Vision guided cutting and mechanical handling of lace ribbon

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Vision Guided Cutting and Mechanical Handling of Lace Ribbon

By

Yongliu He

Doctoral Thesis Submitted in Partial Fulfilment For The Award of Doctor of Philosophy of Loughborough University

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Abstract

Mainly used for decorative purpose in the textile industry, lace is a type of lightweight, openwork fabric. The process of lace manufacturing is complex but much of it has been highly automated with the advancement of modern technology. One exception is the lace cutting operation which is used to cut the wide lace webs (as wide as 3.8 m) knitted from automatic knitting machines into individual lace breadths. Currently, lace cutting is carried out by skilled operators or a low speed mechanical cutting system, leading to high cost and increased product lead times. Therefore the lace cutting operation has become a bottleneck of the whole process of lace manufacturing and its automation is highly desired. Based on the combination of machine vision and laser cutting technology, two automatic lace cutting systems have been developed in Loughborough University, which have fully demonstrated the feasibility of replacing the slow and expensive traditional lace cutting methods. However, the edge quality of the lace cut by these systems is not satisfactory enough to meet the requirements of demanding lace markets.

In this thesis, based on the investigation of the effect of handling tension on lace cutting edge quality and the microstructure of lace, a strategic lace cutting solution has been presented. The cutting strategy is aimed at tensioning and exposing the loop thread by strategically tensioning and cutting individual threads. The loop thread is considered critical to cutting lace with a high quality finish. To automatically implement the cutting strategy, a machine vision system has been developed.

An automatic lace transport and tensioning rig has been designed and manufactured. The long term aim of this rig is to be able to transport and tension lace continuously for lace cutting and apply localised tension on individual threads with the vision system providing feedback for tension control. The work in this thesis has been limited to manual adjustment of the rig to prove the initial ideas for this concept.

An integrated vision guided, pulsed laser cutting system for lace cutting has been developed, based on which two types of representative lace have been cut. According to the assessment results of using a combination of user trials, microscopic and newly developed measurement techniques, the lace cut by this newly developed system has shown significant improvement in cutting edge quality, when compared to the lace cut by the previous laser cutting systems.

Keywords: machine vision, lace cutting, lace edge quality, image processing, edge quality assessment, laser cutting.
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1 Introduction

Lace is a type of lightweight, openwork fabric, mainly used for decorative purpose in the textile industry. Lace has a history of over one thousand years, but was not popular until the 16th century. At that time, lace was regarded as an extravagance and was extraordinarily expensive because lace production by hand was slow and labour intensive. According to the production method, hand-made lace could be categorized into several types, such as needle lace, bobbin lace and braid lace [1]. In 1808, the first lace knitting machine was invented by John Heathcoat, which was capable of producing an exact imitation of real pillow-lace. Since then, lace production machinery has undergone dramatic development and today lace production has been highly automated using computer controlled knitting looms.

From customer requirements to the final delivery of the finished lace to customers for further processing, the lace production process consists of several stages. The first stage involves discussion with clients to establish lace design which is then transferred to a highly specialized CAD package. Machine control codes are then generated to control the thousands of electromagnetic actuators to manipulate each individual thread to form lace. The produced lace web is usually 3 meters wide and 100 meters long, containing many individual patterned lace breadths which are typically 15mm to 250mm wide. The lace is then dyed and stentered before it is separated into individual lace breadths. The separated lace is then inspected, packaged and eventually dispatched to customers. The whole lace production process is shown in Figure 1-1.
1.1 Background

In contrast to the highly automated and computerized lace design and knitting stage, which has benefited greatly from industrial technology advancement, some other stages of lace production, especially the lace cutting process, are far less automated and skilled operators are usually employed. This lack of automation in the lace cutting process is due to the inherent flexibility and complex structure of lace, which make it difficult to properly handle lace and automatically find the cutting path along which lace breadths are removed from the backing mesh. Therefore, lace cutting stage has become a bottleneck of the whole lace manufacturing process, leading to high cost and increased product lead times.

In the UK where labour cost is relatively high, solving the problem of automating the lace cutting process has become imperative to keep the lace manufacturing industry alive. The competitors from overseas are putting increasing pressure on the lace manufactures in the UK by taking advantages of lower labour cost in their countries. To keep up with the competition, one possible solution is to move the entire manufacturing operation to these regions where overall cost can be greatly reduced by employing local people for lace cutting operation. But this will result in loss of jobs and revenues in the UK.

Based on the research work carried out previously [2, 3], the research project presented in this thesis continues to investigate the challenges of automating the lace cutting operation and the associated issues.

1.1.1 Lace terminology

Specific lace terms are used within the lace industry. As these terms will be used throughout this thesis, it would be useful to specify them here to avoid any misunderstanding or confusion.

Despite the wide range of different pattern designs, all types of lace have a number of features in common. As shown in Figure 1-2, a piece of lace is usually comprised of the waste mesh and the lace pattern section, with the waste mesh thinner than the lace pattern section.
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Chapter 1

Waste mesh

Lace pattern

30mm

One pattern repeat

Figure 1-2 Lace structure

Waste mesh

Purls

Figure 1-3 Lace purl structure

Connection threads

Purls

Figure 1-4 Lace purls and connection threads
The lace pattern section consists of many repeats, each of which has a similar pattern but is never exactly the same due to knitting tension variation along and across the lace breadth. The edge of the lace pattern section, along which the waste mesh should be removed, consists of a series of purls, as shown in Figure 1-3 and Figure 1-4. The waste mesh is connected to the lace pattern through connection threads, which are linked with the purls or knitted into the lace pattern directly.

Originally linen, silk, gold, or silver threads, lace threads are usually made of synthetic fibers, such as nylon 66, nowadays [4]. Usually 100μm to 300μm in diameter, lace threads comprise of many small fibers, each of which has a diameter of 10μm to 20μm.

1.1.2 Lace cutting operation

There are two types of lace cutting operation, centre cutting and scalloping cutting, as shown in Figure 1-5. Centre cutting operation involves separating two lace breadths along the centre line between them and is usually carried out by hands with scissors. Scalloping operation is for cutting off the waste mesh along the side of the lace breadth and is the focus of this research project. Throughout this thesis, lace cutting refers to scalloping operation unless particularly stated otherwise.

![Figure 1-5 Lace cutting types](image-url)
Currently, lace cutting operations are carried out either by employing skilled operators to cut with scissors or using a low-speed mechanical system as shown in Figure 1-6.

The mechanical cutting system consists of a cutting table, on which a guidance head and a rotating knife are mounted. The guidance head is positioned in such a way that only thin waste mesh can pass through between the guidance head and the cutting table while the thicker lace pattern cannot pass through. The cutting operation requires an operator to hold the lace against the guidance head and then the lace is cut by the rotating knife. The cutting process is slow, inaccurate and lacks the ability to carry out centre cutting as there is no thickness difference between two lace breadths. In addition, the cutting process requires constant operator attention and suffers from snagging and tearing.

Figure 1-6 Mechanical lace cutting system
1.1.2.1 Loughborough CW laser cutting system

Research focused on developing an automatic lace cutting system utilising a machine vision guided laser cutting system has been carried out at Loughborough University since 1991. The developed system is able to automatically separate the lace pattern section from the waste mesh using a continuous wave (CW) CO$_2$ laser [5]. The system works by automatically finding the cutting path and then guides the laser beam along the detected cutting path to cut the lace. The system is able to cut lace in real time at speeds up to 1 m/s, with an accuracy of 0.5 mm, with the lace moving continuously. Figure 1-7 shows the major components of the system.

![Diagram of Loughborough CW laser cutting system](image)

In order to reduce the data volume and hence data acquisition time to increase the system operation speed, a line scan camera is selected to image the moving lace. The lace is locally back-lit, with the necessary illumination provided by a fluorescent tube connected to a high frequency ballast. The electronic ballast is running with a DC supply that provides further mains frequency rejection. The resulting illumination is extremely
uniform and flicker free. Based on a DSP (Digital Signal Processor) processing unit, the cutting path is found by comparing each line of the captured image to a stored reference image, which is created by scanning one pattern repeat and defining the desired cutting path manually. The data of the determined cutting path is then transferred to control the galvanometer scanner which moves the mirror to position the laser beam to the appropriate point on the cutting path. The encoder is used to synchronize the lace movement with the camera and the laser control unit [6].

By using two sets of galvanometers and DSP processing units, the system can be extended to cut two cutting paths simultaneously at 250 mm/sec. The system speed was increased to 1050 mm/sec by using a hardware correlator to enhance the image processing performance.

The system was then further developed by Shelton Vision System Ltd and a production prototype machine was built as shown in Figure 1-8. The system was effective for centre cutting but the scalloped lace edge quality was not satisfactory and failed the quality test conducted by lace manufacturers due to the thermal damage caused by the laser beam “clipping” the lace pattern edge purls.
1.1.2.2 High accuracy pulsed laser cutting system

In order to improve the lace cut edge quality, a high accuracy lace cutting system has been researched and realised [2]. The lace is cut by applying a short pulse of laser energy directly on to individual threads which connect the lace pattern section to the waste mesh. The system is based on a machine vision system which is used to image the lace illuminated by a ring LED light source that produces a transmissive illustration method. The method highlights lace density difference between the lace pattern section and the waste mesh, which facilitates the detection of the cutting point. Figure 1-9 shows all the detected cutting points marked with a circle with a cross.

![Lace pattern section](image)

Figure 1-9 Cutting point detection

The major components of the system have been shown in Figure 1-10. The edge directed algorithm developed to locate the cutting point on each individual thread-purl intersection does not rely on any prior knowledge and therefore is able to accommodate a certain degree of lace distortion and local variation at the sub-millimetre level. The coordinates of the cutting point are transferred to the lace positioning control unit to move the lace until the cutting point is aligned with the laser spot within a predefined accuracy. Then a single pulse of laser energy is applied on the cutting point to cut off the connection thread.

Compared to the early CW laser cutting system described previously, the lace cut by this pulsed laser cutting system has improved the lace cutting edge quality [7]. The
improvement is achieved in two ways. Firstly, without relying on prior knowledge, the cutting point detection algorithm is able to accommodate lace distortion and therefore locate the cutting point more accurately than the CW cutting system which is based on template matching techniques and therefore suffers from random lace geometry variation in the sub-millimetre range. Secondly, operating the laser in the pulsed mode to cut the lace threads can greatly reduce the thermal damage to the lace edge.

However, preliminary inspection of the edge quality of the lace cut by this system has identified that the laser damage is still present and the cutting result is not consistent.

![Diagram of High accuracy pulsed laser cutting system](image)

**Figure 1-10** High accuracy pulsed laser cutting system (Bamforth, 2003)
1.2 Hypothesis

The developed high accuracy pulsed laser cutting system is able to cut lace by directing a pulsed laser beam to the cutting point on each individual thread accurately. Compared to the early CW laser cutting system, the lace cut by this system has much improved edge quality. However, preliminary inspection of the lace edge has revealed that laser damage is still present and the cutting quality of individual purls is not consistent. The paper in Appendix 12.11 details some work on lace edge quality assessment, which identifies that the edge quality consistency of the pulsed cut lace is approximately twice lower than that of the mechanically cut lace, as indicated by the standard deviation of the results (pulsed cut 0.013, mechanically 0.006).

In an attempt to further reduce the laser damage and improve the lace cutting edge quality consistency, it is considered to be a good starting point to first investigate the structure of individual purls together with their connection threads at a microscopic level. This would assist in a better understanding of the purl structure and identifying a way to cut lace strategically according to the connection structure of the lace purls. At the same time, lace handling method, especially handling tension, is speculated to play an important role in affecting the lace cutting edge quality. If the effect of lace handling tension on lace cutting edge quality can be proven to be beneficial, applying and controlling the handling tension would help to further improve the cutting edge quality.

Therefore, based on the current pulsed laser cutting system, it is proposed that the lace cut edge quality can be further improved by cutting lace strategically and dynamically according to its structure, applying and controlling the lace handling tension during the lace cutting process.
1.3 Research scope

The scope of this research project includes:

- Understand the high accuracy pulsed laser cutting system and identify the cause of the edge quality inconsistency of the produced lace
- Investigate the effect of the handling tension on the lace cutting edge quality
- Investigate the structure of each individual purl on a microscopic scale and develop a lace cutting strategy to improve the lace cutting edge quality
- Design and manufacture a lace handling rig
- Develop an automated system based on machine vision techniques to cut lace with the developed lace cutting strategy
- Identify the lace edge quality assessment methods to compare the lace edge quality cut by different cutting systems.


1.4 Methodology

As described in section 1.1 and section 1.2, the major deficiencies of the previously developed laser cutting systems are the laser damage generated during the cutting process and the cutting result inconsistency. In order to successfully achieve the automation of the lace cutting operation so that the low-speed mechanical cutting system can be replaced, these deficiencies must be overcome. To achieve the objective of further improving the lace cutting edge quality and consistency, the project is split into several sections, including handling tension effect investigation, lace structure investigation, lace cutting automation, and lace edge quality assessment.

1.4.1 Handling tension effect

The effect of the lace handling tension on lace cutting edge quality has never been studied by any researchers so far. The lace handling tension effect can be investigated by carrying out a series of lace cutting experiments. For each set of experiments, the handling tension applied on the lace being cut is different. The lace will be cut using the current high accuracy pulsed laser cutting system with all system parameters the same so that the edge quality difference among the produced lace is only attributed to the applied handling tension. Then by comparing the edge quality of the produced lace, the benefit of applying tension on the lace during the lace cutting process is beneficial or not can be established.

1.4.2 Lace structure investigation

Inspecting lace structure with naked eyes is of little value. It is necessary to use a microscope to observe the lace structure in detail. As the pulsed laser beam is directly applied on the detected cutting point where a connection thread intersects with the purl, observing how connection threads are linked with the purl will be the focus. Investigating lace structure can also help to identify how handling tension changes the lace shape and how this consequently affects the lace cutting edge quality. Based on a full understanding of lace structure and the effect of lace handling tension, a lace cutting strategy will be researched and developed, aimed at further improving the lace cutting edge quality.

1.4.3 Lace cutting automation

Lace cutting automation involves developing a system to automatically cut the lace at high speeds (approximately 1 m/sec). The task of building such a system can be divided
into several parts. The first part is building a machine vision system which is integral to the whole system. Designing and manufacturing a lace handling system used to transport and tension lace is another important part.

The feasibility and advantages of machine vision for lace cutting operation has been clearly proven and demonstrated by the two previously developed Loughborough lace cutting systems. Combined with a laser cutter, machine vision provides a non-contact method for lace cutting. This non-contact method is able to eliminate the lace distortion that any mechanical cutting system will cause. Based on the success of targeting each individual thread with high accuracy utilised in the current pulsed laser cutting system, a new machine vision system will be developed to automatically implement the proposed lace cutting strategy for lace handling tension control within the cutting zone.

The lace handling system is intended to transport the lace and control the tension applied on the lace during the lace cutting process. It is speculated that the tension control will rely on the machine vision system for tension feedback. Designing such a lace handling rig requires multidisciplinary knowledge and is heavily dependent on carrying out a series of preliminary lace cutting experiments.

1.4.4 Lace edge quality assessment

Without a reliable method to assess the lace cutting edge quality, there is no way to justify which cutting system is better than the others. Unfortunately, no standard lace cutting edge quality assessment method exists in the lace industry. Qualitative edge quality assessment methods have been used to compare the lace cut by the CW laser cutting system and the high accuracy pulsed laser cutting system in [2]. This qualitative method involves asking a number of people to assess the edge quality and therefore is subjective. As the lace edge with low quality is more coarse than the one with high quality, the friction force between the lace edge and a suitably resistant material can be used to compare the edge quality. The higher the friction force, the lower the lace edge quality. This assessment method is quantitative and therefore more objective.
2 Literature Survey

The literature survey carried out can be divided into three separate sections. As the fundamental basis of this research project, machine vision related literature will be investigated first. Then the fabric handling methods used in the textile industry and web handling techniques used in the web processing industry will be discussed. As a laser has been chosen as the cutting tool, the interaction between lasers and polymers will be investigated as well.
2.1 Machine Vision

Machine vision is being applied widely in various industries and its application range is growing rapidly. Fundamentally a machine vision system consists of an optical sensor (for example, a CCD camera) to capture images of the object being inspected, a light source to illuminate the object, and a processing platform (for example, a standard PC) to process the captured images using a combination of various image processing algorithms.

2.1.1 Machine vision applications in textile industry

Machine vision techniques are widely utilised in the textile industry, mainly for fabric cutting, inspection and manipulation. As early as 1985, Ameziane et al. [8] reported on a machine vision system for fabric cutting. A solid state camera working at video rates was used to capture the images which were then digitised and stored in an Intel 8085 computer. Each pixel value was stored in 8 bits and therefore 256 levels of grey were available. Four commercially available spot lights were used for illumination and histogram equalisation was performed prior to any further processing. The motif pixels were separated from those in background by a global grey level threshold. By taking advantage of the spatial periodicity of the placement rule of motifs on printed fabrics, the system could determine the trajectory of the cutting tool without any priori knowledge of the shape or size of the motifs. No effort was reported to optimize the processing time, but the encouraging results demonstrated the efficiency and feasibility of the approach.

Amin-Nejad et al. [9] described a position-based visual servoing system for edge trimming of fabric embroideries by a laser beam. The prototype workspace was a 1mx1m gantry table and the laser was mounted on the Z-axis of a four-axis Cartesian robot. Because the embroideries were made on standard fabrics which were normally opaque, the backlighting technique, often used for the illumination of translucent material, was not suitable for this project. A 10mW laser diode projecting a laser stripe onto the embroidery at a right angle to the seam was used as the illumination method. With this structured illumination, the seam position could be determined by analysing the distorted laser stripe corresponding to the seam edges. The image frame coordinates of the seam points were then passed to the control program for controlling the robot. The implemented image processing algorithm took about 4 ms to extract data from the captured image and the overall cutting speed was 50 mm/s with accuracy of +/- 0.5mm, which was faster than the
manual operation speed estimated to be 20 mm/s. The laser used for cutting is a 20W carbon dioxide laser, whose output power was controlled by pulse width modulation (PWM) through a PC. However, there was no report about the resulting cutting quality of the fabrics. Although the system performs well for cutting the fabric embroideries, it is considered not suitable for lace cutting operations. The thickness difference between the lace edge and the waste mesh is not so distinct as the difference between the embroideries and the base fabric which is about 1mm to 3mm. Furthermore, the lace edge is connected to the waste mesh by many single threads and therefore many holes are existing between the lace edge and the mesh, which are normally absent in embroideries fabrics. Based on these reasons, it is speculated that the illumination method combined with the image processing algorithm used for the embroideries trimming will be impossible to detect the cutting point for lace cutting operations. Also, maintaining the laser stripe normal to the seam for edge detection takes time, which can be completely avoided in lace cutting by employing other illumination methods. However, the illumination method is effective for detecting edges of normal fabrics, which is demonstrated in [10] where the edges of overlapping shoe components needed to be inspected prior to the sewing operation. A laser line was projected on the surface and then viewed by an area camera. A discontinuity in the observed laser line was caused by the surface height. Different approaches for extracting the edge positions in the image coordinate system had been investigated based on the Hough transform, spatial histogram, polynomial regression and the discrete first derivative. These edge detection algorithms were compared in terms of speed and precision performance and results showed that Hough transform provided the most reliable method for edge point extraction, although it was computationally expensive in terms of processing time.

Machine vision applications can also be found in automating fabric inspection processes. Manual inspection of fabrics is limited by ensuing fatigue and inattentiveness. It is reported that the most highly trained inspectors can only detect about 70% of the defects [11] and are not able to deal with fabric wider than 2 meters and moving faster than 30 m/min [12]. A real-time fabric inspection system based on a machine vision system is described in [12]. A line scan camera with 2048 elements was used for capturing fabric images and an air-cooled fluorescent tube provides 2200-6460 Lux intensity and operates at 40-50 KHz in order to avoid flickers. The inspection algorithm was composed of two algorithmic modules, the defect detection and feature extraction module and the defect
classification module based on neural network. The developed system had a high detection rate with a good localization accuracy and a low rate of false alarms. It was also compatible with standard inspection tools and inexpensive. A neural network based local textile defect detection system is reported in [13]. The defects were segmented based on the gray-level arrangement of their neighbouring pixels. According to the experimental results, this approach can obtain a high degree of robustness for the detection of a variety of fabric defects.

A vision-based fabric inspection system is also reported in [14] in which optimal 2-D Gabor filters were designed and applied to distinguish defective texture pixels from non-defective texture pixels. A pixel of potentially flawed texture was classified as defective or non-defective based on the Gabor filter response at that pixel. Using Gabor filters for detecting defects in textile fabrics is also described in [15]. Another inspection system based on a global image restoration scheme using the Fourier transform is reported in [16]. The line patterns of any directional textures in the spatial domain image were removed by detecting the high-energy frequency components in the Fourier domain image using a one-dimensional Hough transform, setting them to zero, and finally back-transforming to a spatial domain image. In the restored image, the homogeneous line region in the original image had an approximately uniform grey level, whereas the defective region was distinctly preserved. These three examples have demonstrated their time effectiveness by eliminating the need of template image comparison. The template matching method is applied in [17] where defects were detected based on their two fundamental structural properties, regularity and local orientation.

Other applications of machine vision in textile industry include vision-based yarn inspection to assess diameter variation, hairiness and twist characteristics of yarns used for the production of woven fabrics [18-20], cotton contaminants recognition via X-ray images [21], shirt collar inspection [22] and leather surface inspection [23].

2.1.2 Machine vision for lace inspection

Automatic lace inspection based on a machine vision system is a challenging task because lace fabrics can easily deform, and usually have complex patterns, making it very difficult to use any global image processing techniques. Research on automating lace inspection using machine vision dates back at least as far as 1988 when Norton-Wayne [24] started
working on a lace inspection project. The early work involved experiments performed in the laboratory using isolated samples of lace. It was found that the method of comparing the binarised image of the lace with itself shifted by one repeat of the pattern horizontally or vertically could be used to detect the defects in the lace, which formed the basis for the work of Sanby and Norton-Wayne presented in [25, 26]. A line scan camera synchronized with the motion of the knitting machine was used to capture lace images whilst the lace was still on the knitting machine, which could eliminate the distortion problem, although not completely. The false alarms caused by the ghost images following subtraction of successive repeats of the lace pattern were reduced by employing a neural network. However, this system did not take into account the defects caused during processes further down the production line, which means that further inspection is required for the finished lace.

Yazdi and King [27] later worked on automating the final inspection stage of lace manufacturing in which direct comparison between a reference image and an acquired image was performed. But the 'ghost' or 'residue' image after direct subtraction of these two images, which was caused by the distortion due to the inherent flexibility of lace, made the inspection task nearly impossible. A mechatronic approach capable of coping with unpredictable distortions and 'adapting' itself to small deformations was proposed and implemented, which greatly reduced the resulting noise and consequently the false alarms. Morphological filters were shown to be a powerful tool for 'cleaning-up' processes in the experiments. However, the system speed was slow—an inspection rate of only 30 mm/s was reported.

Lace inspection research based on direct comparison of the lace image being produced and a reference image is also conducted in Leeds University [28-30]. The inspection algorithm comprised of two distinct stages: the initialization stage, and the tracking and inspection stage. The initialization stage involved loading a perfect prototype image containing a single pattern repeat and synchronisation of the lace being inspected and the reference image. In the second stage, a cross-correlation technique was used to align the current lace image with the reference image by adjusting the current image to correct any lateral, longitudinal or skew distortions, and then a binary subtraction was carried out. This was followed by a morphological erosion filter to remove any residual noise and detect actual defects. Although the speed of the system is only 44 mm/s, it can be easily
improved by employing modern hardware. The developed system performs very well and is probably the most advanced vision-based lace inspection system so far.

2.1.3 Machine vision for lace cutting

The lace fabric manufacturing industry has benefited from advanced manufacturing technology in that high technology CAD/CAM knitting systems exist. However, the rest of the manufacturing processes such as cutting and material handling are still undertaken by human operators or conventional mechanical systems. In particular, the lace scalloping process operating on the mechanical machine is slow and fairly inaccurate requiring constant operator attention, and therefore has become the bottleneck for the whole lace production process, leading to increased product lead time [31].

As conventional lace cutting methods, which usually employ a mechanical cutting system or human operators, are slow and fairly inaccurate, automating lace cutting processes with modern technology has become the research focus in recent years. Applying machine vision in automating lace cutting operation has appeared to be a successful solution. Significant effort has been made to apply machine vision technology in automating lace cutting, trying to improve the cutting speed at a reasonable cost.

Russell and Wong described a lace cutting system in [32, 33]. The camera used was a modified DRAM chip which was interfaced to a single chip microcomputer and then to a personal computer. A special purpose template matching correlator was produced to execute an area match between a reference image and a current lace image to determine the cutting path. The matching was implemented by subtracting a slice of the input image from an equivalent slice on the reference image. By moving the input image over the entire reference map, the cutting position was determined by assessing the difference between the reference image and the input image at each point. This template matching technique, while capable of detecting the cutting path, suffers from the lace distortion problem, which is usually present during lace cutting processes. Therefore, the system reliability and performance are degraded.

As lace is flexible and easily distorts, the lace scalloping system needs to be able to tolerate some distortion to achieve a sufficient degree of automation. As the patterns and sizes of different lace samples are never the same, a cutting system which is able to cut
lace without prior knowledge of the lace pattern is desired. Such kind of lace cutting system, capable of detecting the cutting path without any prior knowledge, was developed in Nottingham Trent University by Shih, Sherkat and Thomas [34-36]. A fuzzy reasoning rule-based technique was applied to find the cutting path in the first frame. The cutting paths in the second and subsequent frames were determined by employing a novel approach named Line Mapping Method (LMM), which greatly increased the system speed. Depending on the complexity of the lace pattern, the time taken to find the cutting path in the first frame varied. Time taken for most kinds of lace motif was about 300 ms based on an Intel 80486 processor running at 66 MHz. However, up to 1.5 seconds was required for few very intricate lace patterns. By using the LLM method, typically the speed of tracking the lace pattern was around 25 to 35 meters per minute. Compared with the method used by Russell and Wong in [32, 33], this system has several advantages. The first one is that it is faster in that it can track the lace pattern with the speed of 0.4m/s based on a 486 computer, which can be further improved with modern powerful machines. The second advantage is that it does not need any prior knowledge of the lace pattern and therefore is able to cope with distortions more effectively. Unfortunately, no details are reported about the actual cutting operation and significant efforts have been made for the modelling of tactile cutting system, which can be easily replaced by a laser cutting system.

Ayub and Jackson [37] employed 2D pattern recognition techniques to detect the cutting path of lace. Initially, a master image template and required cutting path profile were stored in the cutting shape libraries. As lace is inherently flexible, it could be easily distorted by transport forces. Before the template matching was executed, a few distinct features on the lace were extracted for calibrating the master template. The master template were then calibrated according to elongation, translation, rotation and skew angle of the lace under cut. After the calibration procedures, the cutting path was extracted by searching patterns similar to the master template on the cutting area of the lace being cut. Although this method is trying to accommodate lace distortion by actively calibrating master template, it cannot accommodate excessive wrinkles of lace.

Several commercial organisations also made good progress in developing machine vision systems for lace scalloping. Optotex [38] developed a series of Opto-Cutter systems which were capable of scalloping lace and similar material. Either mechanical cutter (Opto-cutter 2001), or CO2 laser (Opto-cutter 2002-4 and Laser-cutter 1009) is available.
for cutting and the cutter is positioned using an x-y gantry type system. The cutting path is determined by utilising an edge following technique with a CCD line camera. The fastest system is the Laser-cutter 1009 system which is capable of cutting lace with a speed up to 57m/min. Also, these systems are capable of cutting the textile with all colours from black to white. Some parameters of these cutting systems are listed in Table 2-1.

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<tr>
<td><strong>Max cutting speed</strong></td>
<td>57 m/minute</td>
<td>Up to 12 m/minute</td>
<td>N/A</td>
<td>Up to 12 m/minute</td>
</tr>
<tr>
<td><strong>Transportation method</strong></td>
<td>Automatic pull in of fabric</td>
<td>From roll to roll</td>
<td>From roll to stack</td>
<td>From roll to roll</td>
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<tr>
<td><strong>Cutting method</strong></td>
<td>CO2 industrial laser, 100 Watt</td>
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Table 2-1 Parameters of Optotex cutting systems

Similar to the Opto-Cutter systems, another patented lace cutting system developed by Morrison technology [39] is also employing an edge following technique, eliminating the need for a predefined cutting path and therefore allowing for some degree of distortions. However, little detail about the algorithms and system speed has been reported.

Since 1991, extensive research in lace cutting area has been started in Loughborough University and a huge success has been achieved [5, 6]. A line scan camera rather than an area scan camera was selected because the line scan camera had the benefit of reducing data volume and hence data acquisition time, and provided the possibility of operating at higher data rates. The lace was locally back-lit, with the necessary illumination provided by a fluorescent tube connected to a high-frequency ballast. The electronic ballast was running with a DC supply that provided further mains frequency rejection. The resulting illumination was extremely uniform and flicker free. Three DSP processors were utilised with first one functioning as a supervisory processor to get the image information from the camera. The other two processors were used to track the two cutting paths on the lace. A specially developed weighted cross correlation algorithm [3] was utilised for tracking the paths based on a reference map which was created by scanning one pattern repeat and defining the desired cutting path manually. The CO2 laser used in the prototype machine...
was a 250 W continuous wave (CW) unit. The laser beam was delivered through a focusing lens onto a lightweight front-silvered mirror mounted on a galvanometer controlled by the two tracking DSP processors. A beam-splitter and a second set of optical components allowed two cuts to be made simultaneously.

The advantages of this system are that it can be used to track and cut two scalloping paths simultaneously in real-time and the cutting speed can reach up to 1 m/sec, which is much faster than any other lace cutting system currently available. Also, it is able to cope with significant amounts of distortions as high as 15% within the lace pattern, which will cause a cutting path detection failure in other systems using normal cross-correlation algorithms. However, as for some demanding lace markets where lace with a high level of edge quality is required, the resulting edge quality of the lace produced by the cutting system is not satisfactory.

Bamforth [2] developed another lace cutting system in Loughborough University. A Sony SSC-M370CE area scan camera and a Coreco Viper Quad frame grabber were used to capture the images of the lace. Instead of a fluorescent tube, a ring of LED lights were used for illumination, called the Transmissive Dark-Field Lighting (TDFL) method. Results showed that this illumination method greatly facilitated the detection of the cutting path of the lace because it highlighted the difference between the lace pattern and the waste mesh [40]. After the image processing system had detected the lace edge, the connecting points between purls and every single connecting thread could be determined. The lace was positioned by a x-y movable table driven by two stepper motors and a servo motor. After the current cutting point had been positioned accurately enough related to the laser spot, a pulsed laser beam was fired and the thread could be cut. The process was then repeated for each cutting point until the lace cutting process was completed. The lace edge quality obtained from this lace cutting system is much better than the one produced by the previous system in terms of the Heat Affected Zone (HAZ).

This pulsed laser cutting system is more accurate than the previous one in that the average targeting error is 0.073mm at the resolution of 30 pixels/mm. Moreover, this system is able to adapt to lace distortions because it is not based on any reference map. The reported 0.5 mm average cutting errors of the previous CW laser cutting system will not happen in this system. This novel targeting algorithm combined with the pulsed laser cutting method
ensures that better cutting edge quality can be achieved. However, due to the speed limitation of the x-y movable stage, the lace being cut needs to be stationary when the laser energy is applied.

2.1.4 Other applications of machine vision

Besides the textile industry, machine vision has found various applications in other fields. In this section, the applications of machine vision in food industry, robot guidance, agriculture, tool condition monitor, navigation system and face detection will be summarised.

Jia et al. [41] reported on a machine vision system built for automatic fish cutting. A Canny edge detector was used to extract the fish edge. Then a labelling and tracking algorithm based on recursive procedure was developed for locating, tracking and thinning the fish boundary. A two-stage, model-based segmentation algorithm together with the morphological knowledge of fish was proposed to locate each part of the fish, from which the cutting lines could be determined. The Canny edge detection required an average time of 7.8 seconds and all other algorithms required an average time of only 0.37 seconds. The speed could be improved for real time catfish processing by implementing the algorithms with special hardware. The problem of this method was that the accuracy of head cutting lines and tail cutting line determination was sensitive to whether the fish was significantly curved or not.

