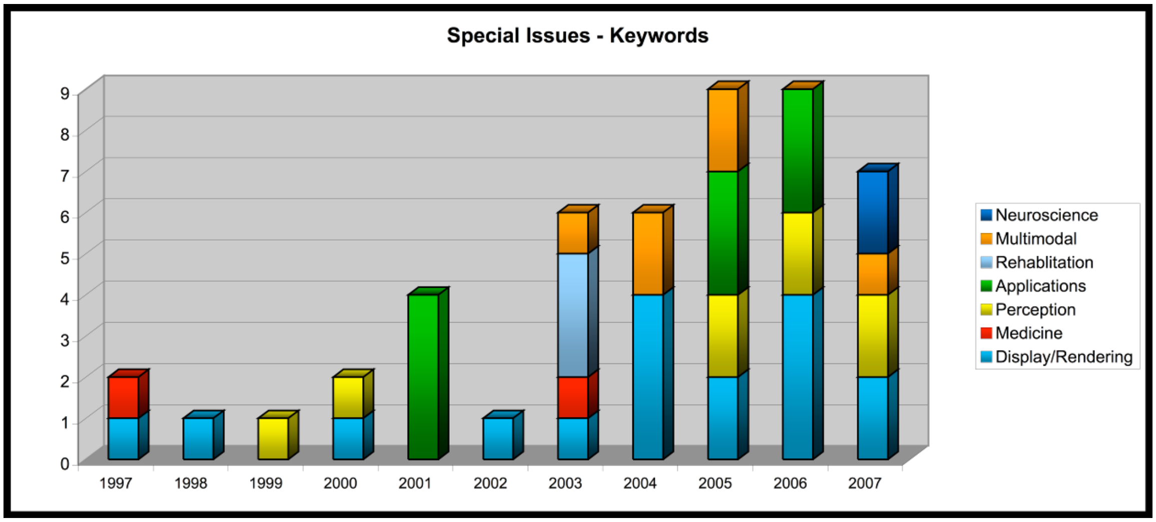
Appendix II International Journals and Conferences on Haptics

This is a list of international journals and conferences in haptic domain which have been investigated in literature review.

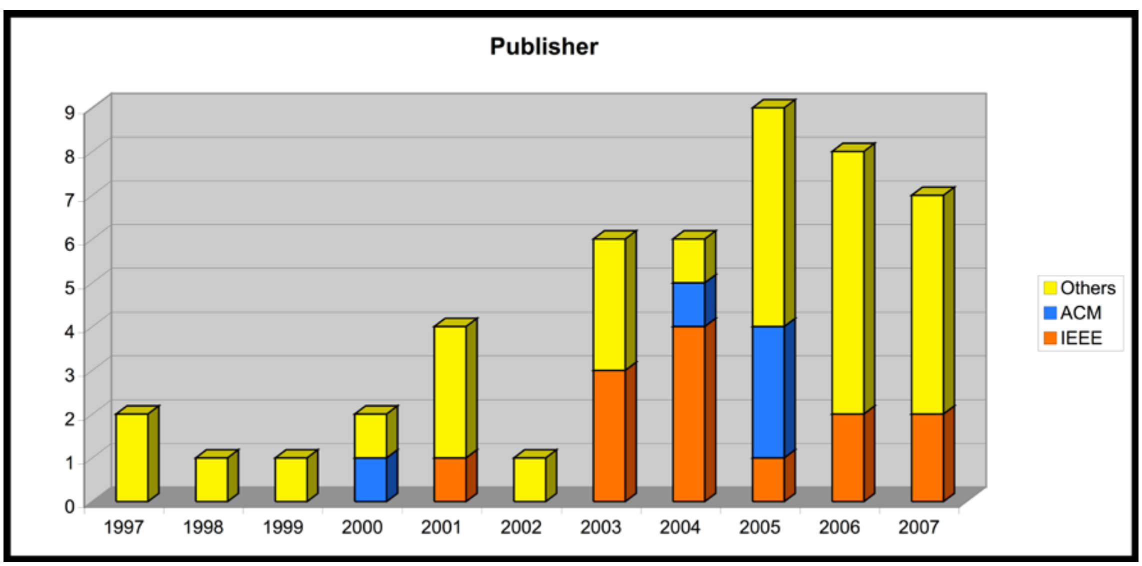
Based on statistics have been presented in TCH March 21, 2007 - Tsukuba, Japan, from 1997 when the first researches in haptic have been launched more than 48 special issues and books collections dealing with haptic have been published. The first special issue was “Haptic Displays in Virtual Environments” Computers and Graphics (Pergamon) V. 21, N. 4, 1997. The following tables show the latest special issues in haptic :