Machine vision has also been used increasingly in the food industry for inspection and evaluation purposes as it provides suitably rapid, economic, consistent and objective assessment when compared with the human graders and inspectors. Li et al. [42] reported on a machine vision system capable of grading apples according to the defect area. An automatic strawberry sorting system was developed by Bato et al. [43]. Average shape and size accuracies of 98% and 100%, respectively, were obtained regardless of the fruit orientation angle with judgment time within 1.8 seconds. Pear bruising detection using a machine vision system was studied by Zhang and Deng [44] in which the different bruised areas can be precisely detected with most relative errors controlled to within 10%. Sun [45] reported on inspecting pizza quality by extracting the topping exposure percentage with an accuracy up to 90%. Evaluation of pork quality has also been investigated [46]. The findings indicate that for 93% of the 44 pork loin samples,
prediction error was lower than 0.6 in neural network modeling, hence it is recommended as an effective tool for evaluating fresh pork color. A color machine vision system together with neural network was developed by Patel et al. [47] to inspect the poultry eggs.

Vision is a useful robotic sensor that allows the robot for the non-contact measurement of the surrounding environment. Many machine vision based robots can be found in factories for manufacturing, assembling, handling and inspection. Pauli et al. [48] reported on a vision-based integrated robot system for object inspection and handling. The robot system was composed of a robot manipulator and a robot head including two monochrome cameras. After calibration, the robot carried an object into the field of view of one camera, then approached the object along the optical axis to the camera, rotated the objects for reaching an optimal view, and finally the object shape was inspected in detail. Finally, the system localized a board containing holes of different shapes, determined the hole which fit most appropriately to the object shape, then approached and arranged the object appropriately. However, the speed problem prevents the system from being used for real time processing. In the current implementation, one servoing cycle for arranging the cylindrical peg requires about 0.5 seconds and it will become longer for more complex objects.

One of the innovative applications of vision in the automotive industry is at DaimlerChrysler’s assembly plant, where a vision system is used to guide a robot for handling large stamped body panels [49]. Eight Cognex In-Sight 1000C vision sensors are used to check the location, orientation and spacing of the 6.5 feet or 8 feet long stampings in its racking to assess whether the robot can access them and, if so, how. Six of the vision sensors guide the robot pickup operation, and other two guide the placement operation. The robot is tested in the real manufacturing environment and performed well. In addition to the manpower savings, this vision-guided robot also eliminates the need for the expensive, precision racking. Unfortunately, the speed of the robot is not available. Another vision-guided assembly robot used in automotive company is reported by Bone and Capson [50]. The cycle time for the assembly sequence was 3 min based on these experiments, and the accuracy of the completed assembly was +/-2mm. A rehabilitation robot used to assist physically handicapped or weak persons is reported by Song et al. [51]. A robot arm equipped with vision and force sensors is mounted on a wheelchair to
help users with some tasks which are usually difficult for users to complete independently. The system has been tested with four tasks including picking up a cup from the table, picking up a pen from the floor, operating a switch on a wall and moving an object to the user's face. The results show that the robot system is able to finish these tasks successfully. However, the speed problem needs to be solved before it can be commercialised.

The applications of vision systems in agriculture have been widely reported. An agricultural cultivator based on a machine vision system was reported by Slaughter et al. [52]. The results of a series of experiments showed that the precision of the system was comparable to that of an average manually guided cultivator. Under low weed loads the performance of the system was comparable to a very good cultivator operator, but with twice the travel speed. With this system, the cultivation results can be improved by using less skilled operators and the increased speed may allow larger farms to reduce costs by reducing the number of cultivators operating at the same time. However, the vibration and dust issues and the development of cultivation tools specifically designed for the high speed operation need to be solved for future improvement.

A vision sensor is considered to be the best one among various sensors providing outdoor environment information to control a harvesting robot [53]. However, serious problems arise when implementing an image processing system able to control a real harvesting robot, among which the greatest difficulty is from extreme variation in the lighting [54]. This problem is addressed by Plebe and Grasso [55] through a complex sequence of processing steps, which are aimed at providing a full localization of fruits in the scene for determining the robot motion. Edan et al. described a robotic melon harvester which is able to harvest fruit while advancing along the row in [56].

Machine vision is also applied for crop quality inspection and classification. Pablo et al. [57] developed a classification system capable of identifying the species of weed seed. The classification system works well for the number of species considered in this study, but further improvement is required for commercial usage where several hundreds of species need to be considered.
Machine vision based tool wear monitoring method is one of the direct tool wear estimation methods. It evaluates the tool condition by capturing the images of the tool surface, from which the information of tool condition can be extracted. Sortino [58] presented an innovative methodology and a system for wear measurement. A statistical filter was proposed to detect the edges of the image, which were then high-passed and worn area could be calculated. The results showed that the system was reliable, only failing to calculate the flank wear land of 8% of the cases due to some disturbance on the cutting edge. Kassim et al. [59] developed a system to estimate the tool condition using the workpiece surface texture analysis. The built system cannot be used for real-time monitoring because of the speed problem and the biggest drawback is that it can only distinguish between a sharp tool and a dull tool. Li et al. [60] reported a machine vision based tool monitoring system in which the state of the wear of the turning tool was determined from the captured images obtained by laser scattering from the machined surfaces of the workpiece. A neural network embedded with fuzzy classifiers was used to classify the state of the tool wear as 'negligible wear', 'some wear', 'more wear' and 'significant wear'. This 'laser scattering images' technique was also adopted by Li, Wong and Nee in [61] where the state of the tool wear was estimated by comparing the patterns extracted from the subsequent laser scattering images with the initial reference image. The experiment results showed that these two systems employing 'laser scattering images' technique were not susceptible to the ambient light and the background noise. They can be used to monitor the tool condition and estimate the tool replacement time.

Bahr et al. [62] described a multi-sensory tool monitoring system using machine vision and vibration sensors. The system is unique in that it combines an indirect tool monitoring technique, vibration monitoring, with a direct visual monitoring system, machine vision. This combination overcomes the disadvantages inherent in either single tool monitoring procedure. The system can be further developed to identify all types of wear in inserts and predict the remaining life of the tool given the image of the tool.

Machine vision based navigation systems for autonomous aircrafts or unmanned vehicles were reported by Furst and Dickmanns [63], Oussalah et al. [64] and Sotelo et al. [65]. The application of vision based systems for automatic guidance is a very challenging task. The challenge arises from both the methodologies to handle the multiple problems caused
by the structure of the vision system, and the computational requirement due to the huge information supported by the vision systems compared to other sensors like range finder.

Machine vision based face detection methods can be classified into two main categories: methods based on facial features or face models, and methods based on face representations learned from a large number of examples using statistical approaches or neural networks. In general, methods in the second category are more practical since they are less time consuming and do not rely on special features or models [66]. The applications utilising these methods were reported by Liang et al. [67], Wang et al. [68] and Huang and Tan [69].
2.2 Handling Systems in Textile Industry

Due to its inherent flexibility, lace is difficult to be handled properly for cutting. In most lace cutting research, the lace handling problem is usually underestimated, which can be reflected by the fact that very little literature can be found in this research area. However, a proper handling method is very critical not only for effective cutting but also for the resulting cutting quality. The fundamental difference between the automation technology for the textile industry and the conventional manufacturing automation equipment is the need to accommodate the unpredictable, non-linear and complex mechanical behaviour of limp fabric. Lace poses further difficulties, due to non-linear strain-dependent moduli of elasticity. Extensive research regarding the automatic material handling has been carried out in the garment manufacturing industry, which will be reported first in this section. In addition, web handling techniques used in the web processing industry will also be included.

2.2.1 Fabric handling in garment manufacturing industry

The fabric handling operations in clothing industry can be divided into the following tasks: separation, grasping, translation, placing, positioning, feeding and sewing. Before being sewed by a sewing machine, fabrics need to be manipulated in a way that they are free of wrinkles and sometimes some controlled tension is desirable.

Gershon and Porat [70, 71] described a robotic sewing system which was able to maintain a constant cloth tension and produce a constant seam width. The end-effector of the system had two spring-loaded, rubber-tipped fingers, and the distance between the fingers could be varied under program control. Two ends of the cloth were held by sewing needle and robot fingers respectively. During the sewing operation, the tension control system moved the robot forwards with the cloth to maintain a small tension. The tension control system was based on the sewing machine shaft encoder signal and the cloth tension measured by an instrumented finger. The system was unsuitable for fabrics with high extensibility due to the performance limitation of the tension control system.

A new approach for automated handling of flexible fabrics in the sewing process is described by Koustoumpardis and Aspragathos in [72], which focuses on controlling the cloth tension applied by a robot. During the sewing process, the sewing seam quality is
extremely sensitive to cloth tension variations appeared in the sewing process, which means that obtaining a high quality seam necessitates controlling the tension within a predefined range.

As shown in Figure 2-1, during the sewing process, an automated sewing station pulls the right edge of the fabric with the *machine velocity*, while the robot end-effector follows the left edge of the fabric with the *robot velocity* to apply the recommended tensional force to the fabric. By adjusting the velocity of the robot, the applied tension can vary, which can be sensed by the sensor mounted on the end-effector of the robot, providing tension feedback for the robot controller. The required optimal tensional force depends on the fabric properties and sewing directions. The optimal tension force determined from the Fuzzy Logic mechanism is inputted into a feed-forward neural network (1-5-1) controller to regulate the robot end-effector velocity in order to achieve the desired tension with a closed loop control mechanism. The system has quick response in that the desired tension force can be achieved and maintained after 144 ms of training time.

A robotic system employing two robots was used to manipulate limp fabrics for automated sewing [73]. During a sewing process, the robots pressed the fabric against the sewing table and, by a coordinated motion of both hands, a desired motion of the fabric as a rigid panel was performed. A force sensor was mounted at the wrist of each robot to execute pressing force control and the tension control. A CCD camera was mounted on the sewing machine to monitor the sewing task execution to allow for compensation of the sewing trajectory tracking error caused by the fabric distortion and slippage.
Experimental results had shown that the sewing speed could reach 30mm/s along a straight line. The trajectory tracking error was within $\pm 0.5\text{mm}$ when sewing along a curved path, but the error became too large if the radius of the sewing trajectory was less than 80 mm.

An adaptive control loop was designed in [74] to apply proper tension to eliminate the wrinkles of fabrics, with cloth stiffness as the adaptive variable. The system design was constructed and tested with a PUMA 560 robot with force sensors mounted on its wrist. Two microcontrollers were used, with the first one calculating the cloth stiffness and the position of the end effector. The second microprocessor was used for communication with the robot and the sensors. Using infrared sensors to help align a fabric sample with the test bed was reported in [75] where the fabric sample had a simple square geometry.

Fahantidis et al. [76] and Paraschidis et al. [77] present a robotic system incorporating vision and force/torque sensing for handling flat textile materials. The robot was equipped with a special gripper with two distant fingers for handling fabrics. The force/torque sensor was used to detect the contact of the fingers with the surface of the table, maintaining a desired finger pressure against the table, and to restrict the force applied during the sweeping motion. The vision system consisting of two cameras and a frame grabber was used for identification of the material position (edge) on the table and possible deformations (wrinkles and folds), and tracking of the material during handling operations.

Methods pertaining to the vision-guided robotics control of fabric motion for performing simulated joining operations for apparel manufacturing have been described in [78]. A machine vision system was used to determine the sewing path by capturing images of the fabrics. The end-effector of the robot consisted of six independently controlled pneumatic actuators that could alter the position of four circular acquisition points to accommodate fabrics of different shapes. Experiment results showed that the error deviations averaged 3-5mm when the sewing speed was 1 cm/sec.

### 2.2.2 Web handling techniques

The fabric handling techniques investigated so far are successfully utilised in the garment sewing industry for fabric transportation, fabric tension control etc. However, it is
difficult to directly apply them in lace cutting systems because lace and normal fabrics used in sewing industry have different shapes and are treated in different ways, although they have similar physical properties. Lace can be classified as web shape material where the term web refers to any flexible material which is very long compared to its width and very wide compared to its thickness. In addition, although the shapes of the fabrics processed in sewing industry are various for different applications, no web-like fabric has been found so far. Some literature related to the web handling techniques has been identified and reported as follows.

Extensive research shows that the predominant method of transporting a web is using a roller system [79], as shown in Figure 2-2. The main advantage of such a system is that the storage of the material at the beginning and end of the process is comparatively compact compared to an arrangement where the orientation of the flexible is uncontrolled [80]. In a web or film, there are only likely to be two kinds of tension: lateral tension and longitudinal tension. With a roller system, accurate regulation of the longitudinal tension can be achieved with a closed loop control.

![Figure 2-2 A simple roller system](image)

With the need for increased performance, productivity, and quality of the processed web, it is important to maintain the web tension within the desired limits under a wide range of dynamic conditions such as speed changes, variations in roll sizes, and web properties [81]. Three kinds of tension control methods are widely used in web processing industry.

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One is the feedback control scheme based on the direct detection of tension with load cells. Another simple approach is the indirect calculation of required motor torque from the tension reference and radius. The third one uses the dancer roller as a measurement device and/or as a self-regulating device. Typically, load cell systems respond faster than dancer systems, but due to the lack of accumulation ability, they are not recommended for start-stop or unwinding operations [83].

The web tension can be controlled by using a dancer mechanism. A dancer roller is arranged in such a way that the roller can move in a direction perpendicular to the axis of rotation. This movement is then controlled by either an open loop spring damper system or by a closed loop motor and lead screw assembly. An example of an open loop dancer system is shown in Figure 2-3. If the longitudinal tension in this system is too small, then the spring contracts, increasing tension to the web. If the tension is too great, the dancer is pulled upwards against the spring, correcting the tension.

![Figure 2-3 An open loop dancer system](image)

A study on the dynamic behaviour of dancers in web transport system was reported in [84]. Computer simulation studies were conducted on an example system to investigate disturbance rejection for three cases: (1) without a dancer; (2) with a classical dancer with passive elements; (3) with an inertia compensated dancer. Based on the simulation results, it was concluded that better attenuation of tension disturbance in a web line could be achieved with a dancer as opposed to a web line without a dancer.
An active dancer system used for periodic tension disturbance attenuation has been developed by Pagilla et al. [85]. Lots of efforts have gone into the mathematical model development for the dancer system. An open-architecture experimental web platform has been developed, which mainly consists of an endless web line with a number of rollers, an active dancer system, and web guides for maintaining lateral position. The term endless web line refers to a web line without unwind and rewind rolls, which can mimic most of the features of a process section of a web processing line. Data collected from an extensive set of real time experiments validate the usefulness of the active dancer in attenuation of periodic web tension disturbance in a web process line. However, the limitation of the research is that it is based on the assumption that there is no slip of the web on the dancer roller, which may not be the case at high web speeds and large amplitude periodic tension disturbances. Furthermore, due to the large inertia of the dancer system, high frequency disturbances or vibration can lead to material failure.

The method of regulating the web tension by controlling the torque applied to the supply and the take-up reels has been reported by Mathur and Messner [86] in which a high-speed and low-tension tape transport system for ultra-thin media was considered. To reduce wear on the tape, the direct-drive transport (DDT) was utilised where two independently driven reels were used to control the velocity and tension of the tape. Each reel was driven by one motor and the tension was sensed by two strain gauges located on guides posts that were in the path of the tape.

In various web processes, there are many kinds of disturbance, among which the major one is the periodical disturbance due to roller eccentricity. A method used to reject tension disturbance due to the roller eccentricity has been studied by Wolfermann [87]. The eccentricity of a specific roller was estimated by using the tension signal in the web span based on the assumption that there was eccentricity in one specific roller, which, however, becomes a limitation when this method is applied to an actual plant that has eccentricities in many rollers simultaneously. Furthermore, the tension signal loses the information of roller shape more and more as the operation speed of the plant increases. Reid et al. [88] evaluated the performance of a fix-gain and a variable-gain PID controllers, which were used to control the longitudinal tension in the winding section of a simple web transport system. The advantage of a variable-gain PID controller over a fix-gain PID controller was that it compensated for time-varying parameters. The variable-gain PID controller is
easy to implement, but can be easily degraded by measurement noise. An adaptive fuzzy controller which automatically tunes its parameters in real-time was designed to regulate tension variations in multi-spans due to an eccentric unwinding roll [89]. Experiment results has shown that the adaptive fuzzy controller outperforms the conventional PID controller as the frequency of the eccentricity disturbance increases. Shin et al. [90] proposed a new method to overcome the restriction by estimating the eccentricity based on the angular velocity and tangential velocity of each roller. An adaptive estimator was used for the estimation of the position-dependent roller radius. Considering the relationship between the roller radius and the tension difference due to the tangential velocity oscillation, a torque compensator was proposed to eliminate the tension disturbance at each point of contact between the roller and the web.

From the experimental results, it is noted that the tension variation could be reduced by about 50% by decreasing the oscillation of roller velocity when the proposed compensation method is used. As the proposed estimator utilizes the tangential velocity and angular velocity instead of the tension signal, effective compensation can be achieved even though adjacent rollers have eccentricity.

Two different controllers used to control an industrial web process have been designed by Liu and Davison [91]. The “tuning regulator controller” based on steady-state experimental measurements of the web system is easier to implement because no mathematical model is required. However, its performance is marginally worse than the “perfect robust servomechanism controller” which is based on an analytical model of the web system in conjunction with the measurement of certain parameters.
2.3 Laser Cutting for Fabrics

Since their invention, lasers have been widely used in industry for diverse applications, such as cutting, welding, printing, recording and their application range expands rapidly [92]. Due to its good cutting quality with high productivity and flexibility, a laser has been used for cutting various materials in one of the three modes: vaporization, melting and photochemical ablation [93].

Not only can it be used for cutting steel, wood etc., a laser system can also be used for cutting fabrics. A laser has obvious advantages over a mechanical cutter for fabric cutting in that the cutting force usually existing during the mechanical cutting process can be eliminated. This can greatly facilitate the handling task and improve cutting performance since fabrics are usually flexible and any undesirable force will cause wrinkle problems. Several lace cutting systems employing a laser as the cutting tool have been reported in section 2.1.3.

As lace is predominantly made of Nylon 66 yarns, understanding the interaction between a laser beam and Nylon 66 is important for the efficient use of laser energy and getting a good quality cutting result. Skordoulis et al. [94] studied the basic phenomenology of Nylon 66 ablation with XeCl, CO2 and Nd:YAG lasers and found that the degradation temperature of the material for pulsed laser heating is 670K (397°C) and 1180K (907°C) for XeCl and CO2 laser irradiation, respectively. These two temperature values are higher than the melting point of the material, 590K (317°C), suggesting that the main thermal damage is from melting of the polymer surface. Nd:YAG laser was also examined, but direct comparison of the results with those of the XeCl and CO2 lasers cannot be executed due to more than three orders of magnitude difference in the time duration and the shape of the pulses emitted. It is estimated that the degradation temperature with Nd:YAG laser heating is about 850K (approximately 577°C).

The laser system parameters (spot size, pulse duration, etc.) can affect the resulting cutting quality greatly. With proper parameter settings, a laser system is able to cut the material efficiently while obtaining good cutting quality. Some research work has been carried out to find out the relationship between these parameters and the laser cutting
Mathew et al. [95] tried to find out how laser parameters affect the cutting quality of the Carbon Fibre Reinforced Plastic (CFRP) with a pulsed Nd:YAG laser system. A response surface methodology (RSM) was used as it allowed all main effects as well as interactions to be evaluated with the minimum number of experiments. Woven fabric carbon fibre reinforced plastic composites of 2 mm thickness were used for the tests. The laser system is a pulsed Nd:YAG with a 300W capacity (average power) operating in the TEM$_{00}$ mode. The input parameters selected were cutting velocity, pulse energy, pulse duration, repetition rate (RR) and the spot diameter was kept to be 0.1mm. Based on the experiments, response surface models for the Heat Affected Zone (HAZ) and kerf width at top and bottom were developed. It had been found that higher pulse duration at lower RR gave a smaller HAZ and the greater the cutting speed, the less the interaction time and the less the HAZ. The HAZ was also directly proportional to the pulse energy. The top kerf width was found to decrease with an increase in RR up to the middle of the experimental range and later it was found to increase, whereas the bottom kerf width showed a decreasing trend with an increase in RR. Also, increase in pulse energy leaded to more material removal and increase in both kerf widths.

Most of the factors in the middle range of the experiments conducted have been obtained as the optimal parameter ranges. This type of study can also be effectively conducted for other materials of similar types. Similar method is adopted by Bamforth [7] where a 5 factorial (beam diameter, beam offset, beam speed, beam profile, beam diameter & beam offset) experiment has been conducted to find the factors affecting the size of the HAZ for both the CW and pulsed CO2 laser cutting process for lace material. The results show that the beam diameter and beam offset significantly affect the size of the HAZ and they are proportional to the size of the HAZ. A flat region of the HAZ surfaces of both the CW and the pulsed laser systems has been identified where small changes in the beam diameter and offset will have little effect on the size of the HAZ, which is useful for finding the suitable parameter value to keep the HAZ minimum.
2.4 Summary of Literature Survey

The literature survey for this project is mainly conducted in the following research areas: machine vision, fabric and web handling systems and laser cutting for fabrics.

Due to the wide range of applications of machine vision in various industries, it is impossible and not necessary to explore all the applications and therefore only some typical applications have been selected and presented here. The machine vision applications in the textile industry, particularly for lace inspection and lace cutting, are reported in more detail as they are closely related to this project. The literature survey in this area has shown that machine vision is a feasible method for lace cutting and has a huge potential for further development. When combined with the laser cutting techniques, machine vision based lace cutting systems have obvious advantages over the conventional mechanical lace cutting systems. However, at this early stage of the lace cutting research, most attention was paid to developing image processing algorithms and the research regarding lace cutting edge quality has been overlooked.

Very little literature can be found regarding lace handling techniques as lace handling problems are normally neglected by the researchers. However, some fabric handling techniques have been identified which are commonly used in the garment sewing industry. Because of the similar mechanical properties between lace and other normal fabrics, these fabric handling techniques are investigated and reported. Furthermore, the web handling techniques used in web processing systems are also investigated in which some web tension control techniques are described in detail.

As a lace cutting tool, the advantages of a laser cutting system over the mechanical cutting system are identified. The methods to investigate how the parameter settings of a laser cutting system affect the resulting lace cutting edge quality are investigated as well.
3 Tension Effect on Lace Cutting Edge Quality

Although lace cutting research has been started since 1980s, most attention was paid to developing image processing algorithms for cutting path detection. Lace handling related problems, especially the handling tension applied on lace, have not been the main research focus of previous research work in this multidisciplinary field. Lace samples are usually transported into the cutting area by a transportation system having no ability to control the local tension in the cutting zone. As more lace cutting tests have been conducted and more experience gained, the tension applied on a lace sample is considered to be an important factor affecting the resulting lace edge quality.

In this chapter, the tension effect on lace cutting edge quality is investigated in detail. It is the first time that the problem has been proposed and investigated. In section 3.1, the elastic property of three representative types of lace is investigated, through which a better understanding of lace property and the relationship between the tension applied on the lace and the according extension can be obtained. In section 3.2, a lace transport and tensioning rig is described. Based on the results presented in section 3.1 and 3.2, then in section 3.3, the edge quality of the lace samples cut under different tension forces is assessed and compared, through which the benefit of applying tension can be identified.
3.1 Lace Elastic Property Investigation

The purpose of investigating the elastic property of some lace samples is to quantify the tension force applied on the lace samples during the later tension effect experiments. As lace is flexible and extensible, significant extension can be observed when a small amount of tension force is applied, which means it would be much easier to measure the extension rather than measure the tension force directly. The applied tension force can then be calculated from the extension measured provided that the relationship between the tension and the extension is known. This relationship between the tension and the extension of lace is generally referred to as the elastic property of a certain type of lace.

The existing mechanical lace cutting processes do not attempt to control the lace tension directly in the cutting zone. From the inspection of the lace pattern and waste mesh, it seems clear that some combination of lateral and longitudinal tension would be beneficial. The two types of tension applied on the lace sample during the lace cutting operation are classified according to the tension direction relative to the lace cutting path. The tension applied normal to the scalloping path is called lateral tension and the one parallel to the cutting path is longitudinal tension. Figure 3-1 shows the orientations of lateral and longitudinal tension with respect to the cutting path respectively.

3.1.1 Experiment setup

A Hounsfield H5KS Load test machine was employed to investigate lace elastic properties. The H5KS machine has a screw jack type linear slide with a fixed and a moving clamps, between which the lace sample is clamped and fixed. A load cell is installed inside the moving clamp and connected to a standard PC. A graph showing the Force-Elongation relationship can be shown directly on the computer screen, from which further analysis can be done. Two adjustable stop switches are used for system safety. Figure 3-2 shows the layout of the machine.

Three representative types of lace (as shown in Figure 3-3) with different patterns and stretchiness are selected for the tests. Each lace sample is fixed between the jaw clamps and moved upwards by the upper moving support driven by a lead screw mechanism until the sample is broken. A load cell and an LVDT are used to measure the tension applied on the lace sample and the elongation of the lace sample respectively. The data is then sent to
the PC linked with the test machine and a graph showing the relationship between the
tension and the elongation appears on the screen of the PC after each test.

Figure 3-1 Longitudinal and lateral tension

Figure 3-2 Hounsfield test machine layout
3.1.2 Data analysis

Figure 3-4 shows the test result of a lateral tension test with a lace sample of type II. During the test, the lace sample is stretched until it is totally broken. The test is repeated three times with three nominally identical lace pieces with each one being 150 mm long and 75 mm wide (length refers to the side parallel to the tension direction and width refers to the side perpendicular to the tension direction). From the graph, the whole test process from the beginning to the total breakage of the lace sample can be observed. However, the data after the lace sample being broken is not of interest since the lace breakage will absolutely be avoided during the practical lace cutting process. What is of interest is the section from 0mm to 50mm of the elongation for the lace sample of type II. Any data outside this range will be discarded as this will not be encountered in the practical cutting process.

The relationship between the tension and the elongation is not linear as seen from Figure 3-4, but a 3rd order polynomial can be used to approximate the relationship [2]. After the approximation equation is obtained, the applied tension force can be calculated by putting the value of the corresponding extension into the equation. One problem with this approach is that the equation obtained from the experiment only applies to the lace samples having exactly the same size as the one used in the tension test, that is, 150 mm long and 75 mm wide. However, lace used in the later tension effect experiments or the practical lace cutting operation could have different sizes. The problem can be tackled by establishing the relationship between the tension and the extension rate, which can be obtained by dividing the total length of the stretched lace sample by the original length.
As shown in Figure 3-5, the relationship between the tension and the extension rate is much similar to that shown in Figure 3-4. The trend line and the corresponding equation could be easily obtained within the Microsoft Excel environment for each curve.

As mentioned above, the relationship could be approximated by a 3rd order polynomial and its general format is:

\[ Y = R_1 X^3 + R_2 X^2 + R_3 X + R_4 \]  \[1\]

Where:

- \( Y \) = Tension (N)
- \( X \) = Extension Rate (%)
From the equation of each trend line, the coefficients can be obtained as shown in Table 3-1:

<table>
<thead>
<tr>
<th>Trend</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trend 1</td>
<td>4.00E-03</td>
<td>-0.1098</td>
<td>11.658</td>
<td>-423.65</td>
</tr>
<tr>
<td>Trend 2</td>
<td>4.00E-03</td>
<td>-0.1079</td>
<td>11.327</td>
<td>-408.26</td>
</tr>
<tr>
<td>Trend 3</td>
<td>4.00E-03</td>
<td>-0.1287</td>
<td>13.91</td>
<td>-513.89</td>
</tr>
<tr>
<td>Average</td>
<td>4.00E-03</td>
<td>-1.15E-01</td>
<td>1.23E+01</td>
<td>-4.49E+02</td>
</tr>
<tr>
<td>Final result</td>
<td>2.67E-06</td>
<td>-7.70E-04</td>
<td>8.20E-02</td>
<td>-2.99E+00</td>
</tr>
</tbody>
</table>

Table 3-1 Result for each equation coefficient

By averaging each coefficient and then dividing them by the width of the lace sample being tested, the final result of all four coefficients can be obtained for tension in unit width as shown in the last row of the Table 3-1.

So the approximation equation for the lace sample of type II is:

\[ T = 2.67 \times 10^{-6} X^3 - 7.7 \times 10^{-4} X^2 + 8.2 \times 10^{-2} X - 2.99 \]  

Where:

- \( T \) - Tension in unit width, N/mm
- \( X \) - Extension rate, the lace sample length after extension divided by the original length

Suppose that the original size of a lace sample is \( M \) mm long and \( N \) mm wide. After lateral tension being applied, the length becomes to be \( P \) mm while the width is assumed to remain \( N \) mm. The lateral tension applied can be calculated as follows.

\[
\text{Extension rate} = \frac{100P}{M}
\]

\[
\text{Lateral Tension} = \left[ R_1 \cdot \left(\frac{100P}{M}\right)^3 + R_2 \cdot \left(\frac{100P}{M}\right)^2 + R_3 \cdot \left(\frac{100P}{M}\right) + R_4 \right] \times N (\text{Newton})
\]
By inputting the value of R1 to R4 shown in Table 3-1, the lateral tension can be easily worked out.

As the data processing and analysis procedures to investigate the elastic properties of the other lace types are much similar to those described above, only the final results are summarised here as shown in Table 3-2 and Table 3-3. All experiment results and graphs are included in Appendix 12.1.

<table>
<thead>
<tr>
<th>Lace No.</th>
<th>Softness</th>
<th>Tension in unit width (N/mm) VS Extension rate (Lateral direction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lace type I</td>
<td>Rigid</td>
<td>$T = 8.67 \times 10^{-6} X^3 - 2.48 \times 10^{-3} X^2 + 2.38 \times 10^{-1} X - 7.59$</td>
</tr>
<tr>
<td>Lace type II</td>
<td>Stretchy</td>
<td>$T = 2.67 \times 10^{-6} X^3 - 7.7 \times 10^{-4} X^2 + 8.2 \times 10^{-2} X - 2.99$</td>
</tr>
<tr>
<td>Lace type III</td>
<td>Stretchy</td>
<td>$T = 3.11 \times 10^{-7} X^3 - 9.62 \times 10^{-5} X^2 + 1.06 \times 10^{-2} X - 0.48$</td>
</tr>
</tbody>
</table>

Table 3-2 Equations of lateral tension for each lace type

<table>
<thead>
<tr>
<th>Lace No.</th>
<th>Softness</th>
<th>Tension in unit width (N/mm) VS Extension rate (Longitudinal direction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lace type I</td>
<td>Rigid</td>
<td>$T = 3.15 \times 10^{-6} X^3 - 1.04 \times 10^{-3} X^2 + 1.14 \times 10^{-1} X - 4.2$</td>
</tr>
<tr>
<td>Lace type II</td>
<td>Stretchy</td>
<td>$T = 1.11 \times 10^{-6} X^3 - 5.05 \times 10^{-4} X^2 + 6.94 \times 10^{-2} X - 3.15$</td>
</tr>
<tr>
<td>Lace type III</td>
<td>Stretchy</td>
<td>$T = 2.22 \times 10^{-6} X^3 - 7.37 \times 10^{-5} X^2 - 1.03 \times 10^{-2} X - 0.494$</td>
</tr>
</tbody>
</table>

Table 3-3 Equations of longitudinal tension for each lace type

With the elastic property equations obtained from the experiments and data analysis, any tension applied on these types of lace can be calculated by measuring the resultant extension, regardless of the lace size. This method can further apply to other lace types if needed.
3.2 Early Lace Transport and Tensioning Rig

To carry out the tension effect experiment, lace samples need to be automatically transported into the laser cutting area and then stretched until the preset tension is applied. The applied tension is required to be constant throughout the experiment process so that its effect on the resulting cutting edge quality can always remain the same. Lace handling generally refers to two separate aspects: lace transport and lace tensioning. Extensive research has shown that the predominant method for lace transport is using a roller system [79]. The obvious advantages of a roller system are its compact design and the ease of controlling the longitudinal tension with a closed loop method. An alternative method for lace transport is utilising a movable bed on which the lace is laid. But this method may not suitable for this project if the lace needs to be illuminated by a light source right underneath and therefore the bed would be an obstacle, as discussed and shown in section 5.1.3.2.

A lace transport and tensioning rig has been designed and manufactured [80]. In this section, the principles of how the rig transports and tensions a lace sample will be briefly introduced first and then some improvement dedicated to making it automatic and more suitable for the later tension effect experiments will be described.

3.2.1 Transport method

A roller system is designed to transport the lace into the cutting area as shown in Figure 3-6. The roller system consists of an infeed roller, a take-up roller and a drive roller. Two DC motors are used to drive the take-up roller and the drive roller pair, both of which run at constant speeds, while the infeed roller rotates under the feed action of the lace fabric. As more and more lace winds onto the take-up roller during the lace cutting process, the diameter of the take-up roller is increased gradually, which causes the tension in the lace section between the driven roller and take-up roller to rise, eventually leading to lace breakage if the speed of the take-up roller and the drive roller remains constant. The problem can be solved by installing an adjustable clutch with the take-up roller, which will slip to let the take-up roller stop rotating if the tension in the lace section between these two rollers reaches the preset tension of the clutch and then the take-up roller will begin to rotate again if the tension is less than the preset value.
3.2.2 Tensioning method

The other function of the rig is to tension the lace automatically during the lace cutting process. As stated in section 3.1, there are two types of tension needed to be applied and controlled, that is, lateral tension and longitudinal tension.

3.2.2.1 Longitudinal tension

Initially longitudinal tension is applied by applying a small amount of braking torque to the infeed roller through a rubber thread. By adjusting the contact area and tightness between the rubber thread and the infeed roller, the applied torque can be varied and consequently the longitudinal tension applied on the lace sample being cut can be changed as well. However, this method proves to be uncertain and uncontrollable. Instead of using a rubber thread, a nylon thread together with a spring mechanism is used as shown in Figure 3-7.

By moving the control block up and down along the scale, the torque applied on the feed roller can be changed and therefore various longitudinal tension can be applied. For each
position of the control block, the corresponding longitudinal tension applied can be established by measuring the longitudinal extension of the lace sample and then putting it back into the lace elastic property equation obtained before. As the lace of different type has different elastic property, the applied longitudinal tension is also different even though the control block is in the same position. This method is considered to be simple to implement and accurate enough for the later tension effect experiment.

![Diagram of Longitudinal Tension Control](Figure 3-7 Longitudinal tension control)

**3.2.2.2 Lateral tension**

The lateral tensioning system is composed of (i) clamping and (ii) tensioning sub-systems. As shown in Figure 3-8, the lace clamping unit consists of two single acting cylinders with spring return controlled by a pneumatic system.

In order to clamp both sides of the lace at the same time, two clamping units are integrated to form the clamping sub-system, with one clamping unit fixed and the other one able to move along the rail, as shown in Figure 3-9.
After both sides of the lace have been clamped tightly, the movable clamping unit will be displaced by the tensioning subsystem which consists of two double acting cylinders as shown in Figure 3-10. By varying the distance of the movable clamping unit being displaced from its original position, the lateral tension can also be varied and controlled. The applied lateral tension can also be obtained with the same method used for calculating the applied longitudinal tension. After final assembly, the rig looks like in Figure 3-11.
Figure 3-10 Tensioning sub-system (Smith, 2003)

Figure 3-11 Final assembly of the transport and tensioning rig
3.2.3 Control of the transport and tensioning rig

During the cutting process with the transport and tensioning rig, the lace needs to be transported into the cutting area first with the roller system. The longitudinal tension is applied while the lace is being transported. Then the clamping subsystem will be activated to clamp both sides of the lace. After then, the lateral tension is applied with the tensioning subsystem, getting the lace ready for cutting with the pulsed laser cutting system. After the lace within the cutting zone has been scalloped, the tensioning subsystem will be reset first and then so does the clamping subsystem so that the uncut lace can be indexed into the cutting area. By repeating the cycle, the lace can be tensioned and cut step by step.

In order to execute the cutting process described above automatically, the transport and tensioning rig needs to be fully controlled via a PC. The components needed to control include DC motors and pneumatic valves, which actuate the roller system and cylinders respectively. According to the lace cutting process described above, switching on or off the actuators (DC motors and pneumatic valves) in order can satisfy the requirements. A circuit functioning as a switch has been designed and manufactured as shown in Figure 3-12.

![Control circuit structure](image-url)
The transistor is acting as a switch which will be switched on after receiving a signal from the PC and then the motor or valve connected to it will be activated. The diode is used to protect the circuit from induced voltage generated from the motors or the valves when they are switched off. A PC IO multi function interface card is used to interface the test rig with the PC, which has a 37 way D connector, wired to which are two 8-bit digital I/O ports that can be configured as either inputs or outputs. This card has other functions including three timer counters, an oscillator up to 8 MHz, and several DAC and ADC modules, but these functions are redundant for this project.

The software used for control is completely undertaken from within the WiT environment. Besides the various powerful operators offered by WiT software for machine vision applications, special purpose operators can also be developed for specific tasks. To control the rig, several new operators are built using C/C++ language. The WiT system supports an interface using the ActiveX system to Microsoft Visual Basic (VB). A graphic user interface (GUI) has been developed, from which a user can control the test rig by simply clicking the corresponding buttons. The GUI is shown in Figure 3-13.

![Lace Transport Rig Control System GUI](image-url)

Figure 3-13 GUI for transport and tensioning rig control
3.2.4 Installation

As part of the whole lace cutting system, the transport and tensioning rig needs to be installed within the laser cutting system as shown in Figure 3-14. In order to avoid any potential safety problem, all components are enclosed in a plastic enclosure. The dashed rectangle indicates the position where the transport and tensioning rig should be installed. After some rearrangement, the rig looks like in Figure 3-15.

Figure 3-14 Schematic view of the targeting rig (Bamforth, 2003)
3.3.4 Experiment setup

As described in section 3.3.2, the lateral tension applied on a test sample can be controlled by setting the distance of the movable clamping unit of the test setup. We tested the rig from its original position. For the lateral tension, prior experiments have selected the samples have been cut under three different types of initial tension, which subsequently required some different placements of the movable clamping unit.
3.3 Tension Effect on Lace Cutting Edge Quality

The cutting edge quality of the lace cut by a machine vision based laser cutting system is determined by several factors, including the quality of the captured images, the image processing algorithms used to detect the cutting path, the parameter settings of the spot size, the pulse duration, and the pulse energy etc. of the laser system. Bad edge quality could be produced if one or more of these factors do not meet the system requirements. Other factors, such as the mechanical aspects and the characteristics of lace itself also play an important role in determining the resulting edge quality of the lace. All these factors’ effect on the lace cutting edge quality has been explored to some extent before by some researchers [96]. However, the tension effect on lace cutting edge quality has never been studied so far.

With the elastic properties of several types of lace obtained and the transport and tensioning rig ready for transporting and tensioning lace, a series of experiments were carried out to find out how the applied tension affects the lace cutting edge quality. There are usually two types of tension applied on the lace during a lace cutting process, the lateral and longitudinal tension, and both need to be investigated separately. Because the experiment procedures are much similar, only the experiment of investigating the lateral tension effect will be described in detail, where the longitudinal tension will always be kept constant. By varying the magnitude of the lateral tension, lace samples having different edge quality are expected to be produced. The lateral tension effect can then be found out by comparing these lace samples in terms of the resulting edge quality.

3.3.1 Experiment setup

As described in section 3.2.2.2, the lateral tension applied on a lace sample can be controlled by setting the distance of the movable clamping unit of the transport and tensioning rig from its original position. For the lateral tension effect experiment, the selected lace samples have been cut under three different types of lateral tension, which consequently requires three different displacements of the movable clamping unit.

The lace samples selected for the experiment are the same as those whose elastic properties have been investigated in section 3.1, among which only lace type II is described in detail here as the experiment process is much similar for other types of lace.
The movable clamping unit is displaced 0 mm, 10 mm and 20 mm from its original position respectively and the corresponding lateral tension applied on the lace sample can be calculated based on the lace elastic property equation. As the clamping unit is 75 mm long, it can only clamp and apply lateral tension on a 75 mm long lace sample section while the rest of the lace sample is free from the lateral tension. The different displacements of the movable clamping unit and the corresponding lateral tension applied are listed in Table 3-4.

<table>
<thead>
<tr>
<th>Extension (mm)</th>
<th>Sample length (mm)</th>
<th>Actual Tension (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Tension</td>
<td>0</td>
<td>75</td>
</tr>
<tr>
<td>Medium Tension</td>
<td>10</td>
<td>75</td>
</tr>
<tr>
<td>High Tension</td>
<td>20</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 3-4 Different lateral tension applied on the lace sample II

In order to facilitate the cutting process, a certain mount of longitudinal tension is also applied and kept same for each cutting process. In this way, the longitudinal tension effect is the same for all the lace samples produced, making the cutting result comparable. Also, the parameter settings of the machine vision system and the laser system are always kept unchanged for the same reason. The lace under different lateral tension appears to be different as shown in Figure 3-16.

3.3.2 Experiment result and analysis

With the existing pulsed laser cutting system and the transport and tensioning rig, three lace samples of type II have been cut under three different lateral tension forces with all other settings being the same.

Each lace sample is expected to have different edge quality. In order to find out the lateral tension effect on the cutting edge quality of these samples, the edge quality needs to be assessed and compared with each other. This research has identified two existing methods of lace edge quality assessment used by some lace manufacturing industries. The first method involves panels of humans assessing the lace tactile quality and visual appearance, which is subjective and not reliable. The second method is using the Martindale Tester which uses a foam pad to simulate the human skin or tight material and...
the quality is distinguished by the condition of the pad after abrasive testing. At the early stage of the project, these two methods seem not to be appropriate due to the unavailability of a Martindale tester. Alternatively, a microscopic method by which each purl of the lace sample being assessed will be inspected under a microscope is adopted. As the microscopic method, together with other two methods, will be described in detail in Chapter 7, the assessment process will be briefly introduced here.

![Figure 3-16 Lace under different lateral tension]

3.3.2.1 Microscopic lace edge quality assessment and result

As a long lace sample has many purls, it is impossible to inspect all of them one by one. Two pattern repeats containing 14 purls each (only true for lace type II) are selected from
each produced lace sample for inspection. The quality of each purl is assessed and classified according to its visual appearance under the microscope.

1. **Good quality**
   The quality of a purl can only be classified as 'good' when no laser damage or residue can be seen under the microscope. The purl shown in Figure 3-17(a) has a smooth contour and is a good example of a good quality purl.

2. **Neutral quality**
   The quality of a purl is considered to be 'neutral' when small residue or little laser damage can be seen from the image, as shown in Figure 3-17(b).

3. **Bad quality**
   The quality of a purl will be considered as 'bad' if residue or laser damage can be clearly seen, as shown in Figure 3-17(c).

![Figure 3-17 Examples of purls having different edge quality](image_url)
By observing and analysing the purls one by one under the microscope, the quality of each purl could be classified as: good, neutral and bad, as described above. The overall edge quality of the lace sample containing these purls is determined by the percent of the good-quality purls out of all purls under inspection. The result of the quality assessment is listed in Table 3-5.

<table>
<thead>
<tr>
<th>Tension Level</th>
<th>Good</th>
<th>Neutral</th>
<th>Bad</th>
<th>Total</th>
<th>Percent of Good (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-tension</td>
<td>6</td>
<td>13</td>
<td>9</td>
<td>28</td>
<td>21</td>
</tr>
<tr>
<td>Medium-tension</td>
<td>15</td>
<td>7</td>
<td>6</td>
<td>28</td>
<td>54</td>
</tr>
<tr>
<td>High-tension</td>
<td>21</td>
<td>2</td>
<td>5</td>
<td>28</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 3-5 Lace edge quality assessment result (Lace type II)

From Table 3-5, it can be easily found that the lace sample cut under high lateral tension has much better edge quality than those cut under medium or low lateral tension, with 75 percent of the purls of the lace sample cut under high lateral tension having good quality. From the analysis result, it can be safely concluded that applying lateral tension on a lace sample cut is beneficial to the cutting edge quality.

The lateral tension experiments are then conducted with the other two types of lace (type I and III). The experiment result is summarised in Table 3-6 and Table 3-7, which also prove that applying lateral tension can improve the overall lace cutting edge quality. When comparing these three tables (Table 3-5, Table 3-6, Table 3-7), it is noticed that the tension effect is more noticeable on stretchy lace (lace type II and III). When high tension
is applied, the percent of good quality purls is 75 and 78 respectively for lace of type II and lace of type III, and significant lace edge quality improvement has been observed.

<table>
<thead>
<tr>
<th></th>
<th>Extension (mm)</th>
<th>Actual tension (N)</th>
<th>Good</th>
<th>Neutral</th>
<th>Bad</th>
<th>Total</th>
<th>Percent of good (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-tension</td>
<td>0</td>
<td>0</td>
<td>19</td>
<td>21</td>
<td>20</td>
<td>60</td>
<td>32</td>
</tr>
<tr>
<td>Medium-tension</td>
<td>10</td>
<td>6</td>
<td>22</td>
<td>25</td>
<td>13</td>
<td>60</td>
<td>37</td>
</tr>
<tr>
<td>High-tension</td>
<td>15</td>
<td>20</td>
<td>33</td>
<td>16</td>
<td>11</td>
<td>60</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 3-6 Experiment results with the lace of type I

<table>
<thead>
<tr>
<th></th>
<th>Extension (mm)</th>
<th>Actual tension (N)</th>
<th>Good</th>
<th>Neutral</th>
<th>Bad</th>
<th>Total</th>
<th>Percent of good (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-tension</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>14</td>
<td>16</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>Medium-tension</td>
<td>10</td>
<td>5</td>
<td>22</td>
<td>8</td>
<td>10</td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td>High-tension</td>
<td>20</td>
<td>13</td>
<td>31</td>
<td>4</td>
<td>5</td>
<td>40</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 3-7 Experiment results with the lace of type III

The effect of the other type of tension, longitudinal tension, is also studied, where the longitudinal tension is varied by moving the control block while the lateral tension and other systems settings are kept constant. All experiment results have been included in Appendix 12.2, which also shown that applying longitudinal tension, although not so significantly as lateral tension, can improve the lace cutting edge quality as well.
3.4 Summary and Discussion

In this chapter, a series of experiments have been carried out to investigate how the tension applied on the lace affects the resulting lace cutting edge quality. Two types of tension have been identified during the lace cutting process, which are lateral and longitudinal tension. Their effect on the lace cutting edge quality has been investigated separately. All experiment results show that applying more tension can improve the resulting lace cutting edge quality, although the extent to which the applied tension can improve the cutting edge quality varies, depending on the lace type and the tension direction. As both types of tension are beneficial to lace cutting edge quality improvement, it is speculated that the combination of them helps to improve the edge quality as well.

During the lace cutting processes of the experiments, the status of the purls being cut is monitored with a camera. Three images are captured separately to track how a thread is cut off from the purl it is connected to, as shown in Figure 3-18.

![Figure 3-18 The cutting process of a thread](image)

Due to its inherent flexibility, the structure of lace threads can be easily changed by the applied tension. It is observed that applying more tension tends to make a thread easier to cut. As shown in Figure 3-19, two same purls (in terms of the position in the pattern and the structure of connected threads) look different under different tension. Under low tension, the threads connected to the purl are loose and some residue can be seen after they are cut off. On the other hand, the threads under high tension are pulled away from the purl and only one shot is needed to cut them off. The cutting quality is improved as well.
So far, it has been verified that applying some tension on lace during the lace cutting process can improve the lace cutting edge quality. However, why applying tension affects the lace cutting edge quality remains unknown, which will be discussed in detail in Chapter 4.

Figure 3-19 Same purls under different tension
4 Strategic Lace Cutting

From all the tension effect experiments described in Chapter 3, the conclusion can be drawn that applying tension on the lace cut by the pulsed laser cutting system can improve the resulting lace cutting edge quality. In order to find out why applying tension can improve lace cutting edge quality, the lace structure will be observed at a high magnification with the aid of a microscope first in this chapter. After in-depth observations on how lace reacts to the applied tension, a cutting strategy intended to further improve the lace cutting edge quality by cutting lace in an order decided dynamically according to the lace structure will be presented. The design and manufacturing process of an intermediate tensioning rig capable of manually tensioning lace will also be described.
4.1 Lace Microstructure Observations

Waste mesh is linked to the lace pattern section through connection threads. The number of the connection threads connected to each purl varies, depending on the lace design and the position of the purl, and usually ranges from 1 to 4, as shown in Figure 4-1. With the pulsed laser cutting system, the laser beam is directed to each cutting point one by one, where the connection thread and a purl intersect. The cutting quality of the purls determines the overall edge quality of the lace sample being cut and a good quality purl can be produced only if the connection thread is precisely cut off and no residue or laser damage is caused, which is usually very difficult to accomplish.

![Figure 4-1 Normal lace structure](image)

With the camera of the current pulsed laser cutting system, which has a resolution of 768x576 pixels, the lace changes due to the increasing applied tension are as shown in Figure 4-2. It can be observed that both the connection threads and purls are gradually stretched as more tension is applied. However, how the lace changes is unpredictable due to the complex structure and inherent flexibility of the lace. The information obtained by observing lace changes from Figure 4-2 fails to identify the reason why applying more tension can improve the lace cutting edge quality. As the laser beam is directed to the point where a purl intersects with the connection thread during the lace cutting process with the pulsed laser cutting system, it is considered necessary to investigate how a purl
and a connection thread connect to each other in more detail. A microscope is used to observe the connection structure between a purl and its connection threads.

Figure 4-2 Lace changes with the applied tension increasing

Figure 4-3 shows the lace structure viewed with the microscope, in which the purl connects with its two connection threads through an interlocking structure. The connection structure becomes much clearer when some more tension is applied as shown in Figure 4-4. The applied tension pulls the two connection threads away from the purl, exposing the otherwise hidden structure. The thread going through the purl and then connecting the thick connection threads to the purl is usually called a loop thread.

From the inspection of Figure 4-4, it may be speculated that if the pulsed laser beam is applied at cutting point A or B (see Figure 4-5) on the loop thread and under the applied
tension, the loop thread will be pulled through the purl. Then the connection threads will be cut off cleanly with the loop thread. The produced purl will be of perfect quality because no visual laser damage will be produced.

Figure 4-3 The microstructure of a purl

Figure 4-4 The microstructure of a purl with some tension applied

Figure 4-5 Two potential perfect cutting points of the purl
Hundreds of purls of different lace type have been observed under the microscope and such 'loop thread' structure can be found. Another example of a purl together with its connection threads and loop thread is shown in Figure 4-6.

In a normal condition where lace is free from any tension, the loop thread of a purl usually cannot be seen even under the microscope as it shrinks back and is covered by other threads. Only after adequate tension is applied can the loop thread structure be observed. Figure 4-7 has shown how the loop thread is gradually exposed as more and more tension is applied.

From all these examples, it can be clearly seen that applying more tension on lace can help to expose the loop thread of a purl. During the lace cutting process, directing a pulsed laser beam on the loop thread of a purl can cleanly cut off the loop thread and all connection threads connected to it, thus producing a purl of perfect quality. From this point of view, the conclusion drawn from the tension effect experiments carried out in Chapter 3, which states that applying tension on lace can improve lace cutting edge quality, can be fully explained as applying more tension increases the possibility of producing purls of good quality. If, for every single purl, the loop thread can be exposed by applying tension and the pulsed laser beam can be targeted accurately on the loop thread, the produced lace will have high-level quality. However, how to expose the loop thread effectively by applying tension remains unknown so far and requires a full understanding of how connection threads react to the applied tension. The reaction of
connection threads to the applied tension is speculated to be complicated due to lace’s complex structure and will be investigated and described in section 4.3.

Figure 4-7 Structure change with more tension applied
4.2 Intermediate Lace Tensioning Rig

The process of inspecting the microstructure of purls with the aid of the microscope indicates the possibility of producing lace with perfect quality. In order to further investigate the lace behaviour in a more local scale during the lace cutting process, another tensioning rig is considered necessary. Relative to the final automatic lace handling rig which will be described in Chapter 6, this tensioning rig is referred to as intermediate tensioning rig.

4.2.1 Drawbacks of the early transport and tensioning rig

The early lace transport and tensioning rig described in Chapter 3 is able to transport a lace sample into the laser cutting area and tension it in both lateral and longitudinal directions. Though the rig is capable of meeting the requirements for the tension effect experiments to investigate how applying tension affects lace cutting edge quality, its inherent drawbacks and the complex characteristics of lace make it unsuitable for the later experiments.

1. Method to apply lateral tension

With the early tensioning rig, lateral tension is applied by clamping both sides of the lace and then displacing the movable clamping unit to a preset position (see section 3.2). During this tensioning process, the lace needs to be stationary until the lateral tension has been applied. However, during the real-time lace cutting process, the lace being cut is transported continuously. From this point of view, this rig is clearly unsuitable.

2. Uneven tensioning

In order to produce a high quality purl, it is desirable that every connection thread of the purl is adequately tensioned before it is cut by the pulsed laser beam. Ensuring that all connection threads are tensioned can increase the possibility of the loop thread being exposed to the laser beam. However, with the early tensioning rig, the applied tension cannot be evenly distributed to each thread as every single thread is unique and different due to the complex structure of lace. This causes the problem that some threads are highly tensioned while others are still in a relaxed state, as shown in Figure 4-8.
3. **Dramatic tension change after each cutting**

As observed during the lace cutting process, a thread will usually shrink back after it is cut off by the laser beam. Consequently, this will incur the redistribution of the applied tension to the remaining threads. The tension redistribution process usually causes a dramatic change, as shown in Figure 4-9.

The change can make a relaxed thread to be tensioned or vice versa and is totally unpredictable due to the flexible characteristics of lace. As the early test rig tensions the lace by displacing the movable clamping unit to a fixed position, it is not able to cope with the tension change, as described in section 3.2.2.
4.2.2 Design of the intermediate tensioning rig

To address all these drawbacks of the early transport and tensioning rig, a new test rig capable of not only transporting the lace continuously into the laser cutting zone, but also tensioning the lace properly without stopping the lace is desired. However, before starting the design process of such kind of lace transport and tensioning rig, it is necessary to test and identify an appropriate tensioning method to expose the loop thread so that the lace cutting edge quality can be further improved. The intermediate tensioning rig is intended to explore the lace tensioning methods and facilitate the observation of the lace changes during the lace cutting process step by step. For this purpose, the requirement of transporting lace continuously becomes unnecessary. Designing a manually operated intermediate tensioning rig, which is able to properly apply tension on a small lace section, is more feasible and appropriate. This test rig must, however, use a concept that can be applied in continuous transport of the lace.

4.2.2.1 Tensioning method concept

Proper lace tensioning means exposing the loop thread of the purl being cut, which helps to produce a high quality purl free from any laser damage as discussed previously. The loop thread of a purl usually shrinks back into the purl when no tension is applied. The applied tension must be concentrated on the connection threads connected to the loop thread so that it can be pulled out and exposed to the laser beam. This indicates that the intermediate tensioning rig should apply tension on a smaller lace area than the early transport and tensioning rig. In the previous research of lace cutting, the loop thread has never been identified or discussed. The tensioning methods used before are mainly for facilitating the lace cutting operation rather than improving the lace cutting edge quality. From the mechanical lace cutting system to this project, the lace tensioning method evolves in a “zooming in” way as shown in Table 4-1.

<table>
<thead>
<tr>
<th>Tensioning system</th>
<th>Tensioning method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical cutting system</td>
<td>Global tensioning (3.8m wide X 200m long)</td>
</tr>
<tr>
<td>Early transport and tensioning system</td>
<td>Controlled tensioning of local area (typical 75x80 mm)</td>
</tr>
<tr>
<td>Intermediate tensioning system</td>
<td>Controlled tensioning of a smaller area (10x10 mm or less)</td>
</tr>
</tbody>
</table>

Table 4-1 Lace tensioning method development
According to everyday experience, a small area of lace can be ideally tensioned with four fingers as shown in Figure 4-10 where each finger independently pulls the lace away in different directions. By varying the magnitude and direction of the tension applied by each finger, the lace section can always be properly tensioned.

From Figure 4-10, it is straightforward to conclude that a tensioning rig capable of emulating four fingers applying tension would be able to adequately tension a small lace section. In order to facilitate applying tension, a small opening is usually cut with scissors beforehand as shown in Figure 4-11.
As lace is flat and very thin when compared to its length and width, it can be considered as a two-dimensional object, which means that lace only needs to be tensioned in the plane of the lace surface. To simulate the movement of the four fingers to apply tension, four aluminium blocks are employed, on which the lace is attached through Velcro. By manipulating these blocks to adjust the directions and magnitudes of the applied tension, the lace section can be adequately tensioned, as shown in Figure 4-12.

![Figure 4-12 Tensioning lace with four blocks](image)

The tension each block applies on the lace can be decomposed into two types of tension relative to the cutting path, lateral tension and longitudinal tension, as shown in Figure 4-13.

![Figure 4-13 Tension decomposition](image)
By moving each tensioning block translationally in lateral and longitudinal directions, the magnitude and direction of the tension applied can be varied and the desired tension to adequately tension the lace can always be achieved. However, as to the tensioning block 1 and 2, there is another option available to vary the tension they have applied, that is, rotating these two blocks around the rotation point while block 3 and 4 are still moved translationally, as shown in Figure 4-14.

Based on the analysis above, two tensioning methods have been identified, which are described and compared as follows.

1. **Translational tensioning method**
   According to the translational tensioning method, all four tensioning blocks are moved in lateral and longitudinal directions, as shown in Figure 4-15.

2. **Mixed tensioning method**
   The lace section is tensioned by moving tensioning block 3 and 4 in longitudinal and lateral directions but rotating tensioning block 1 and 2 around the rotation point, as shown in Figure 4-16.
4.2.2.1 Tensioning method direction

Translation direction

Figure 4-15 Translational tensioning method

Rotation direction

Figure 4-16 Mixed tensioning method
4.2.2.2 Tensioning method decision

Both tensioning methods are capable of adequately tensioning a small lace section. In order to decide which method is more appropriate, their advantages and disadvantages need to be identified and compared. As the only difference between these two methods is how tensioning block 1 and 2 are moved (see Figure 4-15 and Figure 4-16), the effect of translational and rotational movement on tensioning effectiveness and design simplicity is compared.

1. Tensioning effectiveness

As seen in Figure 4-17, the angle $\theta$ between the tension applied by the tensioning block 1 and 2 is a key factor of affecting how well the small lace section is tensioned. Depending on the structure of the lace section being tensioned, there is usually an optimal angle. When the angle value between the tension 1 and 2 reaches the optimal value, provided that the magnitudes of tension 1 and 2 are also appropriate, the lace section will be best tensioned. However, as the lace structure is complex and different, lace sections of a lace sample have different structures. The angle $\theta$ needs to be changed accordingly to cope with the lace structure variation.

![Figure 4-17 Tensioning angle](image)
As shown in Figure 4-18 and Figure 4-19, tension 2 is changed by rotating or translating tensioning block 2. In terms of the effectiveness of changing the angle $\theta$ between tension 1 and 2, rotating the tensioning block 2 around the rotation point is better than translating it in both lateral and longitudinal directions. While translating the tensioning block 2 in the lateral direction increases the angle $\theta$, the translation movement along the longitudinal direction decreases the angle $\theta$. The counteraction between lateral and longitudinal translation movement makes it difficult to control the angle $\theta$.

2. **Design simplicity**

As shown in Figure 4-18, without changing the rotation radius, only the direction of the tension 2 is changed. In order to change both the direction and magnitude of tension 2 at the same time, the rotation radius needs to be increased gradually as tensioning block 2 is rotated, which undoubtedly makes the design more complex. In addition, the radius value
is determined by the distance between the rotation point and the position of lace being attached onto the tensioning block, both of which cannot be decided beforehand. On the other hand, with the translation tensioning method, the direction and magnitude of the tension can be varied concurrently, as shown in Figure 4-19. In terms of the design simplicity, translational tensioning method is more practicable.

Based on the analysis and comparison above, translational tensioning method is considered more appropriate. Although the angle \( \theta \) between the tension 1 and 2 shown in Figure 4-17 needs to be varied to adequately tension a small lace section, it is not necessary to control it precisely. As the intermediate tensioning rig will be operated manually, with the feedback from observing the lace section being tensioned, the operator using the tensioning rig will eventually be able to adequately tension the lace section using the translational tensioning method.

As moving tensioning block 1 or 2 in lateral and longitudinal directions has counteractive effect on changing the angle between the tension 1 and 2, as shown in Figure 4-19, tensioning block 1 and 2 are designed so that they are only able to move in the lateral direction. The final decision of tensioning method is shown in Figure 4-20.

4.2.2.3 Detailed design and manufacturing

After the tensioning method has been decided, there are several other aspects of the intermediate tensioning rig that need to be specified.

1. **Size of the tensioning block**
   
   As the intermediate rig is used to tension a small lace section, usually no more than 30mmx30mm, a large tensioning block will be unwieldy to manipulate the lace section of this small size. 20mmx20mm is considered an appropriate size of the tensioning block.

2. **Translation method**
   
   There are many options for translating the tensioning blocks in longitudinal and lateral directions, such as a linear bearing based system. As the intermediate tensioning rig will be manually operated, speed is not considered as an issue. The combination of extrusions and a plastic rail is considered competent and cost-
effective. A manually operated lead screw mechanism is used to displace the tensioning blocks and secure their positions when the lace has been adequately tensioned. The translation mechanism is shown in Figure 4-21.

3. **Displacement required to tension the lace**

The displacement of each tensioning block required to tension a lace section is dependent on several factors. The first factor is the characteristics of lace itself. Usually, longer displacement is needed to tension stretchy lace. The area of the lace section needed to be tensioned determines how far the tensioning blocks should be displaced as well. The bigger the area, the longer the required displacement. However, some tension can be applied on lace while the lace is being attached on the tensioning blocks, which can reduce the required displacement. A 250mm long rail on which the tensioning block slides is considered long enough to satisfy the requirements.

The final detailed design of the intermediate tensioning rig is shown in Figure 4-21 and the manufactured rig with lace attached on it is shown in Figure 4-22.
Vision Guided Cutting and Mechanical Handling of Lace Ribbon

4.3 Lace Cutting Strategy

In this section, we will discuss the various techniques and strategies employed in the process of cutting lace effectively. The primary focus will be on the intermediate tensioning rig, which plays a crucial role in ensuring high-quality lace production.

**Figure 4-21** Detailed design of the intermediate tensioning rig

The design features a manually operated lead screw mechanism, which allows for precise control over the tensioning process. The rig is equipped with tensioning blocks and rails, with dimensions of 40mm, 180mm, and 200mm, respectively. This setup ensures that the lace is tensioned uniformly, reducing the risk of damage during the cutting process.

**Figure 4-22** The intermediate tensioning rig with lace

The implementation of the intermediate tensioning rig significantly improves the quality of the lace produced. Its use is not just limited to the cutting process but also extends to the overall production line, ensuring a consistent and high-quality output.

Manually operated lead screw mechanism

40mm

180mm

200mm
4.3 *Lace Cutting Strategy*

Inspecting lace purls under the microscope reveals that a purl of perfect quality can be produced only when its loop thread is adequately tensioned and cut off accurately by the pulsed laser beam, as discussed in section 4.1. After the intermediate tensioning rig has been designed and manufactured, it is possible to further observe how lace behaves during the lace cutting process. As the loop thread is the key to producing high quality purls, the observation will be focused on how the status of a loop thread changes.

In this section, a series of lace cutting experiments will be carried out, during which lace is tensioned by the intermediate tensioning rig and cut by the pulsed laser system. The structure and status of lace, especially loop threads, before and after each thread laser cutting event will be tracked and compared. Based on the observations of the lace changes during the lace cutting process, a lace cutting strategy will be proposed, aimed at helping to produce high quality lace.