Virtual Environments, Human Computer Interfaces and Measurement Systems *IEEE Transactions on Instrumentation and measurements*	2007 A. El Saddik
Distributed systems and real time collaborative environments *Simulation: Transactions of The Society for Modeling and Simulation International*	2007 A. El Saddik
New Directions in the Sense of Touch *Canadian Journal of Experimental Psychology*	2007 S. Lederman, R. Klatzky
Re-mediating touch The Senses and Society	2007 M. Paterson, M. and A. Cranny Francis
Robotics and Neuroscience *Brain Research Bulletin*	2007 D. Prattichizzo, S. Rossi
Virtual Reality *IEEE* Trans. on Visualization and Computer Graphics	2007/ 2008 Ming C. Lin
Multi-Modal Modeling in Deign *Computer Computer-Aided Design (Elsevier)*	2007/ 2008 K. H. Lee, I. Stroud

Following figure shows the number of special issues pre year and the keyword:



Next figure demonstrates the publisher:



IEEE Transactions on Haptics is a new journal of IEEE and will address the science, technology and applications associated with information acquisition and object manipulation through touch. Haptic interactions relevant to this journal include all aspects of manual exploration and manipulation by humans, machines and interactions between the two, performed in real, virtual, teleoperated or networked environments.

Other journals and conference proceedings are:

1. IEEE Haptics Symposium Conference Proceedings
2. Haptics-e: The Electronic Journal of Haptics Research
3. Presence: Teleoperators and Virtual Environments Journal
4. ACM Transactions in Applied Perception

WorldHaptics is the Joint Eurohaptics Conference and IEEE Symposium on Haptic Interfaces for Virtual Environment and Teleoperator systems. After a series of successful conferences and events separately organized in the U.S. and Europe, the Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems and the EuroHaptics Conference was held jointly for the first time in 2005 in Pisa, Italy. This has been a great chance to create a truly global community in haptics, capable of answering the challenges, and grab the opportunities, offered by the growing demand of better interfaces to remote and virtual environments.

The goals of the IEEE Haptics TC/TF are to integrate the diverse interests of the highly interdisciplinary haptics research community and to improve communication among the different fields. It will serve to coordinate the scheduling of major haptics conferences, facilitate special conference sessions and journal issues on haptics, organize tutorials focused on haptics, and contribute towards a new IEEE Transactions on Haptics.

After the first successful edition held in Pisa in 2005, WorldHaptics 2007 was held on March 22-24 2007,at Epochal Tsukuba, Tsukuba, Japan. WorldHaptics 2009 will be held in Salt Lake City, Utah, USA, date TBA (likely mid-late March, 2009)

The World Haptic web site address is : http://www.worldhaptics.org/

The EuroHaptics Society has been officially founded on July 2nd, 2007 in Paris, France. Eurohaptics is held annually and is a major international conference and the primary European meeting for researchers in the field of human haptic sensing and touch enabled computer applications. This diverse field covers research in areas including, but not limited to, haptic perception, haptic hardware development, through to end applications and users, such as surgical simulation, rehabilitation robotics, and haptic feedback for design and applied arts applications.

The series of Eurohaptics events provides researchers from academia and industry with an opportunity to present ideas, obtain feedback and establish contacts with other haptics researchers from around the world. Haptic hardware and software developers are also provided with the opportunity to gather information on current theories, as well as to demonstrate their products to a wide audience, and discuss specific requirements first hand with existing and potential customers.

- EuroHaptics 2001 was hosted by the Univeristy of Birmingham, UK, and organised chiefly by Alan Wing
- EuroHaptics 2002 was held in Edinburgh, UK and organised by the University of Edinburgh and Edinburgh College of Art
- EuroHaptics 2003 was held between the 6th and 9th of July 2003. It was co-hosted by Trinity College Dublin and Media Lab Europe, and organised by Fiona Newell, Sile O'Modhrain and Ian Oakley
- EuroHaptics 2004 was held between the 5th and 7th of June 2004. It was hosted by Technische Universität München, and organised by Martin Buss, Marc Ernst and Matthias Harders
- EuroHaptics 2005 was held in Pisa, Italy on the 18th-20th March 2005 in conjunction with the Symposium on Haptic Interfaces
- EuroHaptics 2006 was held between the 3rd and 6th of July in Paris, France. It was organised by Abderrahmane Kheddar
- EuroHaptics 2007 was held in Tsukuba, Japan on the 22nd-24th March 2007 in conjunction with the Symposium on Haptic Interfaces.
- EuroHaptics 2008 is to be held between the 11th and 13th of June in Madrid, Spain.

EuroHaptics is available through: http://www.eurohaptics.vision.ee.ethz.ch/default.shtml

HAPTEX itself is an international conference on haptic modelling of textile. HAPTEX 2005, 2006 and 2007 proceedings are available trough IEEE web site and also HAPTEX project website [5].

Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems, commonly referred to as the "Haptics Symposium". This annual conference brings together researchers in diverse engineering and human science disciplines who are interested in the design, analysis, and evaluation of systems that display haptic (force and touch) information to human operators. Currently, the Haptics Symposium is held at WorldHaptics in conjunction with EuroHaptics in odd years (next in 2009) and in conjunction with IEEE Virtual Reality in even years (next in 2008). The proceedings of the Haptics Symposium are published by IEEE.

The Symposium information is available through: http://www.hapticssymposium.org/

Complete lists of all haptic conferences is available in following webpage of the Symposium:

http://www.hapticssymposium.org/other_conferences.htm

Following websites are haptic community websites which have information on haptic researches and industrial projects:

1. http://haptic.mech.northwestern.edu/index.html
2. Haptic Community Web Page

Appendix III International Haptic Research Laboratories

This is a list of 47 research centres and laboratories in the field of haptic:

1. ALTAIR (A Laboratory for Teleoperation and Autonomous Intelligent Robots), Verona University, Department Computer Science - headed by Prof. Paolo Fiorini
2. Biorobotics Laboratory, University of Washington - headed by Dr. Blake Hannaford
3. BioRobotics Laboratory, Korea University of Technology - headed by Dr. Jee-Hwan Ryu
4. Dexterous Manipulation Laboratory, Stanford University - headed by Dr. Mark Cutkosky
5. GRASP Lab Haptics Group, University of Pennsylvania - headed by Dr. Katherine J. Kuchenbecker
6. Haptic Exploration Lab, Johns Hopkins University - headed by Dr. Allison M. Okamura
7. Haptic Interface Research Laboratory, Purdue University - headed by Dr. Hong Z. Tan
8. Haptics and Embedded Mechatronics Lab, University of Utah - headed by Dr. William R. Provancher
9. Haptics and Virtual Reality Laboratory, POSTECH, Korea- headed by Dr. Seungmoon Choi
10. Haptics Laboratory, McGill University - headed by Dr. Vincent Hayward
11. Haptix Laboratory, University of Michigan - headed by Dr. Brent Gillespie
12. Harvard Biorobotics Laboratory, Harvard University - headed by Dr. Robert D. Howe
13. Human-machine Interaction Lab, Beihang University - headed by Dr. Yuru Zhang
14. Human Machine Interface Lab, Rutgers University - headed by Dr. Grigore Burdea
15. Human Robotics Lab, Imperial College London - headed by Etienne Burdet
16. Interdisciplinary Institute for Neuromusculoskeletal Research (IINR) - headed by Dr John Howell
17. MAHI Lab, Rice University - headed by Dr. Marcia K. O'Malley
18. Microdynamic Systems Laboratory, Carnegie Mellon University - headed by Dr. Ralph Hollis
19. MIT Touch Lab, Massachusetts Institute of Technology - headed by Dr. Mandayam A. Srinivasan
20. LIMS Lab, Northwestern University, directed by Drs. Ed Colgate, Michael Peshkin, and Kevin Lynch
21. Salisbury Research Group, Stanford University - headed by Dr. Kenneth Salisbury

22. Sensory Perception and Interaction Research Group (SPIN) - University of British Columbia, headed by Dr. Karon MacLean
23. Touch Laboratory, Queen's University - headed by Dr. Susan Lederman
24. Virginia Touch Laboratory, University of Virginia - headed by Dr. Gregory J. Gerling
25. Virtual Reality Laboratory - University of Buffalo, headed by Dr. T. Kesavadas
26. Visualization and Image Analysis Laboratory - CMU Robotics Institute and the University of Pittsburgh Department of Bioengineering, headed by Dr. George Stetten
27. Advanced Displays and Spatial Perception Laboratories, NASA Ames Research Center
28. Center for Intelligent Mechatronics, Vanderbilt University (list only)
29. Computer Vision and Robotics Laboratory, UI Chicago
30. Human-Machine Interface Laboratory, Rutgers University
31. Immersive Environment Research, University of Utah
32. Laboratory of Dexterous Manipulation, Umea University
33. Microtechnology Medicine and Biology, University of Wisconsin (list only)
34. Mind/Brain Institute at Johns Hopkins, (list only)
35. Multimodal Interaction Group, Glasgow University
36. Northwestern University
37. Orbital Systems Laboratory, University of Colorado
38. Precision and Intelligence Laboratory, Tokyo Institute of Technology (list only)
39. Princeton Cutaneous Communication Laboratory (list only)
40. Research Laboratory of Electronics, MIT
41. Robotics and Control Laboratory, University of British Columbia
42. Robotics and Intelligent Machines Laboratory, University of California at Berkeley
43. Sensorimotor Research Unit, University of Melbourne (list and abstracts)
44. Stanford Dextrous Manipulation Laboratory
45. Stanford Robotics Laboratory
46. Stanford Telerobotics Laboratory
47. MIRALab - University of Geneva

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