4.3.1 *Lace cutting with the intermediate tensioning rig*

As the loop thread of a purl is so tiny that it can only be clearly observed under the microscope, the system resolution of the pulsed laser cutting system has to be increased. The distance between the lace and the camera is then reduced until the loop thread status can be clearly observed. The system resolution is increased from 30 pixels per mm to be around 80 pixels per mm, with the field of view (FOV) consequently reduced from 27mmx18mm to about 10mmx7mm. The depth of field (DOF) of the camera system also decreases as the object distance is reduced. The DOF deficiency is then compensated by reducing the aperture value, which however degrades the quality of the captured images, making the image processing algorithms of the pulsed laser cutting system incompetent to process them to find cutting points automatically. As the main purpose of these experiments is to observe how lace changes after each cutting operation, cutting the lace manually with the pulsed laser beam seems more appropriate. However, the high resolution camera selected for developing the machine vision system during this project has successfully solved the problem as described in Chapter 5.

The findings based on the observations during the manual laser cutting process are summarised as follows.
4.3.1.1 Lace reactions to tension change

Due to lace’s complex structure and flexible characteristics, lace changes its shape dramatically after each cutting. When a thread is cut off, it usually shrinks back and the tension previously applied on it will be distributed to its neighbouring threads. As the tension redistribution process puts more tension on the neighbouring threads, they are usually better tensioned. As shown in Figure 4-23, after the middle thread is cut, more tension is applied on its neighbouring threads 1 and 2. The loop thread connected with the neighbouring thread 2 is also exposed.

Two conclusions can be deduced from observing the lace change described above.

1. A thread can be better tensioned by cutting off its neighbouring threads first
   If the neighbouring threads of a selected thread are all cut off, the applied tension can be concentrated on the selected thread so that it can be better tensioned.
2. **Progressive thread tensioning**

As the status of a thread always changes after each adjacent cutting, trying to adequately tension all threads within a lace section is unnecessary. If a thread can be ensured to be adequately tensioned just before it is cut by the pulsed laser beam, there is no need to tension other threads. Therefore, by adequately tensioning only one thread at a time and cutting it with the pulsed laser beam, the lace can be cut progressively with a high quality finish.

4.3.1.2 **Loop thread observation**

According to the observations of the lace purl microstructure in section 4.1, each purl has a loop thread connected to it. A high quality purl can be produced if its loop thread is exposed and cut off by the pulsed laser beam. Since it is critically important to the resulting lace cutting edge quality, the status change of loop threads has been carefully investigated during the lace cutting experiments with the intermediate tensioning rig.

A loop thread is usually a very tiny thread connecting a purl and some thicker connection threads whose other ends are usually knitted into the waste mesh. It is important to notice that not all connection threads of a purl are connected to the purl through the loop thread as shown in Figure 4-24.

As the loop thread connects the purl and connection threads together, tension cannot be applied on it directly. The best way to tension and expose a loop thread is to apply tension on the connection thread which is directly connected to it. Depending on the type and pattern design of the lace, the behaviour of every loop thread is different when tension is applied. Lace compliance and the structure of connection threads have been identified as two main factors affecting the behaviour of a loop thread.
According to the observations, the more compliant the lace is, the easier it is to expose the loop thread. Given the same tension, it is more difficult to expose the loop thread of a rigid purl than a stretchy one, resulting in stretchy lace usually having better cutting quality than rigid lace. This can also help to explain the result of the tension effect experiments described in Chapter 3 in which the tension effect on the edge quality of the lace of type II (stretchy) is more significant than the lace of type I (rigid) (more detail in section 3.3). However, for a mechanical lace cutting system, this is a totally different case. The mechanical lace cutting system is more capable of cutting rigid lace because stretchy lace can easily distort and change its shape, making it difficult to cut.

2. **The structure of the connection threads**

The other factor affecting how easily a loop thread can be tensioned and exposed is the structure of the connection threads connected to the loop thread. Two types of connected thread structures have been identified.
2.1 Both ends of the connection thread going through the loop thread are connected to the waste mesh, directly or through other threads, as shown in Figure 4-25. As both parts of the connection thread can be easily tensioned, the loop thread can be adequately tensioned and exposed.

![Figure 4-25 An example of a connection thread with both ends connected to the waste mesh](image)

2.2 Either end of the connection thread is connected to the pattern section or next purl, as shown in Figure 4-26. Although one end of the connection thread has been adequately tensioned, the other end connected to the pattern section is still in the state of relaxation. The loop thread of the purl is still not adequately tensioned and therefore not exposed.

![Figure 4-26 A connection thread with one end connected to the next purl](image)
4.3.2 Lace cutting strategy proposal

With all the information obtained from the lace cutting experiments using the intermediate tensioning rig, a lace cutting strategy has been conceived through a reasoning process shown in Figure 4-27.

The main purpose of the lace cutting strategy is to help to produce high quality lace through progressively tensioning lace threads and strategically cutting connection threads to expose the loop thread of each purl.

4.3.2.1 One purl at a time

Lace edge is made up of many individual purls, each of which is connected to the waste mesh through one or several connection threads. To produce a high quality purl, it is necessary to adequately tension the connection threads connected to the loop thread so that the loop thread can be exposed to the pulsed laser beam. Although each purl is unique as it has different shape and structure, it has similar basic components in that each purl has only one loop thread and one or more connection threads. From this point of view, each purl can be isolated from other purls and treated as an independent unit during the lace cutting process. Only after all connection threads of a purl have been cut off will the next purl be processed. This also indicates that the tension control can be further focused on every single purl and its connection threads. If each individual purl of the lace is free from any laser damage, the produced lace will be of high quality.

4.3.2.2 Cutting order of the connection threads

Through the cutting experiments using the intermediate tensioning rig, it has been learnt that cutting off the neighbouring threads of a selected thread first helps to adequately tension the thread as the applied tension can be concentrated on the thread. In order to expose the loop thread of a purl, it is necessary to adequately tension the connection threads directly connected to the loop thread. As sometimes there are other connection threads which are not connected to the loop thread, it is straightforward to decide that these connection threads should be cut off first so that the connection threads connected to the loop thread can be adequately tensioned.
Figure 4.27 Lace cutting strategy reasoning process

Purl microstructure observation

One purl has one loop thread

A high quality purl can be produced if the loop thread is tensioned and exposed to the pulsed laser beam

One purl at a time

Lace reactions to tension change

A thread can be better tensioned by cutting off its neighbouring threads

Connection thread cutting order

Loop thread observation

Only the thread to be cut needs to be adequately tensioned at a time

Progressive thread tensioning

Loop thread can only be adequately tensioned by applying tension on the connection threads connected to it

Lace cutting experiments with the intermediate tensioning rig
The top section of a purl is considered as the critical area as any laser damage produced in this section would cause lace to snarl with other fabrics and make it feel coarse, greatly degrading the lace quality, as shown in Figure 4-28.

![Critical section of a purl](image)

Figure 4-28 Critical section of a purl

The connection threads connected to the purl in the critical section should be adequately tensioned before being cut off by the pulsed laser beam. These connection threads are called primary connection threads while the connection threads connected to the bottom section of a purl are called secondary threads as their cutting quality result has less effect on the overall quality of the purl when compared to the primary connection threads.

Careful observations of lace structure have shown that the primary connection threads of a purl are usually linked with the loop thread. Therefore, cutting off the secondary connection threads will help to adequately tension the primary connection threads, which consequently helps to expose the loop thread.

A good example is shown in from Figure 4-29 to Figure 4-31. The selected purl shown in Figure 4-29 has two connection threads, with the loop thread not exposed. According to the analysis above, the connection thread 1 is considered secondary as it is connected to the bottom section of the purl and should be cut first. Then as shown in Figure 4-30, the secondary connection thread has been cut off. Without any more tension applied, the primary connection thread is better tensioned and the loop thread is therefore exposed. By directing the pulsed laser beam on the exposed loop thread, the purl after being cut is shown in Figure 4-31.
Firstly cutting off the secondary connection threads which are connected to the bottom section of a purl not only helps to tension the primary connection threads as discussed above, but also helps to solve the problems encountered when the loop thread can hardly be exposed due to the structure of the connection threads. As shown in Figure 4-32, due to the structure of the connection threads, although the connection thread 1 has been adequately tensioned, the connection thread 2 is still in the state of relaxation, leading to the failure of exposing the loop thread. According to the connection thread cutting order determination theory, the connection thread 2 is cut off first as it is connected to the
bottom section of the purl. Then the remaining of the connection thread 2 is pulled through the loop thread by the connection thread 1 and the purl after being cut is shown in Figure 4-33. There is even no need to cut the loop thread.

![Figure 4-31 Cutting result](image)

![Figure 4-32 A purl with two connection thread](image)
4.3.2.3 Lace cutting strategy flowchart

When the proposed lace cutting strategy is applied during the lace cutting process, the cutting process can be represented as in Figure 4-34.
Vision Guided Cutting and Mechanical Handling of Lace Ribbon

Chapter 4

Figure 4-34 Lace cutting process with the lace cutting strategy

1. Pre-tension the lace
2. Take an image of the lace (high resolution)
3. Isolate the first uncut purl (One purl at a time)
4. Applying the image processing algorithms to detect all cutting points of the isolated purl
5. Classify these connection threads and determine the order how these connection threads should be cut
6. Cut off all secondary connection threads one by one
7. Check if the loop thread has been exposed?
   - Yes: Direct the pulsed laser beam onto the loop thread to cut it
   - No: Tension adjustment
8. Next purl
4.4 Summary and Discussion

In this chapter, the microstructure of the lace purls has been investigated under the microscope, based on which, exposing the loop thread of a purl has been identified as the key to producing a high quality purl. The inspection of purl microstructure also helps to explain the conclusion that applying tension can improve lace cutting edge quality as described in Chapter 3.

The design process of the intermediate tensioning rig has been presented. The manually operated tensioning rig is capable of tensioning a small lace section with four tensioning blocks. A series of lace cutting experiments have been conducted with the intermediate tensioning rig, during which how lace, in particular the loop thread changes after each laser cutting has been carefully observed. Then a lace cutting strategy is proposed, aimed at helping to expose loop threads through tensioning and cutting connection threads strategically according to the lace structure.
5 Machine Vision System Development

In order to automatically implement the lace cutting strategy proposed in Chapter 4, a machine vision system is desired. The system should be capable of automatically isolating each purl, detecting all thread cutting points of the isolated purl and determining the cutting order of all these cutting points.

This chapter is divided into two parts. In the first part, the selection process of each component making up the machine vision system will be presented, including camera, lens, illumination and etc. Then in the second part, the development of the image processing algorithms designed to realise automatic strategic lace cutting will be described.
5.1 Machine Vision System

Machine vision techniques are being employed in various industries. Depending on each specific application, a machine vision system can take different forms. However, the basic components making up a machine vision system are similar and a typical machine vision system is illustrated in Figure 5-1.

The light reflected from the object is focused through the lens system onto the image sensor inside the camera. The electrical signal from the camera is then converted into a format suitable for further processing by the image acquisition hardware, usually a frame grabber. After appropriate image processing algorithms are implemented in the main processor, the results can be displayed or used to control other instruments, such as an industrial robot.

For each component of a machine vision system, there are usually several options available in the commercial markets. The selection process of each component for the machine vision system for this project will be presented in the following sections.
5.1.1 Camera selection

The purpose of a camera is to acquire an image projected onto the sensor inside the camera and convert it into a form that can be transferred to another device for display, storage or analysis. Due to the development of the Charge Coupled Device (CCD), camera technology has been advanced greatly over the last decade.

There are two main types of cameras to select for building a machine vision system: area scan camera and line scan camera. The sensor of an area scan camera occupies an area rather than a single line which is the case with a line scan camera. To image an object, a line scan camera requires relative movement between the object and the camera, and usually the object is moved under a stationary camera. With the signal generated from the object handling system, one line of image is built up at a time. Acquiring successive lines at a fixed interval and storing them into a memory can generate a two-dimensional image of a moving object. On the other hand, no relative camera to object movement is required for an area scan camera which scans an area at a time to produce a two-dimensional image. The advantages and disadvantages of area scan and line scan cameras are listed in Table 5-1.

<table>
<thead>
<tr>
<th>Camera type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Area scan   | • Cost effectiveness.  
              • Simple to use | • Relatively low resolution.  
              • Limited speed.  
              • Poor performance for imaging moving objects. |
| Line scan   | • High resolution (up to 12,000 pixels/line).  
              • High relative camera to sample speeds. | • High cost.  
              • Complicated to use.  
              • An object handling system is usually required to provide relative movement and timing signal. |

Table 5-1 Area scan VS line scan

The imaging sensor of a camera can be made from two different technologies: CCD (Charge Coupled Device) and CMOS (Complementary Metal Oxide Semiconductor), with each having unique strengths and weaknesses. Both types of imaging sensor convert light into electric charge and then process it into electronic signals. In a CCD sensor, the
charge of each pixel is transferred through a limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analogue signal. In a CMOS sensor, each pixel has its own charge-to-voltage conversion. It often also includes amplifiers, noise-correction, and digitization circuits, and the chip outputs digital bits. The difference in transfer method and chip structure has resulted in performance difference between CCD and CMOS as presented in Table 5-2.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| CCD         | • Higher image quality  
              • Relatively simple sensor design  
              • High fill factor* | • Relatively high system complexity  
              • Relatively slower |
| CMOS        | • Lower power dissipation  
              • Higher circuit integration | • Lower uniformity  
              • Complex design  
              • Low fill factor* |

*Fill factor is the percentage of the pixel area which is actually sensitive to light relative to the whole pixel area of the sensor

Table 5-2 CCD VS CMOS

However, there is no clear line dividing the types of applications each can serve as CMOS designers have devoted intense effort to achieving high image quality, and CCD designers have reduced the power requirements and pixel sizes. CCD and CMOS will remain complementary, with the choice depending on the application more than the technology.

The image acquisition hardware is used to convert the output signal of a camera into a suitable form for further processing and transfer it to the memory of the image processing system. The output from a camera can take the form of analogue or digital depending on whether the camera contains an ADC and associated circuitry. In the case of an analogue camera, a frame grabber is normally used to digitise the analogue signal using the ADC it contains. A frame grabber often has other functions, such as frame triggers, exposure control, I/O, buffer or embedded pre-processing functions, such as flat-field correction, image arithmetic or convolution filters, which helps to save time for the host processor.
When it comes to a digital camera, the ADC inside the camera digitises the analogue signal directly and outputs a digital signal which maybe in a variety of different forms. Digitising an analogue signal directly overcomes the noise deficiency of an analogue camera, resulting in high fidelity. The transfer of data from a digital camera to the image processing system can be handled using a number of different technologies. An overview of the most common interfaces is presented in Table 5-3.

<table>
<thead>
<tr>
<th>Transfer Type</th>
<th>Parallel Digital</th>
<th>Camera Link</th>
<th>USB</th>
<th>IEEE-1394 (FireWire)</th>
<th>Gigabit Ethernet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. No. of Devices</td>
<td>1</td>
<td>1</td>
<td>127</td>
<td>63 (16 cameras)</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Operational Distance</td>
<td>&lt;10m</td>
<td>&lt;10m</td>
<td>&lt;5m</td>
<td>&lt;4.5m</td>
<td>&lt;100m</td>
</tr>
<tr>
<td>PC Interface</td>
<td>PCI Framegrabber Card</td>
<td>PCI Framegrabber Card</td>
<td>PCI Interface Card</td>
<td>PCI Interface Card</td>
<td>PCI Interface Card</td>
</tr>
<tr>
<td>Max Bandwidth (Mb/sec)</td>
<td>Hardware dependent</td>
<td>&lt;900</td>
<td>&lt;60</td>
<td>&lt;800</td>
<td>&lt;80</td>
</tr>
</tbody>
</table>

Table 5-3 Digital camera interface methods

With the advent of the interface available on standard PC systems, USB and FireWire compatible cameras have become a cost effective solution to building a low cost machine vision system as no frame grabber is needed. Camera Link is a new concept for digital camera interfacing that enables higher data transfer speeds using fewer wires with standardised connectors, cabling and data protocols. The development of Gigabit Ethernet (GigE) makes it possible for cameras to communicate and transfer data using standard network technology, which enables machine vision systems to benefit from the flexibility and cost saving as the communication standard is in widespread use. Setting up complex topologies that support multiple cameras is also feasible with the Gigabit Ethernet technology. Another advantage of Gigabit Ethernet interfacing technology is the length of
Cabling can be as long as up to 100 meters without the need for regeneration, enabling cameras to be situated at greater distances.

The object to be imaged in this project is lace, which is normally transported continuously through the cutting process. As discussed above, the best choice to image a fast moving web-like object is a line scan camera. However, as the main focus of this project is to investigate the image processing algorithms to assist strategic lace cutting, an area scan camera would be more appropriate. In addition, at the initial stage of this project, the lace to be cut will be stationary when it is imaged and cut. After an image of the lace is captured, the results of implementing different image processing algorithms can be seen immediately. It is speculated that a line scan camera can easily replace the area scan camera once image processing algorithms have been proven to be appropriate. The alternative to a line scan camera for capturing images of fast moving objects is a high speed area scan camera, such as Phantom V9.0, which is able to capture 1,000 images per second at a resolution of 1600x1200 pixels. By setting the exposure time down to 2 microseconds, image blur can be avoided. However, accordingly, this kind of high speed camera is extraordinarily expensive in current commercial market (more than £20,000).

The Sony SSC-M370CE camera works with a Coreco Viper Quad frame grabber to output images with a resolution of 768X576 at 8 bits per pixel. The camera is capable of capturing lace images of good quality for the image processing system to extract cutting path and then cutting points when the camera system resolution is about 30 pixels per millimetre, as described in [2]. According to the cutting experiments described in Chapter 4, a loop thread cannot be clearly recognised until the camera system resolution is adjusted to be about 100 pixels per millimetre. Although the Sony camera is still able to produce images at this high resolution of 100 pixels per millimetre, the image quality is so poor that the developed image processing algorithms fail to find the cutting path and cutting points automatically. In addition, the field of view (FOV) of the camera system consequently decreases to be 7.68mm x 5.76mm, which is not big enough for the machine vision system as the lace section to be cut will be moved to align with the laser beam and then could be out of the field of view when some tension is applied on the lace.

Based on the discussion and reasoning above, a monochrome camera from PixeLINK has been selected for the project. This PL-A741 camera has a resolution of 1280 x 1024 pixels,
providing a field of view of 12.8mm x 10.24mm at a camera system resolution of 100 pixels per millimetre. This digital camera has a CMOS imager and data from the camera is transferred to the computer over a standard, inexpensive FireWire adapter and cable, which eliminates the need of a separate frame grabber, thus reducing the system complexity and cost. The camera provides high flexibility in that shutter, gain, brightness, frame rate and trigger mode are all configurable. In addition, the camera has extended functionality including additional trigger modes, general purpose outputs that can be used as communications lines or strobe signals for lighting or motion controllers, on-board user-programmable lookup table (LUT), on-board non-volatile memory for camera configuration, and camera configuration descriptors for rapid changes to camera settings between frames. Combined with the global shutter, all these functions enable the camera to be used as a line-scan camera for low-speed applications, which would be useful for this project when it is developed to the later stage.

5.1.2 Lens selection

The purpose of a lens is to focus the light reflected from the object to be imaged to the image sensor inside the camera. It is important to match the quality of the lens to the rest of a machine vision system. A high quality mega-pixel camera can be compromised by using a low quality lens. When choosing a suitable lens, it is necessary to consider several basic aspects of the machine vision system.

1. Field of View (FOV)

The FOV of a machine vision system is invariably the most important factor to be considered. For this project, although the FOV required is not precisely known at this stage, it is expected that the larger the FOV, the better for the imaging system to keep the purl to be cut always within the FOV when tension is changed during the lace cutting process. As the system resolution is required to be about 100 pixels/mm to image the loop thread of a purl, the FOV of the imaging system is expected to be about 12mm x 10mm.

2. Camera sensor and pixel size

The chosen PL-A741 camera has a resolution of 1280 x 1024 pixels. The physical imaging sensor size is 2/3" which is equivalent to 8.8mmx6.6mm. In order to illuminate the whole area of the imaging sensor, the size of a lens is usually required to be larger than, or at least equal to the size of the imaging sensor. All images through a lens suffer
from intensity variation from the centre to the edge of the image, which is known as the vignetting effect. The effects of vignetting can be reduced by using a larger format lens, thereby taking the effect outside the range of the sensor, as shown in Figure 5-2. Therefore, the desirable lens for this project would be larger than or equal to 2/3".

![Figure 5-2 Effect of vignetting](image)

When selecting a lens for a camera, it is necessary to ensure that the lens is capable of resolving down to the individual pixels of the camera sensor. Pixel size varies widely from camera to camera, depending on the resolution of the sensor and its size. The size of each pixel pitch of the imaging sensor of the PL-A741 camera is 6.7μm.

3. Working distance
Due to the space constraints, a large offset is required for imaging the lace. An offset of 300 mm ensures that no part of the lens will interfere with the laser optics and other components.

4. Depth of field (DOF)
Depth of field (DOF) is the amount of distance between the nearest and furthest objects that appear in acceptably sharp focus in an image. A few factors have a direct relationship with the depth of field, including aperture, focal length and object distance. As lace is very thin when compared to its width and length, and is kept flat when it is imaged, depth of field of 1 mm is considered to be enough for imaging the lace.
Based on the information and analysis above, several parameters of the desired lens can be determined.

1. **Focal length**

The focal length of the required lens can be calculated as [97]:

\[
\text{Focal Length} = \frac{\text{Working Distance} \times \text{Size of Image}}{\text{Size of Object} + \text{Size of Image}}
\]

As the size of object and working distance cannot be exactly determined, the focal length is roughly calculated with the values of working distance and size of object being 300mm and 12mm respectively.

\[
\text{Focal Length} = \frac{300\text{mm} \times 11\text{mm}}{12\text{mm} + 11\text{mm}} \approx 143\text{mm}
\]

A zoom lens whose focal length can be adjustable around 143mm is desirable as the working distance of the machine vision system needs to be varied so that images with different resolutions can be obtained for various experiments.

2. **Magnification**

As the camera sensor size is 8.8mmx6.6mm and the desirable field of view (FOV) is about 12mmx10mm, the lens should have a magnification factor of: [97]

\[
\text{Magnification} = \frac{\text{Image Size}}{\text{Object Size}} = \frac{8.8}{12} \approx 0.7
\]

When the system resolution of the imaging system is increased, the field of view (FOV) will be decreased, and therefore the magnification factor will increase. A lens with a magnification factor of up to 1 would be suitable for this project.

The chosen lens is a zoom macro lens which has a focal length of 90mm to 230mm and offers magnification up to 1:4.5. The f number of the lens system ranges between f4.5 and f22.
As mentioned above, in order to avoid any interference between the lens system and other components, the working distance of the lens should be at least 300mm. With the chosen lens, the least image distance can be calculated as follows [97].

\[
\text{Image Distance} = \frac{\text{Object Distance} \times \text{Focal Length}}{\text{Object Distance} - \text{Focal Length}} = \frac{300 \times 90}{300-90} \approx 129\text{mm}
\]

It is obvious that an extension tube is required to increase the distance between the camera sensor and the lens as the image distance of a standard C-Mount camera is only 17.526 mm. A bellows has been selected which offers a maximum of 150 mm extension between the camera and the lens. The combination of the lens, bellows and camera is shown in Figure 5-3.

![Figure 5-3 The imaging system](image)

The highest system resolution can be achieved when the lens is closest to the lace sample, resulting in the smallest field of view (FOV). Theoretically, with the least working distance of 300 mm established, the system resolution could be as high as 150 pixels/mm. With the selected imaging system, the desired system resolution of 100 pixels/mm can be easily achieved.

When designing an imaging system, another important factor needed to be considered is the resolution limit of the lens, which results from the diffraction effect around the aperture of the lens. The resolution limit of a lens determines the smallest point it is able to resolve. The resolution limit of a lens can be calculated according to the Lord Raleigh Criterion as follows [98].
\[ Z = 1.22\lambda(f\#) \text{ m} \]

Where: \( Z \) = Minimum resolution  
\( \lambda \) = Wavelength of illumination light  
\( f\# \) = F-number of the lens

As the light source used for the machine vision system has a wavelength of 620 nm, the resolution limit of the selected lens can be calculated to be 16.6 \( \mu \text{m} \) when the F number is set to be f22. The pixel pitch of the PL-A741 camera has a size of 6.7 \( \mu \text{m} \), which is much smaller than the resolution limit of the lens. This means that the camera will be losing details when using the f22 aperture stop on the lens. However, the smallest threads of lace are approximately 100 \( \mu \text{m} \), which is much bigger than the resolution limit of the lens. In terms of imaging lace, the chosen lens is good enough for resolving the smallest lace details. In addition, the f number of the lens aperture can be increased to be f4.5, where the resolution limit is increased to be 3.4 \( \mu \text{m} \), smaller than the pixel pitch size.

5.1.3 Illumination

Illumination is the most critical part of a machine vision system. As cameras are far less versatile than human eyes, light conditions often need to be optimised for a camera to image an object which human eyes can well see in uncontrolled conditions. With inappropriate illumination, a simple machine vision task would become difficult or even impossible to be achieved. On the other hand, careful consideration can eliminate the need of expensive software or hardware to enhance the image as well as reduce complexity of feature detection and extraction, leading to the reduction in both cost and processing time.

5.1.3.1 Light source type

Choosing an appropriate type of light source is the first step of designing an illumination system. There are several types of light sources available in the current commercial market, with each type having its respective advantages and disadvantages.

- **Fluorescent illumination**

Although fluorescent tubes are commonly used for domestic purpose, their use in machine vision applications is limited due to the lack of variety in shape and size. Fluorescent
tubes cannot be strobed. Furthermore, they are powered by AC and therefore introduces
flickers, which however can be reduced by high frequency switching.

- **Fibre Optic Illumination**
The basic idea of fibre optic illumination is to harness the intensity of a light source. The
light is guided and focused through an optical fibre lightguide and into a light adaptor
positioned close to the object. Due to the increasing transmission loss per meter, it is not
practical to use fibre optic lightguides in excess of 5 meters.

- **LED illumination**
LEOs (Light Emitting Diodes) are becoming a popular solution for more and more
machine vision applications due to its low cost and long service life. As LEDs are
powered by DC power supplies, no flicker is present, thus providing constant and stable
illumination. Although LEDs are available in a variety of different colours, the most
common colour for LEDs is red. Red LEDs are most widely used and therefore the
cheapest. The disadvantage of LEDs is that the light intensity they are able to provide is
not considered to be as high as the fibre optic illumination.

- **Laser illumination**
Laser illumination is normally used in structured lighting applications, such as
measurements, 3D inspection and equipment alignment. In these applications, narrow and
sharp lines are required with minimal background illumination. The unique properties of a
laser make it the best choice for these applications. The advantages and disadvantages of
these light sources are summarised in Table 5-4.

Determining the illumination light source for a machine vision system is dependent on
specific applications, such as a monochrome or colour application, a high speed or low
speed application. For a monochrome application where the images are captured by a
monochrome camera, the colour of the illumination is considered to be unimportant if the
object is monochrome as well. However, if the object is not monochrome, the
illumination colour will affect the intensity distribution of the resulting image. For
example, the red part of the object appears to be lighter in the captured images when
illuminated by a light source of red colour than by a light source of blue colour. For a high
speed application, a strobe controller is usually required to flash the light source to ‘freeze’ the fast moving object to avoid any blur.

<table>
<thead>
<tr>
<th>Light source type</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Applications</th>
</tr>
</thead>
</table>
| Fibre optic      | • High intensity  
                  • Low heat output | • Short service life  
                  • Low design flexibility | High speed applications |
| Fluorescent      | • Low cost  
                  • Good brightness | • Short service life  
                  • Inherent flicker  
                  • Can not be strobed  
                  • Can not be intensity controlled | Limited for special applications |
| LED              | • Low cost  
                  • Low power consumption  
                  • Fast response  
                  • Stable over time  
                  • Long service life | • Relatively low intensity | Nearly suitable for all machine vision applications |
| Laser            | • High intensity  
                  • Monochromatic  
                  • Coherent | • Fails to illuminate large areas | Applications requiring structured illumination |

Table 5-4 Illumination light sources

At the early stage of this project, as the lace will be stationary when it is imaged, no strobe controller is required. Stability and cost effectiveness are considered to be the priority, which makes the LED light source the first choice for the project. In addition, an LED light source usually has a small physical size, which makes it more appropriate as the space is very limited.

5.1.3.2 Illumination techniques

There are several standard illumination techniques used for various machine vision tasks, ranging from simple ones like top lighting to relatively complex structured illumination.
such as on-axis illumination. The choice of illumination techniques depends on specific applications and it is closely related to the object properties, object shapes and so on. Several standard illumination techniques have been investigated to illuminate the lace and the test results are reported here.

The first illumination method investigated is the top lighting technique. The light is diffused through the diffuser, which makes the illumination less intense but more uniform. As the lace used in this project is white (more different colours in practice), the black background has provided a good contrast. The illumination arrangement is shown in Figure 5-4 and the resulting lace image is shown in Figure 5-5. This illumination method does not cause any shadows and is good at revealing the surface details of the lace, but fails to differentiate the thick lace pattern section and the thin waste mesh, making it difficult to detect the interconnection points where connection threads intersect with the purl.

Figure 5-4 Top lighting illumination
Another illumination method is the back lighting technique. As the lace is not transparent, it appears to be black in the captured images when compared to the white background. The illumination arrangement is shown in Figure 5-6 and the captured lace image is shown in Figure 5-7. With this illumination method, the captured image is nearly binary and the silhouette of the lace can be well viewed. This illumination method was employed in the early Loughborough lace scalloping system [6]. However, like the top lighting illumination method, this illumination method is not able to highlight the difference between the lace pattern section and the waste mesh.

The last illumination method is called transmissive dark field illumination. The illumination method works by projecting a cone of light from the ring light below the lace and allowing this to illuminate the lower surface of the lace. Because of the thickness variation across the lace surface as the purl is usually thicker than a thread, the intensity of the light transmitted through the lace is not uniform. The illumination arrangement is shown in Figure 5-8 and the typical captured image is shown in Figure 5-9. This method is good at emphasising the variation between the purl and its connection threads.

Figure 5-5 Lace image with top lighting illumination
This illumination method was developed and used by Bamforth in [2] and detailed description of the development and optimisation process of the ring light has been reported. The captured images of the lace illuminated with this illumination method have
provided a good basis for the successful detection of the cutting path and the cutting points where connection threads intersect with the purl.

![Image of Camera and Lace Ribbon]

**Figure 5-8 Transmissive Dark Field Illumination**

![Lace image with Transmissive Dark Field Illumination]

**Figure 5-9 Lace image with Transmissive Dark Field Illumination**
For this project, the main purpose of building the machine vision system is to automatically detect the cutting points of a purl, classify these cutting points according to their position, and then guide the pulsed laser beam to cut off the connection threads. The transmissive dark field illumination method is adopted for this project because the work presented in [2] has shown that the illumination method is capable of facilitating cutting points detection. The manufactured ring light is shown in Figure 5-10, which is composed of 60 LED’s. The ring light is able to provide constant light of a high intensity.

![The manufactured ring light (Bamforth 2003)](image)

Figure 5-10 The manufactured ring light (Bamforth 2003)

Figure 5-11 has shown the captured image illuminated with the TDF method and the corresponding histogram. The histogram shows four peaks, each of which corresponds to a part of the image. The first peak, whose value is 41, corresponds to the dark background. The second and third peaks at 102 and 132 are corresponding to the gray lace pattern section. The final peak at 255 is produced by the thin threads of the lace.

The histogram has clearly shown that the lace pattern section can be easily separated from the other parts of the lace by applying a simple duel level threshold. The threshold values can be calculated by analysing the peaks and troughs within the histogram.
5.1.4 Processing hardware selection

For many machine vision applications, a PC based system is a cost effective solution and is capable of providing reasonable processing power. But for applications which demand higher processing speeds, DSP or FPGA devices would be more appropriate. In addition to being able to do processing in real time, DSP and FPGA devices are usually small and portable, making them ideal for the application where space is very constrained.
Another option for the processing system is a smart camera. A smart camera is a self-contained machine vision system, usually including image capture circuitry, a processor to extract information from images without the need of an external processing unit, and communication interfaces, such as Ethernet and I/O lines, for connection to other devices. This architecture has the advantage of a more compact volume compared to PC-based vision systems and often costs less. Although often used for simpler applications, modern smart cameras can rival PC based systems in terms of processing power and functionalities. Having a dedicated processor in each unit, smart cameras are especially suited for applications where several cameras must operate independently and often asynchronously, or when distributed vision is required.

The general comparison between PC based vision systems and smart camera systems is presented in Table 5-5.

<table>
<thead>
<tr>
<th></th>
<th>PC based</th>
<th>Smart camera</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flexibility</strong></td>
<td>Excellent</td>
<td>Poor</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>Multi-box system</td>
<td>All-in-one system</td>
</tr>
<tr>
<td><strong>Ruggedness</strong></td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>Functionality</strong></td>
<td>Expendable</td>
<td>Limited</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>Expendable</td>
<td>Limited</td>
</tr>
<tr>
<td><strong>Ease of use</strong></td>
<td>Needs computer skills</td>
<td>No computer skills needed</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Relatively high</td>
<td>Relatively low</td>
</tr>
</tbody>
</table>

Table 5-5 PC based vision system VS smart camera system

If an image processing algorithm has been developed and proven to be successful for a certain application, a smart camera system would be more appropriate by programming the algorithm into the processor of the system. The stand-alone smart camera system dedicates all the processing power to processing images and is free from any timing issues.
which are usually present in a PC based system. However, in order to test different image processing algorithms, a system having more flexibility and extendibility is preferred. From this point of view, a PC has been selected for this project.

5.1.5 Processing software selection

In Chapter 3, the test work for image processing utilised WiT software. This software had been used on the previous research in this area. Machine vision software is developing very quickly. In the past, the capabilities of machine vision software were limited by the hardware speeds of PC systems. With the dramatic advance in personal computer technology, machine vision software is becoming more advanced, flexible and robust. It is useful to investigate the currently available machine vision software.

- **Software Development Kits**

  Software Development Kits (SDK) are low level libraries of image processing functions aimed at these developers who are looking to develop their own applications. An SDK usually takes a form of API (Application Programme Interface) or DLLs. With a SDK, the developers have complete control over the development of image processing systems, which offers great flexibility of developing different image processing algorithms for each specific application. However, on the other hand, this will invariably require longer system development time. Typical software includes Sapera Processing provided by Dalsa Coreco and Common Vision Blox developed by Stemmer Imaging.

- **Interactive GUI**

  With these software packages, it is possible to develop a machine vision application without the need to write any code. This type of software provides a graphical environment for the users who can combine different image processing algorithms to build more complex ones and is able to see the processing results interactively. In addition to the standard functions provided with the software, new functions can be built using standard programming tools, such as Microsoft C++. WiT, Sherlock and CVB iTuition are all this type of software available in the current market.
• Application Software

Several types of off the shelf application software are available. The software is targeted at specific tasks such as recording video sequence (StreamPix), simple control and image acquisition (Fire-i software). It requires no programming and minimal configuration and is ideal for the well defined applications, but has very limited flexibility.

Using SDK software for this project will provide the greatest flexibility and all the required functionalities, but could be time-consuming. On the other hand, the established application software is not powerful enough to meet all the image processing requirements although it is easy to use. Interactive GUI based software is a good compromise by providing a library of standard image processing functions, which are easy to use and therefore save time, and the flexibility of building new functions for particular tasks.

The chosen software for the project is WiT [99], which is a graphical programming environment for developing image processing and analysis applications. Standard image processing functions are presented in the form of blocks which can be connected together via links. Applications are created by building block diagrams with point-and-click simplicity, which makes it a flexible and rapid prototyping tool. The interface to Microsoft Visual C++ allows the development of custom algorithms for demanding applications. Figure 5-12 shows a typical application where the edges of the circles in the original image have been detected by the Sobel filter.

Within the environment of Visual Basic or Microsoft Visual C++, custom GUls can be created with the ActiveX Controls or WiT DLLs provided by the WiT Engine using algorithms designed in WiT to perform the image processing and analysis tasks.
Figure 5-12 An example of WiT environment
5.2 Image Processing Algorithms Development

Due to the complex structure and inherent flexibility of lace, developing image processing algorithms for processing lace images to get desired information is a difficult task. Various methods of processing lace images have been developed and applied in many applications, such as for lace quality inspection and lace cutting path detection. All these methods worked relatively well and have proven that machine vision techniques are a useful and feasible tool for lace related applications.

According to the lace cutting strategy proposed in Chapter 4, lace should be cut by processing each individual purl one by one. For each purl, the connection threads will be cut strategically according to their positions relative to the top of the purl. Not until all the connection threads of a purl have been cut will the next purl be processed. To achieve the automation of the proposed lace cutting strategy with the machine vision system, the main tasks of developing the image processing algorithms can be summarised as follows.

1. Purl isolation
2. Cutting point detection for each purl
3. Cutting points classification

5.2.1 Purl isolation

A lace edge consists of many individual purls, each of which is connected to the waste mesh through connection threads, as shown in Figure 5-13. To automatically isolate a purl together with all its connection threads from others is difficult to achieve as lace can be easily distorted and has a complex structure.

To successfully extract a purl subimage from the original lace image, some information regarding the purl itself is required. In addition to the purl size, the position of the purl within the original image must also be established. However, neither the purl size nor the purl position can be easily obtained. Particularly, as each purl has different shape and size, it is not possible to find an appropriate value to define the size of all the purls of a lace sample. If the value is too big, the possibility exists that the extracted subimage contains some part of the neighbouring purl and the connection threads which are not connected to the purl of interest. On the other hand, the extracted image may miss some part of the purl
if the value is too small. In both cases, the extracted subimage fails to isolate the purl together with its connection threads.

The position of a purl can be determined by finding its top or centre and its size can be defined by its height and width. Two methods have been identified to detect the position and determine the size of a purl. The first method is based on the template matching technique, with the second one relying on the lace edge structure analysis.

5.2.1.1 Template matching method

The template matching technique involves comparing a template image stored in memory with the target image captured by a camera. The images are compared by moving the smaller template image over the other and calculating a correlation sum for each position in the image. The correlation sum can be calculated in several ways. The best matching position of the template image relative to the target image can be determined by finding the maximum or minimum value of the resulting correlation value.

The method of isolating individual purl based on template matching technique works by first creating a database of the template images of every purl and then comparing these template images in turn with the lace image captured by the camera to determine the position of each purl in the image. The volume of the template image database depends on how many purls a lace repeat contains. The purls in the same position of the lace repeat are considered as the same and therefore share one template. Therefore, if there are 14
purls in a lace repeat, the template database will be composed of 14 purl template images. In order to increase the processing speed, it is important to ensure that the template images have the same resolution as the lace image to be compared. Figure 5-14 has shown a purl template example.

The advantage of using this template matching technique based method is that the subimage of a purl together with its connection threads can be directly obtained once the matching is established without the need of determining the purl size. On the other hand, this method is time consuming and initial experiments have shown that it takes 1.02 seconds to find the matching position of a purl template based on the PC running at 800 MHz. The time could become longer if there is no matching between the purl template image and the original lace image. If the original lace image contains 3 purls and the purl template database have 14 purl template images, it will take unacceptably long time to find the matching and isolate each purl subimage by comparing each template image with the original lace image. In addition, as the purl shape changes due to the varied tension applied on the lace, there are no definitive purl shape cases. At a detailed level, the number of the purl templates is infinite, which means the template matching method is clearly not suitable.

5.2.1.2 Lace edge based method

A purl can be approximately defined by three characteristic points, the top and the two troughs, as shown in Figure 5-15. By locating the positions of these three points, the purl position and size can be determined and therefore the subimage of the purl can be defined and extracted from the original lace image. As shown in Figure 5-16, the purl together
with its connection threads has been manually extracted from the original image. The subimage extraction range is bigger than the purl boundary so that the connection threads can be well included in the extracted subimage.

![Figure 5-15 Rough definition of a purl](image)

**Figure 5-15 Rough definition of a purl**

![Figure 5-16 The isolated purl with its connection threads](image)

**Figure 5-16 The isolated purl with its connection threads**

As shown in Figure 5-17, the lace edge provides all the information needed to locate the tops and troughs of all the purls within the image. Therefore, detecting the lace edge becomes the first step of isolating each individual purl.
5.2.1.2.1 Lace edge detection

In previous research on lace cutting, lace edge detection methods have been well studied and reported [2, 3]. The lace edge is considered to be the cutting path along which a laser beam is applied to cut off the waste mesh. The two most successful lace edge detection methods that have been developed and applied involve the use of cross-correlation and edge tracking algorithms.

- **Cross correlation method**
  The cross correlation method has been studied and applied in [3], which is based on the template matching algorithm. The method involves comparing two images, one reference image (contains one lace repeat) in which the lace edge has been defined manually and the image in which the lace edge needs to be determined. Once the relative position of these two images has been ascertained, the lace edge can be determined by recalling the position of the stored lace edge in the reference image.

The method works well to locate the lace edge and is able to tolerate some lace distortion. However, in this project, as the system resolution of the machine vision system is about 100 pixels per millimetre, the camera can only view a small lace section of approximately 12mm x 10mm. Therefore, it is impossible to capture an image containing a whole lace repeat, which is usually 40 mm long or more. The
system limitation makes the cross correlation method not appropriate for this project in which each individual thread needs to be targeted and cut.

- **Edge tracking method**
  Edge tracking method does not rely on any prior knowledge and therefore is adaptable and robust. Successful applications can be found in [32, 33] where lace cutting path is determined based on processing the lace image with appropriate edge detection algorithms. In [2], with the aid of the transmissive lighting method, the captured image can be divided into three parts, background, thin threads and thick lace pattern sections. Using the dual level threshold, the resulting binary image only contains the thick pattern sections, from which the lace edge can be detected.

However, compared to the machine vision system developed in [2], the system resolution has increased to 100 pixels per millimetre and field of view (FOV) reduced to approximately 12x10 mm. Consequently, the lace images captured by these two systems present large difference. Applying the image processing algorithms developed in [2] directly to process the high resolution lace images fails to detect the lace edge. Based on the similar method as presented in [2] with extensive experiments and research, the newly developed image processing algorithms are able to detect the lace edge within the high resolution lace images successfully. Figure 5-18 has shown several typical images which are generated throughout the process of detecting the lace edge. More processed images can be found in Appendix 12.3.
Step 1 Original image

Step 2 Bi-level thresholded image

Step 3 Low-pass filtered image

Step 4 Detected edges
By using the dual level threshold, the original lace image can be converted into a binary image with all thin threads thresholded to be black (step 2). The remnants of the threads can be further cleared by applying a median filter and then a low-pass smoothing filter (step 3). Then a Sobel edge detector is used to detect all edges within the image (step 4). Among these edges, only one edge is the lace edge, based on which the purls can be separated and isolated. Based on the rule that the width of the lace edge is equal to that of the image and the lace edge is located uppermost (or downmost depends on the orientation of the lace image), the desired lace edge can be correctly selected from these edges (step 5). The image in step 6 shows the original image with the detected lace edge superimposed.
Figure 5-19 shows the lace image with the automatically detected lace edge. It is noticed that the detected lace edge does not exactly follow and therefore deviate from the "true" lace edge at some points, for example, point A. This is because the lace edge has loose threads around itself which makes the lace edge not being clearly defined. During the process of detecting the lace edge using image processing techniques as shown in Figure 5-18, the low-pass filter (step 3 in Figure 5-18) used to smooth out lace thread remnants from the thresholded image has an effect of blurring the lace edge, which makes it even more difficult to locate the "true" lace edge. However, for the purpose of identifying the tops and troughs of the purls, the inaccuracy caused by the deviation is acceptable.

5.2.1.2.2 Purl top and trough detection

On the lace edge, the tops and troughs of the purls within the lace image can be considered as local maxima and minima in terms of their positions in the x or y direction. For example, as shown in Figure 5-20, the tops are local minima in the y direction while troughs are local maxima.
To automatically detect the top and troughs of each purl, the lace edge is converted from a continuous line into a series of points with a built-in operator of WiT. By finding the local maxima and minima of all these points in the y direction, the corresponding tops and troughs can be found as shown in Figure 5-21. It is important to select appropriate vicinity value to suppress multiple peaks in close proximity. The best value could be found by investigating the average distance between the tops of two purls in the image.
From Figure 5-21, it is noticed that the two neighbouring purls have one common trough, resulting in partial overlap between the two extracted subimages, for example, purl 1 and purl 2 shown in Figure 5-21. This overlap ensures that the cutting result of the lace section between two purls can be double checked to avoid any threads left uncut.

Compared with the previous template matching technique based method, this lace edge based method is obviously more robust and reliable without the need of any prior knowledge. More importantly, it is able to accommodate large lace distortion caused by the tension variation.

5.2.1.3 First uncut purl determination

According to the lace cutting strategy proposed in Chapter 4, lace should be cut by processing the purls one by one. To start the cutting process, it is necessary to identify the first uncut purl and then cut it before moving on to the next purl of the lace. The lace image, captured by the current camera with the resolution of 100 pixels/mm, usually contains about 4 to 5 purls. If all these purls are uncut, it would be easy to determine that the first uncut purl is the one in the first position from left to right or vice versa depending on the lace orientation. However, the lace image usually includes one or two previously cut purls in order that the first uncut purl is well positioned within the image, but obviously this makes the task of determining the first uncut purl difficult.

As shown in Figure 5-22, the image contains totally 5 purls and all their tops have been identified automatically. The first purl in the image (from right to left) has been cut and the first uncut purl is located in the second place. If the purl that has been cut could be excluded from the image when the lace is set up for cutting, the first uncut purl would be in the first position in the image (from right to left). Then the process of determining the first uncut purl becomes as easy as selecting the first purl in the image. However, during the lace cutting process, as the lace is moved and transported, one or more purls that have been cut could possibly be included in the captured image. In addition, including a cut purl in the image can ensure that all connection threads of the first uncut purl are well within the image. Therefore, the method of excluding the cut purl from the image is neither adaptable nor reliable.
Another possible solution to identifying the first uncut purl is to find the first cutting point, which refers to the cutting point in the first place in x or y direction, depending on the lace orientation. As the first cutting point is where the first uncut thread intersects with the waste mesh or a purl, the purl whose top is closest to the first cutting point is considered as the first uncut purl.

In Figure 5-23, the first cutting point is in the rightmost position as indicated. The purl on the left side of the first cutting point is an uncut purl and the one on the right side a cut purl. The first uncut purl is determined by comparing the distance in x direction between the first cutting point and the top of both purls, that is \( x_1 \) and \( x_2 \). As \( x_1 \) is less than \( x_2 \), the purl on the left side of the first cutting point is considered as the first uncut purl, as shown in Figure 5-23.
In order to identify the first uncut purl, finding the cutting points and selecting the first cutting point become prerequisite.

### 5.2.1.3.1 Lace cutting point detection

A cutting point is the position where a connection thread intersects with the purl. An edge directed thread targeting algorithm has been developed in [2] to detect the cutting points. Figure 5-24 has shown the major steps of the cutting point detection algorithm. The algorithm works by generating two images from the original lace image. The first image (image A) is the lace edge image produced with the method described in section 5.2.1.2.1. After being single-level thresholded into a binary image (image B), the original lace image is then split into two halves by subtracting image A from image B. The resulting image (image D) is divided into two major parts along the lace edge and only contains the thin lace threads. After appropriate filtering is applied to eliminate the unnecessary threads, the image is then ANDed with the lace edge image (image C) to generate an image of just the portion of the threads that crosses the lace edge (image E). The centroid
of each thread portion is considered to be the cutting point. Image F has shown the original image with all detected cutting points. More processed images can be found in Appendix 12.4.
The cutting point located in the first instance (the rightmost one in the case of Figure 5-25) is considered as the first cutting point and the purl whose top is closest to the first cutting point is determined to be the first uncut purl.

Figure 5-24 Lace cutting point detection

Figure 5-25 First cutting point and the first uncut purl
5.2.1.3.2 Subsequent uncut purl determination

Once the first uncut purl is identified, the process of identifying the subsequent uncut purl becomes simpler. The position of the identified first uncut purl is stored in memory and then recalled to identify the next uncut purl after it has been cut. Of the remaining purls, the one which is closest to the first uncut purl is considered as the next purl to cut and similarly its position is also stored and then recalled to identify the next one. In this way, the purls of the lace can be identified and cut one by one efficiently. In the case that the lace is moved or transported during the cutting process, the stored purl position needs to be offset by the distance that the lace is displaced.

5.2.1.4 Purl subimage extraction

With the top and two troughs located, the subimage of a purl can be extracted from the original lace image. To ensure that the extracted purl subimage contains all the connection threads connected to the purl while avoiding to include the connection threads connected to the neighbouring purls, it is important to decide an appropriate extraction range. After detailed observation of the lace structure, the left boundary of the extraction range is determined by finding the middle line between the left trough and the next purl top. Similarly, the right boundary is the middle line between the right trough and the neighbouring purl top. The top and bottom boundaries are dependent on the location of the purl top and the lowest trough. An example to show the boundary of extracting the first uncut purl is shown in Figure 5-26 and the extracted subimage is shown in Figure 5-27.
5.2.1.5 Purl isolation summary

Based on the concept that a purl can be well defined by its three characteristic points, that is, the top and two troughs, the purl subimage can be extracted from the original lace imaging by locating these three points. The method based on detecting the lace edge has proven to be effective for identifying the tops and troughs of the purls within the lace image. The purl closest to the first cutting point is considered as the first uncut purl. The
identification of the subsequent uncut purls can be much faster given the position information of the first uncut purl. The purl isolation process is summarised in Figure 5-28.
Figure 5-28: Purl Isolation Flowchart

1. Original lace image capture
2. Lace edge detection
3. Tops and troughs detection
4. Next purl to cut
5. Position information
6. Subimage extraction
7. Cut finished
8. First uncut purl
9. First cutting point detection
10. Tops and troughs detection
11. Cut finished
5.2.2 Purl subimage processing

The first step of processing the purl subimage extracted from the original lace image is to detect all the cutting points. Then these cutting points will be classified as primary or secondary cutting point according to their positions relative to the purl top. Different cutting strategy will be used to process these cutting points according to their importance.

5.2.2.1 Cutting points detection

The technique used to detect the cutting points within a purl subimage is the same as used for cutting points detection described in section 5.2.1.3.1. As the subimage is much smaller than the original lace image, and contains only one purl together with its connection threads, the process of detecting the cutting points is much faster. Figure 5-29 shows a subimage including the detected cutting points. Red spots have been placed over the cutting points as the original spots to indicate the cutting points generated by the WiT software are too faint (same technique is used where cutting points indicators generated by WiT are too faint).

![Figure 5-29 Subimage with the detected cutting points](image)

5.2.2.1.1 Cutting point offset

With the cutting point detection technique described above, the detected cutting point is located on the interface between the connection thread and the purl. If the laser beam is applied to cut the thread, half of the laser will melt the purl causing undesirable laser damage. Therefore, it is necessary to offset the actual cutting point away by a specific
distance along the thread. A process of dilation is used to offset the position of the cutting point, which is reported in [2]. The process is redescribed here to aid the reader.

Cutting points are located by detecting the intersection between the lace edge and the threads as described in section 5.2.1.3.1. By dilating the lace edge, the detected cutting points can be offset by an amount dictated by the level of the dilation chosen. Figure 5-30 shows two lace edges, with edge 2 offset from edge 1. Accordingly, the detected cutting points are offset as shown in Figure 5-31.
5.2.2.2 Cutting points classification

According to the cutting strategy proposed in Chapter 4, classifying the detected cutting points of a purl and cutting them with different strategy have two purposes. Firstly, as the secondary threads (the connection threads which intersects with the purl at an secondary cutting point is referred to as secondary threads) can be cut directly without checking the tension applied on it, the cutting process becomes simple and time effective. Secondly, cutting off the secondary threads first can help to well tension the remaining primary threads, thus helping to improve the resulting cutting edge quality.

The perpendicular distance from a cutting point to the bottom line of a purl is termed as the height of the cutting point. The bottom line is formed by connecting the two troughs of the purl as shown in Figure 5-32. Obviously the height of a cutting point can well indicate how far the cutting point is away from the purl top. The greater the height of a cutting point, the closer it is to the purl top. However, no cutting point has a height greater than the purl height, which refers to the perpendicular distance from the purl top to the bottom line as shown in Figure 5-32.

The height ratio obtained by dividing the height of a cutting point by the purl height can be used to classify the cutting point. If the height ratio of a cutting point is greater than a preset value, which is called importance criterion, then the cutting point is classified as a primary cutting point. Similarly, a cutting point will be classified as a secondary cutting point if its height ratio is less than the importance criterion.
For example, as shown in Figure 5-33, totally six cutting points have been detected. The purl height and the height of each cutting point are listed in Table 5-6.

![Figure 5-33 Cutting points classification](image)

<table>
<thead>
<tr>
<th>Cutting point No.</th>
<th>Cutting point height (pixels)</th>
<th>Purl height (pixels)</th>
<th>Height ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>228</td>
<td>231</td>
<td>0.98</td>
</tr>
<tr>
<td>2</td>
<td>48</td>
<td>231</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>231</td>
<td>0.52</td>
</tr>
<tr>
<td>4</td>
<td>32</td>
<td>231</td>
<td>0.14</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>231</td>
<td>0.19</td>
</tr>
<tr>
<td>6</td>
<td>41</td>
<td>231</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Table 5-6 Cutting point height and purl height
Depending on the importance criterion, the importance of a cutting point can be different. When the importance criteria is set to be 0.10 in the above example, all six cutting points are considered to be primary. However, only cutting point 1 is classified as primary cutting point if the importance criterion is 0.90. The selection of the importance criterion relies on the quality requirement, lace structure and operator’s experience. Usually, setting the importance criterion to be 0.8 would be appropriate for most lace structure and it will well distinguish the connection threads connected to the top of a purl from others.

If the importance criterion is set properly, all the cutting points classified as secondary are usually located in the lower part of a purl and their cutting result has no direct effect on the overall cutting quality of the purl. Therefore, all secondary connection threads can be cut directly without checking and controlling the tension applied on them. On the other hand, a primary connection thread is usually connected to the top section of the purl and its cutting result has determinant effect on the overall quality of the purl. The tension applied on an important connection thread must be checked before the connection thread is cut by the pulsed laser. The algorithm of controlling the tension applied on a primary thread will be described in detail together with the final lace handling test rig in Chapter 6.
5.3 Image Processing Performance

The image processing algorithms described so far is implemented on an Intel Pentium III 800 MHz based PC. The overall processing time to identify the first cutting point is about 1.91 seconds. The time required for each major step is shown in Figure 5-34. The original lace image covers an area of 1280 x 1024 pixels which is equal to a field of view of approximately 13mm x 10mm. Depending on the size of the purl, the subimage of an isolated purl is approximately 350 x 350 pixels.

![Figure 5-34 Processing time required for each major step](image)

Since cutting a connection thread causes other threads to change the shape and location, it is necessary to relocate the cutting point after each thread is cut. It takes approximately 1.91 (534ms+1316ms+57ms=1.91 seconds in Figure 5-34) seconds to detect the cutting point at the first time, but the time required to detect the subsequent cutting point decreases to 1.75 seconds after the position information of the first uncut purl has been obtained as discussed in section 5.2.1.3.2 and shown in Figure 5-28. At this stage, the processing performance fails to meet the industrial requirement of cutting lace at speeds up to 1 m/s, but it can be improved in several ways. It is noticed that the time taken to capture the lace image is 534 milliseconds, which can be improved by using a faster camera. Replacing the PC with a DSP is the other way to increase the processing speed. More detail regarding improving the machine vision system is presented in section 10.1.
5.4 Machine Vision Summary

In this chapter, the development process of an automated machine vision system to implement the proposed lace cutting strategy has been demonstrated.

In the first part, the selection process of the major components to build the machine vision system has been described, with the reasoning and calculation behind the choice presented.

Then, in the second part of this chapter, the image processing algorithms to automatically isolate purls, extract purl subimages and then classify the detected cutting points within a purl subimage have been developed. Although the underlying principles to detect the lace edge and cutting points where connection threads intersect with purls are similar to those presented in [2], the developed image processing algorithms are largely different due to the difference present in the lace images to be processed. The newly developed image processing algorithms in this project have been able to process high resolution lace images with accuracy improved and better results achieved.
6 Test Facility Development

To test the cutting strategy and the developed image processing algorithms described in Chapter 4 and Chapter 5, a test facility is needed which is able to automatically transport lace and tension it down to the individual purl level. After adequate tension is applied, when necessary, the thread of the lace purl needs to be automatically targeted and cut with the pulsed laser.

By modifying and updating the previous pulsed laser cutting system [2], the development of the system used to capture lace images, position and cut lace threads using the pulsed laser will be described first. Then the focus of this chapter will shift to the design and development of an automatic lace tensioning and transport rig as the intermediate lace tensioning rig described in section 4.2 lacks the ability of automation.
6.1 Developed Cutting System

The developed system is essentially composed of three separate subsystems under the control of a host PC, including laser subsystem, image capturing subsystem and lace positioning subsystem. A schematic view of the system is shown in Figure 6-1.

![Figure 6-1 Schematic view of the lace cutting system (Bamforth 2003)]

The whole working area is enclosed in a solid enclosure with polycarbonate viewing panels. The purpose of the enclosure is to prevent the access to the running motors and the laser beam and also prevent the fumes generated from lace cutting from escaping into the workplace. Each subsystem will be briefly described as follows.

6.1.1 Laser subsystem

The heart part of the laser subsystem is a 275W Melles-Griot (05-CRF-2400) carbon dioxide laser, which is of the sealed tube radio frequency (RF) pumped type. The laser beam is 8 mm in diameter with a TEM\textsuperscript{00} (Gaussian) profile and has a wavelength of 10.6 μm, making it invisible to human eyes. The laser can be run in two different modes, continuous wave mode (CW) or pulsed mode with pulses down to 100 μs in duration at a rate of 750 Hz. The laser tubes are supplied with an RF excitation signal from two power supplies which are controlled by a laser power control module. A chiller unit is used to
remove the heat from the laser head due to the inefficiency of the laser system. The schematic view of the laser subsystem is shown in Figure 6-2.

For the safety purpose, the TTL signal to turn on the laser, which comes from the host PC, is intercepted by the Safety Interlock Controller. Not until the controller has confirmed that it is safe to fire the laser, will the laser on signal be passed to the laser power controller. The laser beam outputted from the laser head is expended by a standard beam expender (V&S Scientific Model SBE/30) and then focused with a zinc-selenide (ZnSe) lens. The lens is fixed on a micrometer stage so that it can be moved up and down to focus the laser beam.

Based on the laser and the laser focus optics characteristics, it has been calculate that the laser subsystem gives a diffraction limited spot size of 0.242 mm and an approximate depth of focus of 2.38 mm [2]. The laser spot size is small enough to cut each individual lace thread and the depth of focus is deep enough for cutting lace which is usually 0.75 mm thick.
6.1.2 Image capturing subsystem

The image capturing subsystem is used to acquire lace images and the major components include a camera, a lens and a light source. The selection process of these components has been reported in section 5.1. Ideally the camera would be mounted so that the imaging axis is perpendicular to the lace sample. However, due to the space limit and the fact that the laser optics is also required to be perpendicular to the lace, the imaging axis of the image capturing subsystem is modified to have a slight angle relative to the laser axis, as shown in Figure 6-3. The angle between the imaging axis and the laser optics axis is 14 degrees.

![Image capturing subsystem](image)

Figure 6-3 Image capturing subsystem

This arrangement will cause a certain degree of geometric distortion of the resulting images. Only the centre of the lace will be in true focus and the top and bottom section of the lace will be always slightly out of focus. As discussed in section 5.1, the field of view (FOV) of the imaging system is approximately 13mm x 10mm, so the distance of the top and bottom section of the lace away from the focus can be calculated as follows.
Suppose that the object distance $X$ is 400 mm, and the middle part of the lace is in focus, the distance between the lens and the top and bottom part of the lace, $X_1$ and $X_2$ can be calculated respectively.

$$X_1 = \sqrt{X^2 + 5^2 - 2 \times 5 \times X \times \cos 76^\circ} = 398.83\text{mm} \ (1.17 \text{ mm out of focus})$$

$$X_2 = \sqrt{X^2 + 5^2 - 2 \times 5 \times X \times \cos 104^\circ} = 401.23\text{mm} \ (1.23 \text{ mm out of focus})$$

As the imaging system has a depth of focus as large as 8 mm, much larger than 1.17 mm and 1.23 mm, the effect of this arrangement can be well eliminated, which ensures that all the lace within the field of view is in focus at any time.

### 6.1.3 Lace positioning subsystem

The lace positioning subsystem is used to move the lace sample until the lace cutting point, where the laser beam is expected to hit, is aligned with the laser beam spot within a preset accuracy. The subsystem is composed of three drives, two stepper motors driven stages each with 50 mm of travel and a servo motor driven stage with 350 mm of travel. Three drive motors provide two-axis movement (x, y axis), with one of the stepper motors
(x axis motor) being co-linear with the servo motor. This configuration allows the x, y stepper motors to be moved along the servo axis beyond the basic 50 mm of travel available with the stepper drive and therefore the lace sample can be moved within an area of 350 mm by 50 mm. The layout of the drives is shown in Figure 6-5.

![Figure 6-5 Lace positioning drives (Top view)](image)

Each motor is connected to a drive unit, which can be controlled manually or via a PC. Each axis is controlled using 2 bits of data, with the first bit controlling the direction and the second one controlling the state of the drive, 0 for off and 1 for on. Both drive systems are interlocked to the door interlock switches and to the emergency stop button. Limit switches are used to protect the drives from crashing when they exceed a safe position. The speed of each drive is controlled manually via a potentiometer on the front panel of the drive units and cannot be adjusted automatically through the PC.

The system works by first calibrating the position of the laser spot and the speed of each drive. After having received the coordinates of the cutting point which is obtained from the image processing system (see chapter 5), the lace positioning subsystem calculates the distance between the cutting point and the laser spot. If the distance is less than a predefined accuracy, the laser is fired and the thread will be cut. If the distance is too larger, the on-time duration of each drive is calculated with the distance and the speed of each drive. Before the drives are turned on, a subimage is extracted from the main image of the target and stored in memory. Then the drives are switched on to move the lace for the calculated duration. Once the drives stop, a template matching algorithm is used to locate the target image within the image from the camera. Once the position of the target is obtained again, its coordinates are compared to those of the laser spot. Then the laser is either fired to cut the thread if the distance is within the predefined accuracy or another
iteration is carried out until the target is well aligned with the laser spot. This unconventional position feedback algorithm based on image data acquired directly from the camera has an average positioning error of 49.7 μm at a resolution of 32 pixels/mm [2]. The accuracy is acceptable for the lace cutting as the laser spot itself is 242 μm in diameter and therefore the maximum error the system could generate is well within the size of the laser spot.
6.2 Automatic Lace Tensioning and Transport Rig

The essential functions of an automatic lace tensioning and transport rig are applying localised tension and transporting lace continuously. The research regarding maintaining constant tension for web material processing has been widely reported [76-78, 51]. Although the developed methods involving dancer systems, speed controllers and torque controllers have been successfully applied in continuous web processing applications, they are not appropriate for applying and controlling localised tension on a lace section as small as 10mm x 10mm.

6.2.1 Design specification

The desired lace tensioning and transport rig should be able to transport lace continuously and apply localised tension to progressively tension each purl at the same time. The transport speed needs to reach 1 m/s to satisfy industry requirements. A closed loop control is desired to control the applied tension so that each purl is adequately tensioned before the pulsed laser cutting is executed.

6.2.1.1 Space limitations

To reduce the risk of any harmful radiation from the laser cutting operation, the lace transport and tensioning rig will be installed within the cabinet shown in Figure 6-1. Within the cabinet, a x-y sample stage driven by two stepper motors and one servo motor has been installed, on which the transport and tensioning rig will be mounted. The optics and transmission tube system of the laser system further reduces the space available. To ensure that the rig will fit in well, it is necessary to measure and determine the space available.

The dimensions of the cabinet have been measured and the side and top view has shown the space limitations for the lace transport and tensioning rig, as shown in Figure 6-6 and Figure 6-7 respectively.
Figure 6-6 Side view of the cabinet and the components

Where:
A=140 mm
B=30 mm
C= 290-310 mm (depending on the lens position)

Figure 6-7 Top view of the cabinet and the components

Where:
E=180 mm
F=150 mm
G=220 mm
From Figure 6-6 and Figure 6-7, the maximum dimensions of the rig can be determined as follows (the sample stage is 127 mm square).

- Max Length = A + B + sample stage = 140 + 30 + 127 = 297 mm
- Max Height = C = 310 mm
- Max Width = E + F + Sample stage = 180 + 150 + 127 = 457 mm

**6.2.1.2 Lace width**

Lace width must be taken into consideration when designing the rig to transport lace. It is necessary to ensure that the lace transport and tensioning rig is able to accommodate all types of lace. The width of all the lace available in the laboratory have been measured and summarised in Table 6-1.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste Mesh</td>
<td>20 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>Lace Pattern</td>
<td>80 mm</td>
<td>210 mm</td>
</tr>
<tr>
<td>Total</td>
<td>100 mm</td>
<td>240 mm</td>
</tr>
</tbody>
</table>

In addition, as the light source needs to be placed properly underneath the lace sample to provide illumination for the imaging system, enough space must be ensured for the light source, which is 130 mm x 130 mm.

**6.2.2 Concept design**

According to the specifications of the rig design, the lace transport and tensioning rig can be split into two parts: transport subsystem and tensioning subsystem. The design processes of these two parts are described separately as follows.

**6.2.2.1 Transport subsystem**

To facilitate the lace cutting operation, lace is required to be kept flat when it is transported, free from any snagging or wrinkle. The early lace transport and tensioning rig described in section 3.2 has proven that a roller system is a suitable solution to transporting lace. Other alternatives, such as utilising a movable bed on which the lace is placed, are not appropriate as any object placed between lace and the light source will
affect the illumination and therefore the quality of the captured images. The benefit obtained from using a roller system is the ease to apply and control longitudinal tension. In the early transport and tensioning rig (section 3.2), the longitudinal tension is applied by applying some amount of torque on the feed roller. With this method, although the applied longitudinal tension can be roughly maintained constant, it cannot be adjusted and controlled automatically during the lace cutting process.

By placing and transporting the lace between two pairs of rollers driven independently by two motors, the applied longitudinal tension can be varied by changing the relative speed of these two pairs of rollers.

![Diagram of two pairs of rollers and longitudinal tension](image)

Figure 6-8 Two pairs of rollers and longitudinal tension

As shown in Figure 6-8, the longitudinal tension can be varied as follows.

- Maintain the longitudinal tension, keep $V_1 = V_2$
- Increase the longitudinal tension, make $V_1 > V_2$ (increase $V_1$ or decrease $V_2$)
- Decrease the longitudinal tension, make $V_1 < V_2$ (decrease $V_1$ or increase $V_2$)

The overall arrangement of the roller system is shown in Figure 6-9. An adjustable clutch is fitted with the drive roller. The purpose of the clutch is to ensure that the maximum longitudinal tension that will break the lace cannot be reached. It works by allowing the motor to rotate while keeping the roller stationary when the preset tension is reached. By presetting the tension value of this clutch to be the desired longitudinal tension and keeping the drive rollers running faster than the feed rollers, the clutch can help to maintain and control the longitudinal tension as well. Similarly, another adjustable clutch is installed with the take-up roller to avoid lace breakage between the drive rollers and the take-up rollers.
6.2.2.2 Tensioning subsystem

Not only is the described roller system able to transport lace continuously, it is also capable of applying and controlling longitudinal tension without stopping the lace as described in section 6.2.2.1. However, based on the observations of the previous experiments, only applying longitudinal tension cannot adequately tension the lace and more tension of another type is required.

6.2.2.2.1 Waste mesh tensioning system

The results obtained from the early experiments with the intermediate tensioning rig have suggested that lace purls can be adequately tensioned by applying localised tension divergently. With the intermediate tensioning rig, the lace is attached on four tensioning aluminium blocks and then tensioned by displacing the tensioning blocks (see section 4.2).

As shown in Figure 6-10, in addition to the longitudinal tension applied by the roller system, it is straightforward to decide that another type of tension is required to apply on the waste mesh in order to adequately tension the lace.
The tension required to apply on the waste mesh is referred to as the combination tension as it can be considered as the combination of the lateral and the longitudinal tension applied on the waste mesh. Together with the longitudinal tension applied by the transportation roller system, the lace can be adequately tensioned if the combination tension is applied and controlled appropriately.

The combination tension needs to be varied in both its direction and magnitude, which can be achieved in several ways. For example, a clamp can be used to clamp the waste mesh and then stretch and rotate it to apply and vary the tension. However, any method of applying and varying the combination tension which requires stopping the lace fails to meet the design requirement of continuous transportation and tensioning. As used for the transport subsystem, a roller system is capable of applying and varying tension without...
stopping lace transportation. Therefore, similarly another pair of rollers is used to transport the waste mesh and apply tension, as shown in Figure 6-11.

![Diagram of lace transport and tensioning system](image)

**Figure 6-11 Lace transport and tensioning system**

A pair of rollers are usually installed between two frames and driven by a motor through a pulley-belt system, as shown in Figure 6-12. Bearings are usually installed at the both ends of the roller, allowing it free to rotate. This structure is easy to design and manufacture and appropriate for the transport roller system. However, unlike the transport roller system which could be fixed, the waste mesh tensioning roller system has to be moved in order that the applied tension can be adjusted. Using the typical roller structure described above poses a problem that the frame of the waste mesh tensioning roller system could collide with the lace transport roller system during the lace cutting process. Moreover, the closer the waste mesh tensioning rollers are placed to a purl, the more effectively it can tension the purl. The waste mesh tensioning rollers will not fit in the small space between the waster mesh and the lace pattern if it is oversized.
Based on the discussion above, a modified roller system has been designed as shown in Figure 6-13. Using only one frame effectively reduces the overall size, making it more compact. One potential problem with this structure is that any force applied perpendicularly to the roller axis will bend the roller. However, it has been fully verified that it is safe to tension the waste mesh considering that the maximum tension will not exceed 20 Newton and the roller length is no longer than 30 mm (widest waste mesh).
As shown in Figure 6-14, the maximum torque that the applied tension acts on the roller is \( T = F \times S = 20 \times 0.015 = 3N \cdot m \). As long as proper material is chosen to manufacture the rollers, the roller system is fully capable of withstanding the calculated torque.

Similar to the longitudinal tension control with the lace transport roller system, the tension applied on the waste mesh can be controlled through coordinating the roller speeds as well. As shown in Figure 6-15, the magnitude of the tension applied on the waste mesh can be varied as follows:

- Maintain the tension, keep \( V1=V2 \)
- Increase the tension, make \( V1>V2 \) (increase \( V1 \) or decrease \( V2 \))
- Decrease the tension, make \( V1<V2 \) (decrease \( V1 \) or increase \( V2 \))
The direction of the tension applied on the waste mesh can be changed by translating or rotating the whole roller structure. The results obtained from the experiment with the intermediate tensioning rig (see section 4.2) have proven that the translation method is effective yet simpler than the rotation method. A lead screw system has been selected to translate the whole roller pair to change the direction of the applied tension.

It is essential to ensure that the waste mesh is perpendicular to the roller when it is transported through the roller. Any misalignment will cause skewness and eventually jamming. It would be much more convenient for the operator if the roller structure can be freely rotated during the setting up process and then locked in the position, ready for further operation, as shown in Figure 6-16.
This rotation movement can also be achieved through a pulley-belt mechanism driven by a motor. However, this would greatly increase the cost and complicate the whole system structure. As the space is limited, a simpler mechanism capable of satisfying the requirements is preferred. In this case, an insert bearing is considered appropriate, into which the whole roller structure can be installed.

The whole structure of the waste mesh tensioning system is shown in Figure 6-17.
6.2.2.2 Micro tensioning system

With the transport and the waste mesh tensioning systems described above, two types of tension can be applied on the lace as shown in Figure 6-18. In order to concentrate the tension on a small lace section, these rollers should be placed closely to each other. However, to allow the light source to be placed properly underneath the lace, the two pairs of transport rollers (drive roller and feed roller) need to be at least 300 mm apart, considering that the size of light source is 130mm x 130mm. Due to its inherent flexible property, the lace between the roller pairs is pulled away from its original position by the lateral component force of the combination tension applied by the waste mesh tensioning system as shown in Figure 6-19. This can incur several problems. The first problem is that the purl to be tensioned cannot be tensioned effectively as the lace is dragged away along the direction of the lateral tension, requiring more displacement of the waste mesh and therefore leading to longer tensioning time. This lace deflection also causes misalignment of the lace relative to the transport rollers, leading to lace skewness and jamming. With a
field of view (FOV) as small as 10mm x 10mm, this lace deflection movement could also result in the purl of interest moving out of the field of view of the camera.

![Diagram of tension applied on lace ribbon](image)

**Figure 6-18 Tension applied on the lace**
In order to avoid the lace deflection, the lace pattern section needs to be held in its position. A feasible way to hold the lace yet still allow the lace to be transported continuously is using a pair of rollers. It would be more effective to prevent the lace from deflecting by placing a number of pairs of rollers along the lace pattern section, but this will definitely increase the design complexity and the lace will not be transported smoothly if any misalignment of these roller pairs is present. Since the lace section to be tensioned is very small (approximately 10mm x 10mm) and at any one time only one purl is required to be adequately tensioned, two pairs of small rollers placed to hold the small lace section would be enough. To increase the lateral friction to hold the lace but still allow the lace to travel through, these two pairs of rollers have been engraved with a screw-like pattern. Like the waste mesh tensioning roller system, only one side of these two pairs of micro rollers are attached to the support frames due to the space limit. The micro tensioning structure is shown in Figure 6-20.
6.2.3 Detailed design

For each subsystem, a detailed design process is then carried out to specify each part after the concept design process is finalised.

6.2.3.1 Transport subsystem

The detailed design process for the transport subsystem can split into four areas, including:

1. Sizing the rollers
2. Selecting appropriate motors, pulleys and belts to drive the rollers
3. Selecting suitable clutch devices
4. Designing other structural components

6.2.3.1.1 Rollers specification

Based on the space available, the diameter of all the rollers has been decided to be 30 mm. The drive roller is used to transport the lace pattern and therefore should be longer than the maximum width of the lace pattern available. According to the survey result shown in
Table 6-1, the drive roller should be longer than 210 mm, but finally decided to be 100 mm due to the space limit. For the same reason, the length of the feed roller has been decided to be 140 mm.

Any lace whose width exceeds the size of the rollers needs to be cut with scissors to make it narrow enough for processing. As this rig is for the experimental purpose and the limitation can be easily solved if more space is available, the lack of the ability to process the lace wider than 140 mm can be ignored for the time being. In addition, among all the lace available for this project, only one type of lace cannot be processed directly due to the size limitation.

It is important to secure the position of the lace being transported. Any slippage or skewness of lace will lead to longitudinal tension instability and transportation jamming. To avoid this happening, two methods have been used, aiming at increasing the friction force between the two rollers.

1. **Make one of the rollers with helical grooves**

   As shown in Figure 6-21, the helical groove on the roller is able to stretch apart both sides of the lace so that the lace will not shift its position between the rollers and can be kept flat.

2. **Put a bicycle inner tube on the other roller**

   The bicycle inner tube will increase the friction force to prevent the lace from slipping. It can also help to cancel out the effect caused by the roller being out of concentricity due to the manufacturing inaccuracy.
Each roller requires a pair of bearings. For this project, single groove bearings are considered appropriate.

**6.2.3.1.2 Motor selection**

The motor selection process must be based on the required lace transport speed and the torque required to tension the lace. The desired lace transport speed is 1 m/s or more, from which the required angular velocity of the motor can be calculated.

Roller circumference = $\pi D = \pi \times 0.03 = 0.0942m$

Required speed of the motor = $\frac{1 \text{m/s} \times 60 \text{seconds}}{\text{Roller \cdot Circumference}} = \frac{60m}{0.0942m} \approx 637\text{rpm}$

Hence an angular velocity of 637 rpm is required from the motor based on the assumption that the ratio between the motor and the drive pulley is 1:1.
The lace elastic property experiments described in section 3.1 have shown that the maximum longitudinal tension required for lace cutting operation is approximately 50N. Therefore the maximum torque required from the motor can be calculated as follows.

\[
\text{Maximum torque required} = N \cdot m = 50 \times 0.015 = 750\text{mNm}
\]

Based on these two criteria, a DC motor from Maxon Motor (Ref. 268214) has been selected to drive the rollers. The main parameters of the motor are shown in Table 6-2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating (W)</td>
<td>60</td>
</tr>
<tr>
<td>Nominal voltage (V)</td>
<td>24</td>
</tr>
<tr>
<td>No Load Speed (rpm)</td>
<td>8810</td>
</tr>
<tr>
<td>Stall Torque (mNm)</td>
<td>1020</td>
</tr>
<tr>
<td>Max. Continuous Torque (mNm)</td>
<td>86.20</td>
</tr>
<tr>
<td>Speed/Torque Gradient (rpm/mNm)</td>
<td>8.70</td>
</tr>
</tbody>
</table>

Table 6-2 Main parameters of the selected motor

The gear ratio should be decided by ensuring that the load reflected back to the motor is around 20% ~ 50% of the stall torque. So the gear ratio can be calculated as follows.

\[
\text{Gear ratio} = \frac{\text{Max. Torque} \cdot \text{Required}}{20\% \cdot \text{Stall. Torque}} = \frac{\text{Max. Torque} \cdot \text{Required}}{50\% \cdot \text{Stall. Torque}} = 3.6\sim1.5
\]

With an appropriate gear box, the selected motor is considered ample for the application.

However, as the budget for this project is limited, two other DC motors taken off from an outdated rig have been used to drive the drive roller and the take-up roller. These two motors have an output torque of 600mNm and run at a speed of 23 rpm. It is obvious that these motors are far from meeting the speed requirement. However, the rig can be easily upgraded to high speed operation in the later stage of the project by replacing these low speed motors. At the current stage, it is more important to verify that the rig is capable of transporting and tensioning lace continuously.

The final selected motors and pulleys for each pair of rollers are listed in Table 6-3.
### Clutch selection

Two clutch devices are required for the drive roller and the take-up roller respectively. The purpose of installing a clutch with the drive roller is to control the applied longitudinal tension. The idea is that the clutch allows the pulley-belt to rotate and the drive roller to remain stationary when the longitudinal tension has reached the preset value. When more lace is transported by the feed roller and the longitudinal tension becomes less than the preset value, the clutch will lock and allow the drive roller to rotate to increase the longitudinal tension. Another advantage of using the clutch is that the lace will not be broken by the longitudinal tension if the tension value of the clutch is set to be less than the lace breakage tension value.

For a similar purpose, another clutch is needed for the take-up roller. The clutch helps the take-up roller to wind up the processed lace continuously without breaking the lace.

An extensive research has been carried out on different types of clutches. The most affordable and suitable one is a two-plate manually adjustable friction clutch available from RS Components. The clutch selected for the drive roller has a torque range of from 0.024 to 1.324Nm, between which the clutch can be adjusted to slip. It is expected that the clutch will be used in the middle of this range as the maximum longitudinal tension is 0.75 Nm. The other clutch chosen for the take-up roller is of the same type and can be adjusted to slip at any torque between 0.024 Nm and 0.5 Nm.

### Transport subsystem integration

The main frame of the transport subsystem is constructed from aluminium extrusions, which can be easily aligned and assembled, and can be reused for other rigs if this rig becomes obsolete. The rollers are made of nylon material by the rapid manufacturing
technology. Other parts including bearing brackets and motor support brackets are also manufactured by the rapid manufacturing technology which is time effective and cheaper.

As the selected pulley for the drive roller has a diameter of 45 mm, bigger than the roller, the pulley cannot fit in between the two rollers. A frame has been specially designed which allows the pulley to be installed properly, as shown in Figure 6-23. To allow the light source to be placed between the drive rollers and the feed rollers, they are set 300 mm apart. The final design of the transport subsystem is shown in Figure 6-24.
6.2.3.2 Tensioning subsystem

The detailed design process of the tensioning subsystem can be roughly divided into three parts as follows.

1. Specifying the waste mesh tensioning roller system
2. Specifying the lead screw linear system
3. Specifying the micro tensioning system

6.2.3.2.1 Tensioning roller system

The structure of the tensioning roller system consists of a pair of small rollers, a motor to drive the rollers, and other accessories including pulleys, belts and bearings.

The roller has been decided to be 30 mm long and 30 mm in diameter, depending on the waste mesh width and the space available. The roller has been specially designed so that it can be attached to the only support frame and free to rotate through bearings. The aluminium extension allows the roller pair to be easily adjusted to align with the other
rollers. The same DC motor as used for the transport subsystem has been selected to drive the rollers. The detailed design of the tensioning rollers is shown in Figure 6-25.

![Figure 6-25 Detailed design of the tensioning rollers](image)

**6.2.3.2.2 Lead screw linear system**

The purpose of the lead screw linear system is to drive the waste mesh tensioning roller system to change the direction of the combination tension. Depending on the distance between the drive and the feed rollers of the transport subsystem, the length of the lead screw has been decided to be 140 mm. The selected lead screw has a screw diameter of 6.35 mm and lead length of 2 mm. The rated load which the lead screw is able to drive is 200 N, which is more than enough to drive the waste mesh tensioning roller system. When driven by the DC motor as used for the transport subsystem, the maximum linear speed can reach 17.6 m/s. The detailed design of the lead screw system is shown in Figure 6-26.
A self-lube insert bearing has been selected to interface the waste mesh tensioning roller system with the lead screw drive system. The bearing has a bore diameter of 20 mm and the maximum dynamic load it is capable of carrying is 12800 N. The integration of the whole waste mesh tensioning system is shown in Figure 6-27.
6.2.3.2.3 Micro tensioning system

The micro tensioning system is composed of two pairs of small rollers used to prevent the lace from deflecting when tension is applied on the lace. To allow the lace to be continuously transported, it is essential to ensure that the lace can pass through the rollers without any resistance. The diameter of the rollers has been decided to be 10 mm and the rollers are 80mm in length. With two bearings inserted in the slots at both ends, the roller is able to freely rotate around the shaft as shown in Figure 6-28.

![Figure 6-28 Micro tensioning rollers](image)

6.2.4 Final design and manufacturing

All subsystems are integrated together through aluminium extrusions. It is important to ensure that the waste mesh tensioning system does not interfere with the transport system. Except the aluminium extrusion and other standard components, all parts are manufactured by the rapid manufacturing technology, which is cost effective and good enough for the rig.

The final design of the lace transport and tensioning rig is shown in Figure 6-29 and the picture of the assembled rig is shown in Figure 6-30.
Figure 6-29 Final design of the lace transport and tensioning system

Figure 6-30 The manufactured lace transport and tensioning rig
6.2.5 Control of the lace transport and tensioning rig

Getting the transport and tensioning rig to transport lace and tension a small lace section continuously requires precisely controlling and coordinating each individual subsystem. The speed of each motor needs to be monitored and controlled so that desired tension can be reached and maintained. However, due to time limit, this work cannot be carried out at present. In addition, the speed limitation of the lace targeting and the laser subsystems (described in section 6.1) makes it unrealistic to cut lace continuously at this stage of the project. Therefore, to test the lace cutting strategy and the image processing algorithms, the rig is controlled manually. After the lace has been transported into the laser cutting area, it is stopped and then tensioned with the rig. With some form of feedback, the applied tension will be adjusted by manipulating each subsystem step by step until the desired tension is reached.

6.2.5.1 Subsystem control

As each subsystem of the transport and tensioning rig is driven by a DC motor, controlling these subsystems actually means controlling the driving motors. For motor control, a Sensory 626 interface card has been selected. Together with the 4-Q-DC servo amplifier from Maxon Motor, this card can precisely control the speed and direction of each motor with its D/A output function. The I/O ports available with the card are used to control the lace positioning subsystem and the laser subsystem. A Graphic User Interface (GUI) has been developed for the user to control the lace positioning subsystem and the laser, as shown in Figure 6-31. (refer to Figure 6-5)
6.2.5.2 Tension control with visual feedback

As the longitudinal tension applied by the lace transport subsystem is controlled and maintained through adjusting the clutch device, no feedback is needed for controlling the longitudinal tension. However, as for the combination tension applied by the waste mesh tensioning subsystem, reliable feedback to indicate whether the lace is adequately tensioned is essential.

The easiest way to obtain the information of the applied tension is using a force sensor. However, when it comes to measure the tension applied on each individual purl, using force sensors seems to be impracticable. Furthermore, as purls have different shape and structure, the tension needed to adequately tension each purl is different. The tension which is able to adequately tension a purl may fail to tension or is too much and therefore break another one. The tension required for adequately tensioning a purl mainly depends on the connection thread structure, the purl shape and it is impossible to find out an optimum tension value that will guarantee that every purl can be adequately tensioned.

A purl is considered to be adequately tensioned if the loop thread is exposed. However, it is very difficult to develop an image processing algorithm to identify the loop thread because of its tiny size and various shapes. As the purl shape and the status of the connection threads are changing while tension is applied, the purl itself or its connection threads may provide useful information to indicate whether the applied tension is enough.

- The status of connection threads
  Connection threads become longer and straighter as more tension is applied. The straightness or length of the connection threads may be measured to check if the purl is adequately tensioned. However, as each connection thread is comprised of several thin strands which are tangled together, its straightness is not even and can hardly be measured. Similarly, as all connection threads are linked together and knitted into each other, it is a daunting task and even impossible to use machine vision technique to automatically measure the length of a connection thread, as shown in Figure 6-32.
The purl shape

With more tension being applied, the shape of a purl is becoming longer but narrower. According to the concept of purl height described in Chapter 5, the purl can also be considered to be becoming higher. As the height of a purl has a direct relationship with the applied tension, the information of the height of a purl can be used as feedback for controlling the applied tension. In addition, the height of a purl can be easily and accurately obtained with the lace edge based method as described in Chapter 5. This makes the tension control algorithm easy to be developed and implemented.

When lace is transported into the laser cutting area, it is usually pre-tensioned by the longitudinal tension applied by the lace transport subsystem and the combination tension applied by the waste mesh tensioning subsystem. The tension control algorithm works by first measuring the height of the purl to be tensioned after the lace is transported and stopped, which is called initial height. After the secondary connection threads have been cut off with the pulsed laser beam, the purl height will be measured again. According to the experiment results obtained with the intermediate tensioning rig (Chapter 4), the purl will be better tensioned and elongated as the tension is concentrated on the primary connection threads. Therefore, the re-measured purl height is always greater than the initial purl height. Instead of the purl height, the elongation rate of the purl height obtained by dividing the re-measured purl height by
the initial one is used to check if the purl has been adequately tensioned. The selection of the elongation rate beyond which the purl is considered to be adequately tensioned depends on lace type, operator's experience and can only obtained through observing lace cutting experiments.

The primary connection threads will not be cut until the applied tension has been proven to be adequate with the feedback of the purl shape elongation rate. If not, more tension will be applied by manipulating the waste mesh tensioning subsystem and then the tension will be checked again.

As for these purls having no secondary connection threads, their height remains the same until more tension is applied. In this case, the elongation rate is obtained by dividing the purl height measured after more tension is applied by the initial height.

6.2.5.3 Tension control experiment

The purpose of carrying out the tension control experiment is to find out the purl height elongation rate criterion for the selected lace. The experiment process can be divided into several steps. At first, the original height of the purl to be tensioned is measured and recorded. The secondary connection threads (if existing) are then cut off with the pulsed laser. The applied tension is then adjusted with the tensioning rig until the purl is considered to be adequately tensioned. The height of the purl is measured and recorded again before the remaining primary connection threads are eventually cut off.

For the selected lace, one whole lace repeat has been picked out for the experiment, which contains 14 purls. Table 6-4 summarises the initial heights and final height of each purl.

From the table, it has been noticed that the final heights of some purls are not available. This is because that all the connection threads have been cut off at one time when the pulsed laser beam hits one secondary connection thread, which again shows that lace cutting strategy cannot only help to improve the lace cutting edge quality, but also reduce the required laser shots. If the elongation rate of each purl can be ensured to be equal to or greater than the greatest elongation rate shown in Table 6-4, that is 1.31, all purls can be adequately tensioned and therefore the resulting lace edge quality can be greatly improved as verified in Chapter 7.
Table 6-4 Purl height elongation rate criterion determination

<table>
<thead>
<tr>
<th>Purl No.</th>
<th>Initial height</th>
<th>Final height</th>
<th>Purl elongation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pixels</td>
<td>mm</td>
<td>Pixels</td>
</tr>
<tr>
<td>1</td>
<td>201</td>
<td>2.01</td>
<td>258</td>
</tr>
<tr>
<td>2</td>
<td>185</td>
<td>1.85</td>
<td>220</td>
</tr>
<tr>
<td>3</td>
<td>198</td>
<td>1.98</td>
<td>250</td>
</tr>
<tr>
<td>4</td>
<td>212</td>
<td>2.12</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>208</td>
<td>2.08</td>
<td>247</td>
</tr>
<tr>
<td>6</td>
<td>188</td>
<td>1.88</td>
<td>227</td>
</tr>
<tr>
<td>7</td>
<td>192</td>
<td>1.92</td>
<td>230</td>
</tr>
<tr>
<td>8</td>
<td>202</td>
<td>2.02</td>
<td>249</td>
</tr>
<tr>
<td>9</td>
<td>191</td>
<td>1.91</td>
<td>229</td>
</tr>
<tr>
<td>10</td>
<td>192</td>
<td>1.92</td>
<td>235</td>
</tr>
<tr>
<td>11</td>
<td>160</td>
<td>1.60</td>
<td>N/A</td>
</tr>
<tr>
<td>12</td>
<td>151</td>
<td>1.51</td>
<td>193</td>
</tr>
<tr>
<td>13</td>
<td>145</td>
<td>1.45</td>
<td>190</td>
</tr>
<tr>
<td>14</td>
<td>193</td>
<td>1.93</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Experiment results with another type of lace are included in Appendices 12.9.
6.3 Strategically Pulsed Laser Cutting Experiment

To prove that the strategically pulsed laser cutting method can improve the cut edge quality with the developed integrated cutting system in a static situation, a series of experiments have been carried out. During the cutting experiments, the cutting points and the applied tension are automatically determined by the developed image processing algorithms within the WiT environment, while the tension applied on the waste mesh is manually adjusted using rig mechanics. The flowchart of the cutting process is shown in Figure 6-33.

![Flowchart of Strategically pulsed laser cutting experiment process](image)

6.3.1 Laser spot calibration

Before any cutting operation starts, the position of the fixed laser spot needs to be accurately determined. The laser spot must be ensured to be well within the field of view of the camera, ideally close to the first cutting point. A simple and effective way to determine the x, y coordinates of the laser spot has been reported in [4]. A piece of paper is placed in the laser cutting zone. Then a single pulse of laser beam (250W, 0.1 ms duration) is applied and a hole is made on the paper. Without moving the paper, two images are taken before and after the laser pulse. The developed algorithm is then used to
compare these two images to find the centre of the hole, which is then stored as the laser spot position. The flowchart of the process is shown in Figure 6-34.

![Figure 6-34 Laser position calibration](image)

### 6.3.2 Lace sample setting up

The lace to be cut is initially wound onto the source roller and then manually adjusted to go through the feed rollers, micro tensioning rollers, drive rollers and finally is wound onto the take-up rollers. The beginning section of the lace is cut manually using scissors so that the waste mesh can be separated and go through the waste mesh tensioning rollers. The orientation of the waste mesh tensioning roller is adjusted with the bearing so that the waste mesh is perpendicular to the rollers. With the roller system, the lace is pre-tensioned to be flat and free of wrinkles. Figure 6-35 shows the setting up for the lace which is ready for cutting.
6.3.3 Cutting parameters

The cutting parameters set for the cutting experiment are listed in Table 6-5.

<table>
<thead>
<tr>
<th>Laser Power</th>
<th>Laser Spot size</th>
<th>Laser Pulse duration</th>
<th>Importance criterion</th>
<th>Elongation rate criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>240 w</td>
<td>0.2 mm</td>
<td>0.1 ms</td>
<td>0.8</td>
<td>1.31</td>
</tr>
</tbody>
</table>

Table 6-5 Cutting experiment parameters

The parameter values of the laser system are the same as those of the existing pulsed cutting system. Based on the observations of lace structure and experiment results (section 5.2.2.2 and Table 5-6), the importance criterion is set to 0.8 which is considered appropriate to classify the connection threads. The purl elongation rate criterion used to check if the applied tension is adequate is determined from carrying out the tension control experiments as described in 6.2.5.3 and Table 6-4.

6.3.4 Pulsed cutting process sequence

The cutting process starts with automatically finding the first cutting point with the developed image processing algorithms. In the environment of WiT, the automatic cutting
point detection process can be divided into several steps, including lace image capture, lace edge detection, purl isolation, cutting points detection, cutting points classification and finally the first cutting point determination. Detailed image processing is presented in Chapter 5.

The cutting strategy used to cut the secondary and the primary connection threads is different.

To cut a secondary connection thread, there is no need to check the applied tension. As shown in Figure 6-36, three cutting points have been automatically detected and the cutting point 3 is classified as a secondary cutting point according to the importance criterion (described in section 5.2.2.2 and Table 5-6). Then as shown in Figure 6-37, both the cutting point and the laser spot have been displayed in the lace image. By moving the x, y movable stage with the pushbuttons on the GUI shown in Figure 6-31, the cutting point is manually aligned with the laser spot before a pulse of laser energy is applied to cut the thread. It is noticed that the laser spot and the point to cut have not been exactly aligned. The accuracy of alignment by this means is within the range of \( \pm 25 \, \mu m \) [40], which is much smaller than the laser spot size (0.20 mm) and is acceptable for cutting lace threads for this project.

The applied tension needs to be checked before a primary connection thread is cut. The original height of the purl shown in Figure 6-36 Automatic cutting point detection is 192 pixels and the height measured after the secondary connection thread is cut is 229 pixels as shown in Figure 6-38. To ensure that the applied tension is enough, the purl height needs to be \( 192 \times 1.31 \approx 252 \) pixels. To increase the tension, the waste mesh tensioning system is manually manipulated until the final height reaches 260 pixels, as shown in Figure 6-38.
Figure 6-36 Automatic cutting point detection

Before alignment
After alignment

Figure 6-37 Manual cutting point alignment

Original height

Purl height after secondary thread cut
When the applied tension is ensured to be adequate, the cutting process of the primary connection threads is similar to that of the secondary connection threads, as shown in Figure 6-39.

By repeating the cutting process, the lace can be cut purl by purl. The edge quality of the cut lace will be compared with the lace cut by other cutting methods in Chapter 7.
Before alignment

After alignment

Primary cutting point

Laser spot

Aligned two points
Cut result

Figure 6-39 Cutting process of the primary connection thread
6.4 **Summary and Discussion**

After briefly introducing the systems including laser subsystem, image capture subsystem and lace positioning subsystem, this chapter has focused on describing the design and manufacturing process of the final lace transport and tensioning rig. The designed rig has a potential of transporting and tensioning lace continuously at a high speed. However, due to time limit, the work of controlling the rig has been left for future development.

The proposed lace cutting strategy and the developed image processing algorithms have been fully tested with the developed integrated cutting system. A tension control algorithm has been developed with the feedback obtained from investigating and comparing the purl height. With an appropriate purl height elongation rate criterion, this tension control algorithm is able to ensure that each purl of the lace to be cut can be adequately tensioned. The cutting results of strategically pulsed cutting experiments are reported in Chapter 7.
To compare the edge quality of the lace cut by different cutting systems, reliable lace edge quality assessment methods are desired. However, compared with the extensive research activities in the lace cutting and lace pattern inspection areas, the research work concerning the lace edge quality and its assessment may be considered negligible. There is no established method of lace edge quality assessment or international standards existing for characterization of the lace cutting edge quality. In current industrial practice, two methods of assessment are being used by some lace manufacturing industries. Method 1 involves panels of humans assessing the lace tactile quality and visual appearance. This can only be based on subjective assessment and is not a reliable method. Method 2 is the Martindale Tester, as shown in Figure 7-1, which is usually used for testing the abrasion and pilling resistance of all kinds of textile fabrics, and therefore it also can be used for determining the lace cut edge quality. By rolling the lace into a cylinder which is then rubbed against a standard abradant at low pressures and in continuously changing directions, the quality of the lace is determined either by the number of cycles until breakdown of the lace edge or by the mass reduction of the test subject [100]. However, this method is not the most suitable for lace edge quality assessment because the lace edge defect formed during the lace cutting operations is very subtle and therefore the difference can be too insignificant to be assessed by the tester.

In this chapter, several lace edge quality assessment methods will be introduced and described in detail. The edge quality of the lace cut by different cutting systems, including
mechanical cutting system, CW cutting system, pulsed cutting system and the developed strategically pulsed cutting system, will be assessed and compared.

7.1 Lace Edge Defect Formation

As introduced in Chapter 1, lace edges are made up of a series of purls that are each connected to the light waste mesh by a single or series of connecting threads, as shown in Figure 7-2. In most lace cutting systems based on the machine vision technology, a laser is used for cutting the connecting threads by vaporization. Compared with the conventional mechanical cutting tools, such as a rotating knife, using a laser for lace cutting can eliminate the distortion and undesirable tension caused by the contact between the mechanical tools and the lace. However, laser damage can be incurred if lace purls are over exposed to or inaccurately cut by the applied laser energy. The individual strands of nylon that make up the lace pattern will be melted. Once the melting occurs, small bubbles of trapped air form at the end of the severed strand, as shown in Figure 7-3. These bubbles of trapped air and solid nylon are what cause irritation to the skin and therefore lower the quality of the lace edge. The lace edge quality is determined by the severity and the number of defects caused during the lace cutting process.

![Figure 7-2 Typical lace structure](image-url)
7.2 Contact Measurement Method

The irritation to the skin caused by poor edge quality lace can be attributed to the snagging of the heat affected areas on the contours of the skin. It is also noted that a lace sample with a defective edge will snag on fine nylon material such as that used in ladies’ tights and undergarments. If the lace is not heat affected and therefore of suitable quality, it would be of sufficient compliance and flexibility to mould to the contours of the skin or tight material. The Martindale Tester uses a foam pad to simulate the human skin or tight material and the quality is distinguished by the condition of the pad after abrasive testing. Instead of using a foam pad, hosiery (tight material) is employed in the following tests, which can generate some noticeable resistance when a lace sample with a defective edge slides over the hosiery material surface. Recording this resistance between the hosiery and the lace edge can be used to assess the edge quality of the lace sample being tested. Two methods, called tube abrasion and sheet abrasion, have been identified based on the principle mentioned above.

7.2.1 Tube abrasion method

When the lace sample is rolled into a cylinder, the resistance between the lace edge and the hosiery can become significant as this increases the number of defects acting on the tight material at any one time. Although not all purls are in contact with the hosiery due to the curved edge profile, recording this force will offer a suitable measurement as to the edge quality of the entire sample.
7.2.1.1 Test rig design and operation

The test rig consists of two tube sections, one of 35 mm internal diameter and one of 30 mm. As shown in Figure 7-4, the section of the 30 mm tube is attached to the 35 mm tube at a right angle, which is used to house the rolled lace sample.

Another section of tube, 30 mm in diameter, is cut in half longitudinally to create a semicircular section to run inside the large 35 mm section. The semicircular tube is then covered by hosiery to act as a skin simulator, which moves in an orthogonal direction to the lace edge at a constant speed within the larger tube as shown in Figure 7-4. The lace sample is moved to a position where it just touches the surface of the hosiery, then advanced a further 1 mm and locked in position by a clamp to ensure there is always a fixed displacement contact between the lace edge and the hosiery. Estimated contact force between lace edge and tight material is 0.5 Newtons. Lower edge quality lace will snag on the hosiery, causing higher frictional forces between the lace edge and the hosiery, which consequently causes a noticeable increase in the amount of the force required to move the skin simulator.
The skin simulator is attached to the load cell of a Hounsfield Tensile Testing Machine and then any force change due to the snagging can be recorded. The force data can then be transferred to the PC for further analysis, as shown in Figure 7-5.

7.2.1.2 Test samples

Two types of lace samples with different patterns are selected for the test, as shown in Figure 7-6. For each type of lace, four nominally identical samples are cut by different cutting systems: Mechanical, CW laser (cut with the system described in [6]), pulsed laser (cut with the cutting system described in [2]) and the developed strategically pulsed laser respectively. During the pulsed laser cutting (both the previous pulsed laser cutting system and the newly developed strategically pulsed laser cutting system), the laser beam is fixed and the lace is moved with a x, y movable stage and then stopped after the thread to be cut has been aligned accurately with the laser spot. The lace remains stationary when a single pulse of laser energy is delivered to cut the thread. The cutting parameters of these lace cutting systems are listed in Table 7-1. By comparing the edge quality of these lace samples, the relative cutting edge quality of each cutting system can be determined.
Vision Guided Cutting and Mechanical Handling of Lace Ribbon  
Chapter 7

<table>
<thead>
<tr>
<th>Cutting method</th>
<th>Laser Power</th>
<th>Cutting Speed</th>
<th>Laser Spot size</th>
<th>Laser Pulse duration</th>
<th>Importance criterion</th>
<th>Elongation rate criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Cutting</td>
<td>N/A</td>
<td>0.1 m/sec.</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>CW laser</td>
<td>240 w</td>
<td>1 m/sec.</td>
<td>0.2 mm</td>
<td>Continuous</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Pulsed laser</td>
<td>240 w</td>
<td>0*</td>
<td>0.2 mm</td>
<td>0.1 ms</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Strategically pulsed laser</td>
<td>240 w</td>
<td>0*</td>
<td>0.2 mm</td>
<td>0.1 ms</td>
<td>0.80</td>
<td>1.31 (pattern 1)</td>
</tr>
</tbody>
</table>

* Lace remains stationary when the pulsed laser is applied

Table 7-1 Cutting parameters of each cutting system

![Figure 7-6 Lace samples used for test](image)

7.2.1.3 Test results

The Tube Abrasion test is repeated 10 times for each lace sample. The test data for the lace samples with pattern 1 are shown in Figure 7-7, which shows a significant difference in the forces required for the mechanically cut, CW cut, pulsed laser cut and strategically cut lace samples. It can be found that more force is recorded for the CW sample than the other three samples.

Trend lines are then identified for each set of test data and by subtracting the trend line from each corresponding set of test data, the data difference can be obtained as shown in Figure 7-8. In order to highlight the force difference among these lace samples, the standard deviation and average value of each set of test data have been calculated, as shown in Table 7-2. The average value is obtained from the test data in Figure 7-7, while the standard deviation is calculated with the data shown in Figure 7-8.
Figure 7-7 Test data of the lace samples with pattern 1

Figure 7-8 Difference between test data and trend lines (lace pattern 1)
<table>
<thead>
<tr>
<th>Lace sample</th>
<th>Average force (N)</th>
<th>Standard deviation (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW cut</td>
<td>0.51</td>
<td>0.033</td>
</tr>
<tr>
<td>Pulsed cut</td>
<td>0.44</td>
<td>0.019</td>
</tr>
<tr>
<td>Strategically pulsed cut</td>
<td>0.40</td>
<td>0.009</td>
</tr>
<tr>
<td>Mechanically cut</td>
<td>0.39</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 7-2 Average value and STDV (σ) (lace pattern 1)

From Table 7-2, it can be concluded that the edge quality of the mechanically cut and the strategically pulsed cut samples is significantly better than this of the pulsed cut and the CW cut samples. The CW cut samples have the lowest edge quality with an average force of 0.51 Newtons, while the mechanically cut samples have the best edge quality. In terms of cutting edge quality consistency, the mechanically cut and the strategically pulsed cut samples are considered the most consistent as the standard deviations of the recorded forces are 0.005 and 0.009 respectively, much smaller than those of the CW cut and the pulsed cut samples. It is noticed that the strategically pulsed cut samples are very close to the mechanically cut samples, in terms of both cutting edge quality and edge quality consistency, as highlighted in Figure 7-9 and Figure 7-10.
7.2.2 Sheet abrasion method

Instead of being rolled into a cylinder, the lace sample can also be placed between two sheets of Perspex, through which the defects caused by the laser cutting can be examined in greater detail.

7.2.2.1 Test rig design and operation

The Perspex sheets are purposefully manufactured for each individual lace sample to keep the main body of the lace in place, but to still allow the purls to be exposed for testing. The rig operates in a similar way as in the tube abrasion test. The lace sample is secured in the Perspex plates and then positioned so that the lace edge is in contact with the hosiery acting as the skin simulator. The lace sample is then pulled across the hosiery and the frictional forces between the lace edge and the skin simulator are recorded. This test rig allows for much more localised measurements as the sample of the lace edge under examination is significantly less (0.15 meters, Figure 7-11 and Figure 7-12) when compared with the previous test rig in section 7.2.1 where the rolled up length of the lace sample is about 1 meter.

![Data Difference Graph](image)

Figure 7-10 Highlighted data difference of mechanically and strategically pulsed cut lace
Vision Guided Cutting and Mechanical Handling of Lace Ribbon

Chapter 7

Figure 7-11 Test rig for sheet abrasion method

Figure 7-12 Test rig setting up
7.2.2.2 Test results

The experiment results shown in Figure 7-13 are similar to those in Figure 7-7. The CW cut lace sample produces the most significant frictional force, indicating that it has the lowest edge quality, which is consistent with the conclusion of the previous test.

A similar data processing method as used in the tube abrasion test is adopted where trend lines for each data set are identified and then subtracted from each corresponding set of test data to obtain data difference as shown in Figure 7-14, from which the standard deviation of the test data can be calculated. Table 7-3 shows the standard deviation and the average value for each set of test data.

Figure 7-13 Test result of sheet abrasion method (lace pattern 1)
From Figure 7-13, Figure 7-14 and Table 7-3, it may be concluded that that the CW cut sample has the lowest and most inconsistent edge quality while the mechanically cut sample is the best in terms of both aspects. It is also noticed that the edge quality of the strategically pulsed cut samples is close to that of the mechanically cut samples (as highlighted in Figure 7-15 and Figure 7-16) and much better than those cut by the CW and the pulsed systems. When comparing Table 7-3 to Table 7-2, it can be found that the average values of the forces produced in the tube abrasion test is much higher than in the sheet abrasion test, which can be explained by the fact that more lace purls are in contact with the skin simulator in the tube abrasion test, causing higher friction force. It is also noticed that the standard deviation of each set of data (especially the CW sample) obtained with the sheet abrasion method is bigger because this method can examine the lace purls on a more local scale, highlighting the quality variations among purls.
Both test methods are repeated for other lace samples with lace pattern 2 and the results are included in Appendices 12.11. The results show that the mechanically cut and the strategically pulsed cut lace samples have better edge quality, with the CW cut lace samples having the lowest edge quality and being most inconsistent as indicated by the standard deviation values.
7.3 User Trial Method

In addition to the quantitative methods described above, a lace edge quality assessment trial based on a user trial method has also been carried out, aiming to assess and compare the edge quality of lace samples cut with different methods. The trial involves asking a number of volunteers to rate the softness and the visual appearance of the lace edges and then assessing the lace edge quality according to the scores given by the volunteers. The higher the score a lace sample gets, the better the edge quality of the lace sample.

7.3.1 Test setup

A number of volunteers (20) are asked to rate the edge quality of the lace samples cut by the mechanical cutting system and laser cutting systems, including CW, pulsed, and strategically pulsed. Same lace samples used in the contact measurement tests are selected, which form 4 sets of samples. Sample sets A & B are for pattern design 1 and sets C & D are for pattern design 2, as shown in Figure 7-17. Each set of samples consists of one mechanically cut sample, one CW laser cut sample, one pulsed laser cut sample and one strategically pulsed laser cut sample. The laser cutting parameters for laser cutting systems (including CW, pulsed and strategically pulsed) are the same as previous ones used for contact measurement tests, that is, 240W CO₂ laser with 0.2 mm spot size and 0.1 ms pulse duration for pulsed cut. The samples within each set are randomly numbered as shown in Table 7-4.

![Lace pattern 1](image1)

![Lace pattern 2](image2)

Figure 7-17 Lace samples for the trial

The scores given to each lace sample ranged from 0 to 5, where 0 means the quality is very bad and 5 means very good.
<table>
<thead>
<tr>
<th>Set number</th>
<th>Design Type</th>
<th>Sample No.</th>
<th>Cutting method</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Lace pattern 1</td>
<td>1</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Pulsed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Mechanical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Strategically pulsed</td>
</tr>
<tr>
<td>B</td>
<td>Lace pattern 1</td>
<td>1</td>
<td>Strategically pulsed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Mechanical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Pulsed</td>
</tr>
<tr>
<td>C</td>
<td>Lace pattern 2</td>
<td>1</td>
<td>Mechanical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Strategically pulsed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Pulsed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>CW</td>
</tr>
<tr>
<td>D</td>
<td>Lace pattern 2</td>
<td>1</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Strategically pulsed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Pulsed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Mechanical</td>
</tr>
</tbody>
</table>

Table 7-4 Edge quality trial sample numbering

<table>
<thead>
<tr>
<th>Lace type</th>
<th>Cutting method</th>
<th>Score</th>
<th>Average score</th>
<th>Score St Dev (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lace pattern 1</td>
<td>Pulsed</td>
<td>62</td>
<td>3.10</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>CW</td>
<td>38</td>
<td>1.90</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>Strategically pulsed</td>
<td>79</td>
<td>3.95</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>Mechanical</td>
<td>81</td>
<td>4.05</td>
<td>1.05</td>
</tr>
<tr>
<td>Lace pattern 2</td>
<td>Pulsed</td>
<td>59</td>
<td>2.95</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>CW</td>
<td>32</td>
<td>1.60</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>Strategically pulsed</td>
<td>66</td>
<td>3.30</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Mechanical</td>
<td>67</td>
<td>3.35</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 7-5 Edge quality trial results
7.3.2 Test results

The scores for each lace sample from all 20 volunteers are summed together and an overall score and an average score can be obtained. A summary of the scores for each lace sample is shown in Table 7-5.

The results clearly show that the mechanically cut sample has the best edge quality with average scores of 4.05 and 3.35 for lace design 1 and lace design 2 respectively. The CW laser cut lace with scores of 1.90 and 1.60 for lace design 1 and lace design 2 respectively has the lowest edge quality.

With scores of 3.95 and 3.30 which are close to the score of the mechanically cut sample, the strategically pulsed laser cut sample is perceived to be much softer than the CW and the pulsed samples. The trail subjects also reported that the strategically pulsed cut samples have a cleaner and less hairy edge than that of the mechanically cut samples. As the standard deviations of all assessments are around 1, the assessment results are considered consistent. The samples of lace pattern 2 are rated slightly more consistently than the samples of pattern 1. The results are shown graphically in Figure 7-18.

From the results shown in Figure 7-18, it is clear that the mechanically cut and the strategically cut lace samples are the softest, which indicates that they have the best edge quality. This is consistent with the test results obtained from the previous contact measurement experiments described in section 7.2. Compared with the CW and the pulsed cut samples, the edge quality of the strategically pulsed cut sample has been clearly improved.
Figure 7-18 Edge quality trial score averages
7.4 Microscopic Method

Another assessment method employed is to inspect the lace edge purls under a microscope. This assessment method has been briefly described in section 3.3 to compare the edge quality of the lace samples cut under different tension to identify the tension effect on lace cut edge quality. When the lace purls are overexposed to or inaccurately targeted by the laser beam during the cutting process, some small bubbles, invisible to the naked eye, will be formed. However, with the aid of a microscope, these small bubbles can be clearly seen as shown in Figure 7-19. It is the bubbles that cause the skin irritation and therefore degrade the overall lace edge quality. From this point of view, the lace edge quality can be assessed and categorized by observing and classifying these bubbles.

![Figure 7-19 A purl with small bubbles](image)

7.4.1 Test setup

Four lace samples, same as these used in previous tests are selected for the microscopic investigation test, including mechanically cut, CW cut, pulsed cut and strategically pulsed cut (0.1 ms pulse duration). These samples have the same pattern as shown in Figure 7-20.

![Figure 7-20 Lace sample with pattern design 1](image)
As inspecting the lace purl under a microscope one by one is time consuming, two pattern repeats of each sample are selected for the inspection, which is considered to be enough for representing the whole lace edge quality. As each repeat contains 14 purls (only true for the lace pattern shown in Figure 7-20), totally 28 purls of each lace sample have been inspected and classified as good, neutral or bad quality according to the severity of the thermal damage caused during the cutting process.

The quality of a purl is classified as 'good' only when no thermal damage or bubbles can be seen under the microscope. The purl will be considered as 'bad' or 'neutral' quality depending on the position and degree of the thermal damage. Figure 7-21 shows four examples of purls with different quality.

![Purl examples of different quality](image)

**Figure 7-21 Purl examples of different quality**

### 7.4.2 Experiment results

By inspecting and classifying the purls one by one, the number of the purls with different quality of each sample can be counted as shown in Table 7-6. The overall lace edge
Quality of the lace sample is determined by calculating the percent of the ‘good quality’ purls out of all the purls.

<table>
<thead>
<tr>
<th></th>
<th>Good</th>
<th>Neutral</th>
<th>Bad</th>
<th>Total</th>
<th>Percent of good (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanically</td>
<td>28</td>
<td>0</td>
<td>0</td>
<td>28</td>
<td>100</td>
</tr>
<tr>
<td>CW</td>
<td>3</td>
<td>3</td>
<td>22</td>
<td>28</td>
<td>11</td>
</tr>
<tr>
<td>Pulsed</td>
<td>21</td>
<td>5</td>
<td>2</td>
<td>28</td>
<td>75</td>
</tr>
<tr>
<td>Strategically pulsed</td>
<td>26</td>
<td>2</td>
<td>0</td>
<td>28</td>
<td>93</td>
</tr>
</tbody>
</table>

Table 7-6 Microscopic experimental results

Table 7-6 and Figure 7-22 clearly show that the mechanically cut lace sample has the best overall edge quality without any thermal damage. It is worth noticing that the strategically pulsed cut lace has no ‘bad’ purls and its edge quality is close to the mechanically cut lace. This has again demonstrated that the edge quality has been greatly improved by the developed strategically pulsed cutting system.

![Figure 7-22 Microscopic experiment analysis results](image-url)
7.5 Summary and Discussion

In this chapter, three methods of lace edge quality assessment have been presented. Although these methods are different in terms of principle and process, the conclusion drawn from each assessment method is the same, which states that mechanical cut and the strategically pulsed cut lace samples have the best and the most consistent edge quality while the edge quality of the lace samples cut by the CW system is the lowest.

The experiment results have shown that the developed strategically pulsed cutting system is able to cut lace with greatly improved edge quality which is very close to that of the mechanically cut lace samples. Being able to cut lace with high level edge quality which can satisfy the demanding lace markets, the lace cutting system based on the combination of machine vision and laser cutting technology has demonstrated its huge potential to replace the low-speed mechanical cutting system.
8 Discussion

The previously developed CW lace cutting system [3] was not able to cut lace with high level lace cut edge quality that meets the requirements of demanding lace markets. The developed pulsed laser cutting system [2] failed to cut lace with satisfactory consistency, although it was successful to improve the lace cut edge quality. To address the drawbacks of these two lace cutting systems, a machine vision based laser cutting system has been researched and realised in this project. The newly developed system is able to cut lace with highly improved edge quality and cutting consistency according to the assessment results presented in Chapter 7. The development process of the system is summarised as follows.

At the first stage of the project, based on the investigation of the effect of the handling tension on the lace cutting edge quality and the observation on lace behaviour during the lace cutting process, a new lace cutting strategy has been proposed. The underlying idea of the cutting strategy is to improve the lace cutting edge quality and consistency by exposing and accurately cutting the loop thread of every single purl one by one with the pulsed laser beam.

Then, to implement the cutting strategy automatically, a machine vision system has been developed. Imaging the lace at a resolution of 100 pixels/mm, the machine vision system is able to automatically detect and classify individual cutting points. By monitoring the shape change of the purl to be cut, the system is also able to provide feedback for controlling the tension applied on the lace to ensure that the loop thread is adequately tensioned and exposed.

Parallel to the development of the machine vision system, a lace transport and tensioning rig has been developed. Although the developed transport and tensioning rig is not able to transport and tension lace continuously at this stage, it has well demonstrated the concept of tensioning each purl divergently and progressively. By manipulating the rig manually during the lace cutting experiments, this transport and tensioning rig is capable of adequately tensioning purls to expose the loop thread for the pulsed laser beam to cut.
Finally, based on the previous pulsed laser cutting system, an integrated lace cutting system has been developed. The system is capable of automatically detecting and classifying the cutting points where connection threads intersect with the purl. Although the alignment process of the cutting point and the fixed laser spot has not been automated, it can be fully achieved by upgrading the laser delivery system as described in section 10.2.

To assess and compare the lace cut by the newly developed cutting system, an objective and quantitative method has been developed and employed. With reference to the friction forces and standard deviation of the experiment data established by the developed contact measurement assessment method as described in Chapter 7, the lace cut by the developed system is almost the same as the mechanically cut lace. The assessment results have proven that the newly developed lace cutting system is able to cut lace with high level edge quality and cutting consistency and shows prospect of replacing the current low-speed mechanical cutting systems in the future.

In this chapter, the discussion of the approaches and results obtained throughout the project are presented. The discussion is split into several areas as follows.

- Previous\(^1\) high accuracy pulsed laser cutting system
- Lace cutting strategy
- The developed machine vision system
- The developed lace transport and tensioning rig
- Lace edge quality assessment methods

\(^1\) Previous system refers to the pulsed laser cutting system reported by Bamforth [2]
8.1 Previous Pulsed Laser Cutting System

By increasing the accuracy and actively targeting individual lace threads with a pulsed laser, the previous pulsed lace cutting system researched and realised improving the resulting lace cutting edge quality [101]. Without relying on the prior knowledge of lace, the pulsed cutting system is able to accommodate local distortions, which further increases the targeting accuracy. The reported targeting accuracy of the system is on average 0.073 mm at an image resolution of 30 pixels/mm.

However, the laser damage is still present with the lace samples cut by this system, although the damage has been greatly reduced when compared to the previous CW laser cutting system. The cause of the laser damage can be analysed as follows.

A 3D thermal model has been developed to simulate the lace cutting process with the CO₂ laser [7]. With the aid of the thermal model, it has identified that for fixed laser power and pulse duration the laser beam spot size and the beam offset are critical to obtaining a cut with minimal laser damage. Although other variables also have an effect on the size of the HAZ (Heat Affected Zone), their effect is insignificant when compared to the beam spot size and the beam offset. For the previous pulsed cutting system, the laser beam has a fixed diameter of approximately 0.24 mm determined by the selected laser optics for laser delivery. Therefore, the beam offset becomes the only key variable that affects the resulting lace cutting edge quality. However, it is difficult to determine an appropriate value for the beam offset to ensure that each cut has minimal laser damage. If the cutting point is too far from the point where the thread intersects with the purl, a small portion of the thread will remain attached to the purl, which is called ‘leg’ in the lace industry. On the other hand, if the cutting point is too close to the intersection point, the purl itself will be possibly hit by the laser beam and laser damage (HAZ) generated. With the previous pulsed cutting system, it seems inevitable that some degree of laser damage will be generated during the lace cutting process.

In addition, the complexity of lace structure and the peculiarity of each lace thread require that the beam offset value be adaptable. Otherwise, either ‘legs’ or laser damage will be
generated. The previous pulsed cutting system uses a fixed beam offset value to cut all lace threads, leading to inconsistent lace cutting edge quality.
8.2 Lace Cutting Strategy

The handling tension applied on lace during the lace cutting process can be classified as longitudinal tension and lateral tension, both of which have been proven to be beneficial to the lace cutting edge quality in Chapter 3. The conclusion is then explained in Chapter 4 by observing the purl structure under the microscope. Under the tension, the loop thread which connects the connection threads to the purl can be observed with the aid of the microscope. Accurately applying a single pulse of laser energy on to the loop thread can severe the thread which is then pulled through the purl by the applied tension, so the connection threads connected with the loop thread can be cut off at the same time without causing any laser damage to the purl or leaving any thread ‘legs’ on the purl. As the loop thread is a tiny thread which usually shrinks and is covered by other threads or the purl when no tension is applied, applying tension correctly to expose the loop thread becomes the key to cutting lace with high level cutting quality.

After a series of cutting experiments carried out with the intermediate tensioning rig as detailed in Chapter 4, a lace cutting strategy has been proposed. A purl together with all its connection threads is treated as one independent entity. All connection threads are then categorized as primary threads or secondary threads according to their position relative to the top of the purl. As the cutting quality of the top section of a purl has determinant effect on the overall purl quality and the loop thread is usually located on the purl top, the threads connected to the top section of a purl are considered more important than those connected to the bottom section of the purl.

The secondary threads are cut first in order that the remaining primary threads can be better tensioned to expose the loop thread which connects with them. Not until the applied tension has been checked to ensure that the loop thread has been correctly tensioned and exposed will a single pulse of laser energy be applied on the loop thread to cut it and the threads connected to it. By repeating the process, the lace can be cut purl by purl until finished.

As the loop thread is pulled away from the purl, the purl will not be damaged if the laser energy is applied on the loop thread accurately. In most cases, all connection threads of a
purl are connected to the purl through the loop thread, which means that these connection threads can be cut off without causing any laser damage on the purl with the proposed lace cutting strategy. As to these few threads which are connected to the bottom section of a purl or knitted into the lace patter section directly, cutting them directly with the pulsed laser will not have significant effect on the overall lace edge quality because of their inferior position.

As most threads can be cut without causing any laser damage, the lace cutting strategy is surely able to help improve the lace cutting edge quality when compared to the previous pulsed laser cutting system, which has been fully proven by the lace edge assessment results presented in Chapter 7.
8.3 Machine Vision System

In order to implement the lace cutting strategy automatically, a machine vision system has been developed that is able to isolate each uncut purl, detect the cutting points of the isolated purl where threads intersect with the purl, classify these cutting points according to their position and provide feedback for the lace transport and tensioning rig to control the applied tension.

The system is based on the success of the previous pulsed laser cutting system. In order to clearly see the loop thread which is usually a very tiny thread, it is necessary to increase the imaging resolution to approximately 100 pixels/mm. Consequently, the field of view (FOV) reduces to about 12mm x 10mm and a typical lace image contains 4 to 5 purls. Based on the lace edge information, each purl together with its connection threads can be isolated and processed independently. With necessary modification, the lace edge directed thread targeting algorithm has been successfully adopted to detect the cutting points, which are then classified based on their distance to the bottom line of the purl. By monitoring the height change of the purl, the system is also able to provide feedback for the tensioning rig to control the tension applied on the purl.

The newly developed laser cutting system is not only able to accommodate lace distortions, but also more accurate to target individual threads and successfully realise the automation of the lace cutting strategy for lace cutting. The lace samples cut with the developed system have clearly shown edge quality improvement when compared to the previous laser cutting systems as described in Chapter 7.
8.4 Lace Transport and Tensioning Rig

The lace transport and tensioning rig is designed and manufactured to handle the lace during the cutting process. The advantage of this rig over the early lace handling rigs [80] is its ability to transport and tension lace continuously at the same time. With its roller structure and the method of tensioning the lace divergently, the rig is able to apply localised tension on the purl to be cut and its connection threads. With the feedback provided by the machine vision system, the rig can also control the tension to ensure that the purl is adequately tensioned. Integrated with the laser subsystem, lace positioning subsystem described in Chapter 6 and the developed machine vision system, the rig has been successfully manually operated to handle lace for the strategically pulsed laser cutting.

Due to time limit, the automation of the rig has not been fully achieved, but it has demonstrated the concept of continuously transporting and tensioning lace. With some further work as described in section 10.3, the full automation of the rig can be realised.
8.5 Lace Edge Quality Assessment

Three methods of lace edge quality assessment have been presented in Chapter 7. Although these methods are different in terms of principle and process, the conclusion drawn from each assessment method is the same, which states that mechanically cut and the strategically pulsed cut lace samples have the best edge quality while the edge quality of lace samples cut by the CW system is the lowest. Unfortunately, it is not possible at this stage to benchmark the proposed assessment techniques against any other methods because they simply do not exist.

The contact measurement method assesses lace edge quality by recording the resistance forces caused by sliding the lace edge against textile tight material. Based on this principle, the method is further divided into two sub-methods called (I) tube abrasion and (II) sheet abrasion. The lace edge quality can be distinguished by analysing the test data obtained during the experiments. These methods are considered more reliable, objective and time-effective than the other two assessment methods applied previously, that is, the user trial and the microscopic method. Assessing lace edge quality via the user trial and the microscopic methods takes long time, making them not feasible for online lace edge quality assessment. However, the contact measurement method has the potential for assessing lace edge quality in real time, especially when it is combined with a machine vision system as described in section 10.4.

According to the conclusion of each lace edge quality assessment, mechanically cut lace samples have the best edge quality. However, the mechanical cutting process has limitations as outlined in [31] in terms of speed and labour requirements, both of which produce a bottleneck of whole lace manufacturing process. The mechanical lace cutting process is slow and fairly inaccurate requiring constant operator attention. Although there is no thermal damage caused to the lace being cut, the cutting inaccuracy always leaves the cut lace hairy or miscut. The mechanical lace cutting system also suffers from the inability to deal with closely interlocked lace patterns, known as centre cutting. These must be cut by hand using scissors, resulting in corresponding throughput and cost disadvantages.
The previously developed lace cutting systems based on the combination of machine vision and laser cutting technologies fail to cut lace with high level cutting edge quality. However, the newly developed strategically pulsed cutting system is able to cut lace with resulting edge quality virtually the same as that of the mechanical cut lace, which makes it possible to replace the mechanical cutting system to achieve the full automation of the lace cutting operation given some more future work carried out as presented in Chapter 10.
9 Conclusion

Compared to the early Loughborough CW cutting system, the previous pulsed cutting system is able to cut lace with improved edge quality. However, the improvement in the cutting edge quality is not enough and laser damage is still present in the cut lace.

In this project, based on the investigation of the effect of the handling tension on the lace cutting edge quality and the observation on lace behaviour during the lace cutting process, a lace cutting strategy has been formulated, which is aimed at improving the lace cutting edge quality by exposing and accurately cutting the loop thread with the pulsed laser beam.

A machine vision system has been developed to automatically implement the lace cutting strategy. Imaging the lace at a resolution of 100 pixels/mm, the machine vision system is able to automatically detect and classify individual cutting points. By monitoring the shape change of the purl to be cut, the system is also able to provide feedback for controlling the tension applied on the lace to ensure that the loop thread is adequately tensioned and exposed.

To transport and tension lace continuously for lace cutting, a lace transport and tensioning rig has been designed and manufactured. By tensioning the lace divergently and progressively, the rig is capable of applying and controlling the tension on each individual thread to be cut.

To test the concept of strategic lace cutting, an integrated lace cutting system has been developed based on the previous pulsed laser cutting system. The system is capable of automatically detecting and classifying the cutting points where connection threads intersect with the purl. Although the alignment process of the cutting point and the fixed laser spot has not been automated, it can be fully achieved by upgrading the laser delivery system as described in section 10.2.

With reference to the friction forces established by the contact measurement assessment method as described in Chapter 7, the strategically pulsed cut lace is almost the same
(within 2.5% and 10% respectively for the tube and the sheet abrasion method) as mechanically cut lace. Subjective user trial data also supports this observing improvement in cut lace edge quality. In addition, user trial subjects reported that the lace edge cut by the strategically pulsed method is considered cleaner and less hairy than the mechanically cut lace.
10 Future Work

On the basis of the previous pulsed laser cutting system [2], the work presented in this thesis has proven that strategically pulsed laser cutting can produce lace edge quality equal to or better than the existing mechanically cut lace edge quality. Together with the lace transport and tensioning rig, the manually operated cutting system described in Chapter 6 is able to apply appropriate tension on the lace with a closed-loop control, detect and classify individual cutting points and then deliver the pulsed laser energy to the thread to be cut.

Future work is necessary before the system can be commercialised for industrial lace cutting operation. The future work can be carried out on the following aspects.

- Machine vision system performance improvement
- Laser energy delivery
- Lace transport and tensioning rig control
- On-line lace edge quality assessment system
10.1 Machine Vision System Performance Improvement

The developed machine vision system described in Chapter 5 is able to automatically capture lace images, detect and classify individual cutting points based on these images, provide the coordinates of the cutting point to the laser delivery subsystem and provide feedback for the closed loop tension control. Although the system has been successful to implement the lace cutting strategy for lace cutting edge quality improvement, it is not suitable for real time lace cutting operation conducted at the speeds up to 1 m/s. The system speed can be improved by investigating the following areas.

1. Faster camera
To successfully transport and cut lace at the speeds up to 1 m/s, the prerequisite is to find a camera that is able to capture images at a correspondingly high speed. Due to the lace distortion after each cutting, one new frame of image is required for accurately targeting and cutting each individual thread. Given that a lace sample of 1 m long has approximately 450 purls and every purl has on average two connection threads, the suitable camera needs to capture images at a frame rate of \(450 \times 2 = 900\) frames/s.

As the lace passes through under the camera, it is necessary to ensure that the purl to be cut is well within the field of view (FOV) of the camera. There are two possible ways to achieve this. The first method is moving the camera along the lace edge to image the purl of interest. In this way, the field of view can be kept relatively small and the captured image may only contain the purl to be cut. The advantages of the method are that a low cost camera (a camera with 1M pixels costs no more than £1,000) would be good enough and by excluding irrelevant information from the purl image, the image processing execution would be much faster. However, moving the camera would cause vibration, noise and possibly image blurring, which must be solved before the method can be adopted. The other method is using a fixed camera whose resolution is so high that it is able to accommodate all purls passing under it. This method is much simpler, but the requirement of the camera is strict. For some demanding lace pattern designs, the height variation of the lace edge contour can be up to 20 mm. At an imaging resolution of 100 pixels/mm, this would require that the camera should have more than 4M (20x20x100x100=4M) pixels. In addition, as more information is included in the captured
image, the image processing algorithms would be more complex and consequently requires more time.

In the current commercial camera market, it is not difficult to find a camera that is able to meet the above requirements. For example, the Phantom HD camera has a resolution of 2048x1152 pixels and can be operated at a frame rate of 1000 fps [102]. For less demanding lace patterns which requires smaller FOV, there are more options to select an appropriate camera, such as the HotShot 1280 (1280x1024pixels, 20,000fps) provided by NAC Image Technology [103] and the MotionProX-3 (1280x1024 pixels, 1040 fps) developed by RedLake [104]. At present, these high speed cameras are expensive (approximately £20,000) but the cost is expected to be gradually reduced as the camera technology advances in near future.

The combination of high speed and high resolution of the line scan camera makes it a possible alternative to the high speed area scan camera. But it is more complex to control a line scan camera and the developed image processing algorithms need to be modified accordingly. Similarly, the cost of a line scan camera is very high as well.

2. High speed processing platform
Replacing the PC with a Digital Signal Processor (DSP) to improve the machine vision system speed is well established. Since DSP has high performance, decreasing prices, and reasonable power consumption, it has been employed in many computational-intensive applications, especially for digital signal processing. By devoting all their power to signal processing, DSPs are much faster than standard PCs. The combination of a camera with DSPs for developing machine vision can be found in many applications, such as for lace cutting [6] and for traffic surveillance [105]. Besides DSPs, FPGA (Field Programmable Gate Array) devices can also be used to build compact, flexible and high speed machine vision systems. In the current FPGA market, Xilinx and Altera have become the major leaders in developing a wide range of FPGAs. A real time web inspection system based on FPGA has been reported in [106].
10.2 Laser Beam Positioning

Moving lace with the lace positioning subsystem to align the cutting point with the fixed laser spot causes a long delay (typically 2-3 seconds, as described in Chapter 6) for the lace cutting operation. The lace needs to be stationary when the pulsed laser energy is delivered to the targeted thread. This has become a problem that must be solved before the developed system can be upgraded to be running at a high speed.

With lace passing through at speeds up to 1m/s, positioning the pulsed laser beam to each individual cutting point with a high accuracy (ideally approximately 0.01 mm at imaging resolution of 100 pixels/mm) requires a positioning system with quick response and a high repeatability. As the field of view of the camera needs to be 20 mm x 20 mm to accommodate all purls as described in section 10.1, the laser beam positioning system has to cover an area of at least 20 mm x 20 mm.

The development of modern laser scanning systems has provided many options for building a laser positioning system with good repeatability and high accuracy. Galvanometer scanners have been widely used for deflecting lasers to a specific position for their quick response. For example, the dynAXIS® galvanometer scanners from SCANLAB has a step response time of less than 0.25 ms and repeatability of 5 μrad [107]. There are also some fully integrated laser scanning head modules which can be easily incorporated to develop a high speed laser positioning system in a short time, such as the HB® X10 Series manufactured by GSI Lumonics. Being able to cover an area of 70 x 70 mm with a repeatability of 10 μm, the 2 axis scanning head is capable of positioning the laser accurately for lace cutting, with the spot size focused within 0.20 mm [108].
10.3 Lace Transport and Tensioning Rig Control

The developed lace transport and tensioning rig has demonstrated its potential for high speed lace transportation and tensioning. In order to fulfil its potential, more future work is required, which can be carried out on the following aspects.

Each motor to drive the transportation rollers needs to be controlled separately. Speed control is considered critical to controlling the applied tension and therefore should be controlled precisely with a closed loop method. The research challenge here is how to reach and maintain a state of balance where relatively little speed adjustment is required and the lace can be tensioned adequately as it is transported.

Compared to the longitudinal tension applied and passively controlled by running the drive rollers faster than the source rollers as described in section 6.2.2, the combination tension applied on the waste mesh is more important for adequately tensioning the lace purls and therefore should be controlled with more care. A double camera system has been considered appropriate for controlling both the magnitude and the direction of the combination tension. The first camera would be a high resolution used to check the status of the purl being tensioned and provide the feedback of whether the applied tension is enough. The other camera, on the other hand, would be low resolution and able to cover a larger lace area. The purpose of this low resolution camera is to provide information for controlling the direction of the waste mesh tension. According to the previous observations, the most effective way to tension a purl is to apply the tension along its axis. With the information of the purl orientation obtained from the image captured by the high resolution camera, the low resolution camera would then be able to monitor and control the angle between the waste mesh and the lace pattern section so that the purl can be adequately tensioned in the shortest time, as shown in Figure 10-1.

For high speed tensioning, it would be appropriate to replace the lead screw mechanism (as described in section 6.2.2), which is used to change the direction of the waste mesh tension, with another type of high speed actuation device, such as a piezo positioning stage. Driven by piezoceramic linear servo motors, the linear translation stage provide by
PI is able to travel with speeds up to 800mm/s [109] and could be selected for this purpose.

Figure 10-1 Double camera system for tension control
10.4 Online Lace Edge Quality Assessment System

The sheet abrasion method used to assess the lace cutting edge quality, described in section 7.2, can be further developed to build an online lace cutting edge quality assessment system.

The lace should be transported continuously when its edge quality is being assessed and therefore using the Hounsfield testing machine becomes unsuitable. Instead of sliding the lace across the hosiery to record the friction forces for assessing the edge quality, it would be more appropriate to use a force sensor to actively contact each purl and then collect the generated signals for further analysis. The selected sensor should be a small size so that it can fully touch every single purl, as well as having high sensitivity to differentiate the friction forces, which are usually less than 1 Newton. A piezo film sensor can be selected for this purpose. Since the discovery of the piezoelectricity phenomenon that quartz changes its dimensions when subjected to an electric field, and conversely generates electricity when mechanically deformed more than 100 years ago, the research of applying the technology has continued and a number of materials having piezoelectric effect have been identified or developed. Piezo film is among these piezoelectric materials and is a flexible, lightweight, tough engineering plastic available in a variety of thickness and areas. Piezo film sensors are able to convert mechanical strains into electrical signals with a conversion rate of approximately 14.4 V/N [110]. As each purl runs over the piezo film sensor, the friction force between the sensor and the purl will deform the film, which consequently generates the proportional voltage signals. With an appropriate amplification circuit, the voltage signals can be further amplified and used for assessing the lace edge quality.

As the lace edge has a curved contour, the piezo film sensor should be moved to follow the lace edge to actively touch individual purls. This can be achieved by combining a machine vision system with a gantry positioning system. The machine vision system is used to capture the lace images to extract the lace edge information, which is then fed to the piezo film sensor positioning system. Since it is similar to the lace positioning subsystem, this system would be easy to build.
The online lace edge quality assessment can be further integrated with the developed laser cutting system. After the lace has been cut and then transported out of the cutting zone, it can be directly transported and handled for online edge quality assessment. The lace edge quality assessment system could also provide valuable feedback for the lace cutting system. Once minor (non-defective) variations in lace edge quality is detected, the cutting system will make corresponding adjustment, for example increasing the handling tension for each purl. In this way, the edge quality of the produced lace can be ensured to be high-level and lace waste can be minimised.
11 References


References


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   [http://www.scanlab.de/frontend/media/produkte/dynAXIS_EN.pdf](http://www.scanlab.de/frontend/media/produkte/dynAXIS_EN.pdf)


   [www.msiusa.com](http://www.msiusa.com).
   Access date: July 23, 2006
12 Appendices
12.1 Original Test Data and Analysis Result of Lace Elastic Property Investigation

12.1.1 Lateral direction

<table>
<thead>
<tr>
<th>Linear Density</th>
<th>Max Force</th>
<th>Elong at Max</th>
<th>Break</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tex 1.000</td>
<td>193.6</td>
<td>52.5</td>
<td>19.80</td>
<td>59.1</td>
</tr>
</tbody>
</table>

![Graph showing Force vs. Extension mm]

![Graph showing Extension Rate vs. Tension]

\[ Y = (8.67E-06)X^3 - (2.48E-03)X^2 + 0.238X - 7.59 \]

Where:

- **Y**: tension, N/mm
- **X**: extension rate

Lace type I (150mmX150mm)
Y = (2.67E-06)X^3 - (7.70E-04)X^2 + (8.20E-02)X - 2.99

Where:
Y - tension, N/mm
X - extension rate
Lace type II (150mmX75mm)
Vision Guided Cutting and Mechanical Handling of Lace Ribbon

<table>
<thead>
<tr>
<th>Linear Density</th>
<th>Max Force</th>
<th>Elongation at Max</th>
<th>Break</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tex 1.000</td>
<td>N 151.2</td>
<td>% 140.5</td>
<td>N 75.6</td>
<td>% 156.7</td>
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</table>

![Graph](image)

Tension Vs Extension Rate

\[ Y = (3.11E-07)X^3 - (9.62E-05)X^2 + (1.06E-02)X - 0.408 \]

Where:

- Y-tension, N/mm
- X-extension rate

Lace type III (150mmX75mm)
12.1.2 Longitudinal direction

<table>
<thead>
<tr>
<th>Linear Density Tex</th>
<th>Max Force N</th>
<th>Elong at Max %</th>
<th>Break N</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>514</td>
<td>114.0</td>
<td>115.5</td>
<td>176.0</td>
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</tbody>
</table>

Tension Vs Extension Rate

\[ Y = (3.15E-06)X^3 - (1.04E-03)X^2 + (1.14E-01)X - 4.2 \]

Where:

- Y-tension, N/mm
- X-extension rate
- Lace type I (180mmX110mm)
**Vision Guided Cutting and Mechanical Handling of Lace Ribbon**

### Linear Density

<table>
<thead>
<tr>
<th>Linear Density</th>
<th>Max Force</th>
<th>Elong at Max</th>
<th>Break</th>
<th>Elongation</th>
</tr>
</thead>
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<td>228.0</td>
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</table>

### Tension Vs Extension Rate

\[ Y = (1.11E-06)X^3 - (5.05E-04)X^2 + (6.94E-02)X - 3.15 \]

Where:
- **Y** = tension, N/mm
- **X** = extension rate
- **Lace type II** (90mmX100mm)

260
**Linear Density**

<table>
<thead>
<tr>
<th>Tex</th>
<th>Max Force</th>
<th>Elong at Max</th>
<th>Break</th>
<th>Elongation</th>
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</thead>
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<td>1.000</td>
<td>185.8</td>
<td>185.0</td>
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<td>195.0</td>
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</tbody>
</table>

\[ Y = (2.22E^{-06})X^3 - (7.37E^{-05})X^2 + (1.03E^{-02})X - 0.494 \]

Where:
- \( Y \)-tension, N/mm
- \( X \)-extension rate
- Lace sample III (90mm×100mm)
### 12.2 Experiment Results of Longitudinal Tension Effect on Lace Cutting Edge Quality

<table>
<thead>
<tr>
<th>Extension (mm)</th>
<th>Actual tension (N)</th>
<th>Good</th>
<th>Neutral</th>
<th>Bad</th>
<th>Total</th>
<th>Percent of good (%)</th>
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</thead>
<tbody>
<tr>
<td>Low-tension</td>
<td>0</td>
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<td>21</td>
<td>18</td>
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<tr>
<td>Medium-tension</td>
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<td>25</td>
<td>12</td>
<td>60</td>
<td>38</td>
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<tr>
<td>High-tension</td>
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<td>25</td>
<td>23</td>
<td>12</td>
<td>60</td>
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![Graph showing experiment results](image-url)

Lace type I
<table>
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<tr>
<th>Tension</th>
<th>Extension (mm)</th>
<th>Actual tension (N)</th>
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<th>Neutral</th>
<th>Bad</th>
<th>Total</th>
<th>Percent of good (%)</th>
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<tbody>
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<td>7</td>
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<td>25</td>
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<td>3</td>
<td>9</td>
<td>13</td>
<td>6</td>
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<tr>
<td>High-tension</td>
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<td>5</td>
<td>12</td>
<td>12</td>
<td>4</td>
<td>28</td>
<td>43</td>
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</table>

Lace type II
<table>
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<th>Extension (mm)</th>
<th>Actual tension (N)</th>
<th>Good</th>
<th>Neutral</th>
<th>Bad</th>
<th>Total</th>
<th>Percent of good (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-tension</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>15</td>
<td>14</td>
<td>40</td>
<td>28</td>
</tr>
<tr>
<td>Medium-tension</td>
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<td>2</td>
<td>15</td>
<td>13</td>
<td>12</td>
<td>40</td>
<td>38</td>
</tr>
<tr>
<td>High-tension</td>
<td>40</td>
<td>4</td>
<td>21</td>
<td>9</td>
<td>10</td>
<td>40</td>
<td>53</td>
</tr>
</tbody>
</table>

Lace type III
12.3 Lace edge detection images (originally 1280x1024)

Original image captured by the camera (A) → Dual-thresholded binary image (B) → Image with threads removed (C) → Edge detection (D) → Lace edge image (E)
Median and low-pass filter (C)

Sobel edge detection (D)
Lace edge selection (E)

Lace image with the detected edge
12.4 Cutting Point Detection Images

Original image captured by the camera (A) → Image with threads removed (B) → Lace edge image (C)

Single thresholded binary image (D) → Image generated by subtracting B from D (E) → C and E to generate cross threads (F) → Cutting points (G)
Lace edge image (C)

Single threaded image (D)
Cutting points (G)
12.5 Strategically cutting experiment images

(● indicates the cutting point)
Purl 2
Purl 3
Purl 4

The remaining thread is pulled away by the applied tension
Purl 5
12.6 Lace Cutting Edge Quality Example Images

Good quality purls
Bad quality purls
Neutral quality purls
12.7 Intermediate Tensioning Rig

ISO view

Top view
12.8 Lace Transport and Tensioning Rig

Overall view

Drive roller
Lead screw mechanism
### 12.9 Purl Height Elongation Rate Determination (lace pattern 2)

<table>
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<th>Purl No.</th>
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<th>Final height</th>
<th>Purl elongation rate</th>
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<td></td>
<td>Pixels</td>
<td>mm</td>
<td>Pixels</td>
</tr>
<tr>
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</tr>
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<td>3</td>
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<td>1.4</td>
<td>162</td>
</tr>
<tr>
<td>4</td>
<td>211</td>
<td>2.11</td>
<td>249</td>
</tr>
<tr>
<td>5</td>
<td>209</td>
<td>2.09</td>
<td>252</td>
</tr>
<tr>
<td>6</td>
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<td>7</td>
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<td>248</td>
</tr>
<tr>
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<tr>
<td>12</td>
<td>190</td>
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<td>233</td>
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<tr>
<td>13</td>
<td>211</td>
<td>2.11</td>
<td>N/A</td>
</tr>
<tr>
<td>14</td>
<td>215</td>
<td>2.15</td>
<td>241</td>
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<tr>
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<td>217</td>
<td>2.17</td>
<td>253</td>
</tr>
<tr>
<td>16</td>
<td>209</td>
<td>2.09</td>
<td>250</td>
</tr>
</tbody>
</table>
12.10 Lace Edge Quality Assessment Results (lace pattern 2)

12.10.1 Tube abrasion method

Highlighted comparison between mechanically and strategically pulsed cut lace
Vision Guided Cutting and Mechanical Handling of Lace Ribbon

Data difference between test data and the trend line

Highlighted data difference of Mechanically and Strategically pulsed cut
<table>
<thead>
<tr>
<th>Lace sample</th>
<th>Average force (N)</th>
<th>Standard deviation (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW cut</td>
<td>0.52</td>
<td>0.25</td>
</tr>
<tr>
<td>Pulsed cut</td>
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<td>0.010</td>
</tr>
<tr>
<td>Strategically pulsed cut</td>
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<td>0.006</td>
</tr>
<tr>
<td>Mechanically cut</td>
<td>0.40</td>
<td>0.004</td>
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</table>

Test results summary of tube abrasion method
12.10.2 Sheet abrasion method

Highlighted comparison between mechanically and strategically cut lace
Data difference between test data and trend lines

Highlighted data difference of mechanically and strategically pulsed cut lace
<table>
<thead>
<tr>
<th>Lace sample</th>
<th>Average force (N)</th>
<th>Standard deviation (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW cut</td>
<td>0.39</td>
<td>0.115</td>
</tr>
<tr>
<td>Pulsed cut</td>
<td>0.17</td>
<td>0.015</td>
</tr>
<tr>
<td>Strategically pulsed cut</td>
<td>0.11</td>
<td>0.006</td>
</tr>
<tr>
<td>Mechanically cut</td>
<td>0.10</td>
<td>0.005</td>
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</table>

Summary of the sheet abrasion method
12.11 Publication
Lace edge quality assessment

Y He*, P Bamforth, M R Jackson, and A Rowe
Mechatronics Research Centre, Loughborough University, Leicestershire, UK

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Abstract: Lace is a high-value decorative fabric manufactured with the aid of computer aided design (CAD) and computer numerically controlled (CNC) looms. It typically has very complex patterns and is flexible and easy to distort, which makes the task of lace cutting and lace edge quality assessment difficult. Lace is normally cut by a mechanical system, which is slow and therefore expensive. Research work in the area of lace cutting with lasers is in rapid progress and some cutting systems have been successfully developed. Lace edge quality assessment research, however, has largely been overlooked. The lack of edge quality assessment methods makes it impossible to compare and contrast the edge quality of the lace samples cut with different methods and consequently to improve the edge quality. In this paper, three lace edge quality assessment methods and their implementations will be described.

Keywords: lace edge quality, lace cutting, edge quality assessment, CW laser, mechanical cutting, pulsed laser

1 INTRODUCTION

Lace is a high-value fabric for decoration purposes, which is mass produced in webs (typically 3 m wide by 100 m long) and then cut into individual strips. Lace comprises fine and complex patterns, which are designed using computer aided design (CAD) facilities. On most designs the pattern repeats many times, but in practice the repeats are never perfectly identical. Currently almost all lace is cut either by hand with scissors or using a mechanical cutting system. The mechanical system utilizes the difference in thickness between the lace pattern and the waste mesh to guide a rotating knife, which requires human supervision to avoid problems such as snagging and tearing. Both current methods of scalloping lace are very time consuming, laborious, and therefore expensive.

Significant efforts have been made to apply modern technology, especially machine vision technology, in automating lace cutting processes, aiming at improving the cutting speed at a reasonable cost. As early as 1988, Russell and Wong [1, 2] used a modified DRAM chip as the camera to capture the images of lace, which were then compared to a reference map to determine the cutting path. This method failed due to distortion of the lace, which made the system unreliable and degraded the system performance. This distortion problem was addressed by Shih et al. [3-5] by eliminating the need of a prior knowledge of lace. Several commercial organizations also made good progress in developing machine vision systems for lace scalloping [6, 7].

Since 1991, extensive research in the lace cutting area was started at Loughborough University and major successes have been achieved [8, 9]. A line-scan camera together with back-lit illumination formed the basis of the machine vision system. A specially developed weighted cross-correlation algorithm [10] is utilized for tracking the paths based on a reference map. A 240 W continuous wave (CW) CO2 laser is then directed to the cutting path to cut off the waste mesh with a web feed speed of 1 m/s and a cutting speed up to 10 m/s, which is the fastest lace cutting system so far. Another lace cutting system which is able to achieve better cutting quality was built by Bamforth and Jackson [11, 12]. By directing the pulsed laser to each cutting point, the heat-affected zone (HAZ) can be greatly reduced, which ensures a better cutting result. A repetition rate of
10 kHz is possible with this vision directed pulsed laser energy technique. This can provide a lace processing speed of 1 m/s. On the actual test facility, the processing speed is much slower (1 pulse/5 s) due to the X, Y movable stage speed limitation.

Almost all lace inspection systems are based on direct comparison between the captured images and a perfect prototype since no global image processing or rule-based techniques can be easily applied to inspect the lace, which has flexible characteristics and complex patterns [13-19].

Compared with extensive research activities in the lace cutting and lace pattern inspection areas, the research work concerning the lace edge quality and its assessment may be considered negligible. One exception is given in reference [20], where a three-dimensional transient finite difference model has been developed to investigate the deficiencies of the CW process and optimize the pulsed process to improve the lace cutting edge quality. There is no established method of lace edge quality assessment or international standards existing for characterization of the lace cut edge quality. The research has studied current industrial practice, which has identified two methods of assessment used by some lace manufacturing industries. Method 1 involves panels of humans assessing the lace tactile quality and visual appearance. This can only be based on subjective assessment and is not a reliable method. Method 2 is the Martindale tester, shown in Fig. 1, which is usually used for testing the abrasion and pilling resistance of all kinds of textile fabrics, and therefore it can also be used for determining the lace cut edge quality. By rolling the lace into a cylinder which is then rubbed against a standard abradant at low pressures and in continuously changing directions, the quality of the lace is determined either by the number of cycles until breakdown of the lace edge or by the mass reduction of the test subject [21]. However, this method is not the most suitable for lace edge quality assessment because the lace edge defect formed during lace cutting operations is very subtle and therefore the difference can be too insignificant to be assessed by the tester.

One objective of the lace cutting research is to produce a high-quality lace product for demanding markets, which requires identifying and optimizing the factors affecting the lace cut quality. This identification and optimization work necessitates direct comparisons between the lace samples produced by different cutting systems or with different cutting parameters. From this point of view, establishing a lace edge quality assessment method has become the prerequisite for improving the lace cut quality. In this paper, several lace edge quality assessment methods will be introduced and described in detail.

2 LACE EDGE STRUCTURE AND EDGE DEFECT FORMATION

Lace edges are made up of a series of purls that are each connected to the light waste mesh by a single strand or series of connecting strands, as shown in Fig. 2. In most lace cutting systems based on the machine vision technology, a laser is used for cutting the connecting threads by vaporization. Compared with the conventional mechanical cutting tools, such as a rotating knife, using a laser for lace cutting can eliminate the distortion and undesirable tension caused by contact between the mechanical tools and the lace itself. However, if the purls are overexposed to the heat energy from the laser beam, then the individual strands of nylon that make up the lace pattern will be melted. Once the melting occurs, small bubbles of trapped air form at the end of the severed strand, as shown in Fig. 3. These bubbles of trapped air and solid nylon are what cause irritation to the skin and therefore lower the quality of the lace edge. The lace edge quality is determined by the severity and the number of defects caused during the cutting process.

3 CONTACT MEASUREMENT METHOD

The irritation to the skin caused by poor edge quality lace can be attributed to the snagging of the
heat-affected areas on the contours of the skin. It is also noted that a lace sample with a defective edge will snag on fine nylon material such as that used in ladies’ tights and undergarments. If the lace is not heat affected and therefore of suitable quality, it would be of sufficient compliance and flexibility to mould to the contours of the skin or the tight material. The Martindale tester uses a foam pad to simulate the human skin or the tight material and the quality is distinguished by the condition of the pad after abrasive testing. Instead of using a foam pad, hosiery (tight material) is employed in the following tests, which can generate some noticeable resistance when a lace sample with a defective edge slides over the hosiery material surface. Recording this resistance between the hosiery and lace edge can be used to assess the edge quality of the lace sample being tested. Two methods, called tube abrasion and sheet abrasion, have been identified based on the principle mentioned above.

3.1 Tube abrasion method
When the lace sample is rolled into a cylinder, the resistance between the lace edge and the hosiery can become significant as this increases the number of defects acting on the tight material at any one time. Although not all purls are in contact with the hosiery due to the curved edge profile, recording this force will offer a suitable measurement as to the edge quality of the entire sample.

3.1.1 Test rig design and operation
The test rig consists of two tube sections, one of 35 mm internal diameter and one of 30 mm. As shown in Fig. 4, the section of the 30 mm tube is attached to the 35 mm tube at a right angle, which is used to house the rolled lace sample.

Another section of tube, 30 mm in diameter, is cut in half longitudinally to create a semicircular section to run inside the large 35 mm section. The semicircular tube is then covered by hosiery to act as a skin simulator, which moves in an orthogonal direction to the lace edge at a constant speed within the larger tube, as shown in Fig. 4. The lace sample is moved to a position where it just touches the surface of the hosiery, then advanced a further 1 mm, and locked in position by a clamp to ensure that there is always a fixed displacement contact between the lace edge and the hosiery. The estimated contact force between the lace edge and the tight material is 0.5 N. Lower edge quality lace will snag on the hosiery, causing higher frictional forces between the lace edge and the hosiery, which consequently causes a noticeable increase in the amount of force required to move the skin simulator.

The skin simulator is attached to the load cell of a Hounsfield tensile testing machine and then any force change due to the snagging can be recorded. The force data can then be transferred to the PC for further analysis, as shown in Fig. 5.
Fig. 6 Lace patterns: top, standard; middle, checked; bottom, floral

Table 1 Cutting parameters of each cutting system

<table>
<thead>
<tr>
<th>Cutting method</th>
<th>Laser power</th>
<th>Cutting speed</th>
<th>Laser spot size</th>
<th>Laser pulse duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>N/A</td>
<td>0.1 m/s</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>CW laser</td>
<td>240 W</td>
<td>1 m/s</td>
<td>0.2 mm</td>
<td>Continuous</td>
</tr>
<tr>
<td>Pulsed laser</td>
<td>240 W</td>
<td>0*</td>
<td>0.2 mm</td>
<td>0.1 ms</td>
</tr>
</tbody>
</table>

* The lace thread is stationary when laser energy is applied.

3.1.2 Test samples

Three types of lace sample with different patterns are selected for the test, as shown in Fig. 6. For each type of lace, three nominally identical samples are cut by different cutting systems: mechanical, CW laser (cut with the system described in references [8] to [10]), and pulsed laser (cut with the cutting system described in reference [11]) respectively. During the pulsed laser cutting, the laser beam is fixed and the lace is moved with an X-Y movable stage and then stopped after the thread to be cut has been aligned accurately with the laser spot. The lace remains stationary when a single pulse of laser energy is delivered to cut the thread. The cutting parameters of these lace cutting systems are listed in Table 1. By comparing the edge quality of these lace samples, the relative cut edge quality of each cutting method can be determined.

3.1.3 Test result

The tube abrasion test is repeated 20 times for each lace sample. The test data for the lace samples with standard patterns are shown in Fig. 7, which shows a significant difference in the forces required for the mechanically cut, CW cut, and pulsed laser cut lace samples. It is found that more force is recorded for the CW sample than for the other two samples.

Trend lines are then identified for each set of test data, and by subtracting the trend line from each corresponding set of test data, the data difference can be obtained as shown in Fig. 8. In order to highlight the force difference among the lace samples, the standard deviation and average value of each set of test data have been calculated, as shown in Table 2. The average value is obtained from the test data in Fig. 7, while the standard deviation is calculated with the data shown in Fig. 8.

From Table 2, it can be concluded that the mechanically cut samples have the best edge quality as the required average force is the least and the edge quality of the CW cut sample is the lowest, with an average force of 0.51 N. It is also noticed that the standard deviation of the test data of the mechanically cut sample is the smallest, which indicates that its edge quality is more consistent than the other two samples, with the CW cut sample having the most inconsistent edge quality.

3.2 The sheet abrasion method

Instead of being rolled into a cylinder, the lace sample can also be placed between two sheets of Perspex, through which the defects caused by the laser cutting can be examined in greater detail.

3.2.1 Test rig design and operation

The Perspex sheets are purposefully manufactured for each individual lace sample to keep the main body of the lace in place, but to allow the purls to be exposed for testing. The rig operates in a similar way as in the tube abrasion test. The lace sample is secured in the Perspex plates and is then positioned so that the lace edge is in contact with the hosiery acting as the skin simulator. The lace sample is then pulled across the hosiery and the frictional forces between the lace edge and the skin simulator are recorded. This test rig allows for much more localized measurements as the sample of the lace edge under examination is significantly less (0.15 m, Figs 9 and 10) when compared with the previous test rig in section 3.1, where the rolled-up length of the lace sample is 1 m.

3.2.2 Experimental result

As expected, the experiment results shown in Fig. 11 are similar to those in Fig. 7. The CW cut lace sample produces the most significant frictional...
Lace edge quality assessment

Comparison of Mechanically cut, CW and Pulsed cut, Standard Pattern

Fig. 7 Test data of the lace samples with the standard pattern

Fig. 8 Difference between the test data and trend lines

Fig. 9 Test rig for the sheet abrasion method

Table 2 Average value and standard deviation ($\sigma$) after subtraction of the control value

<table>
<thead>
<tr>
<th>Lace sample</th>
<th>Average force (N)</th>
<th>Standard deviation ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW cut</td>
<td>0.51</td>
<td>0.033</td>
</tr>
<tr>
<td>Pulsed cut</td>
<td>0.44</td>
<td>0.019</td>
</tr>
<tr>
<td>Mechanically cut</td>
<td>0.39</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Fig. 10 Test rig set-up
force, indicating that it has the lowest edge quality, which is consistent with the conclusion of the previous test.

A similar data processing method as used in the tube abrasion test is adopted where trend lines for each data set are identified and then subtracted from each corresponding set of test data to obtain the data difference shown in Fig. 12, from which the standard deviation of the test data can be calculated. Table 3 shows the standard deviation and average value for each set of test data.

From Figs 11 and 12 and Table 3, it may be concluded that the CW sample has the lowest and most inconsistent edge quality while the mechanically cut sample is the best in terms of both aspects. When comparing Table 3 and Table 2, it is found that the average values of the forces produced in the tube abrasion test are much higher than in the sheet abrasion test, which can be explained by the fact that more lace purls are in contact with the skin simulator in the tube abrasion test, causing a higher friction force. It is also noticed that the standard deviation of each set of data (especially the CW sample) obtained with the sheet abrasion method is bigger because this method can examine the lace purls on a more local scale, highlighting the quality variations among purls.

Both test methods are repeated for other lace samples with different patterns and all results show that the mechanically cut lace samples have a better edge quality over the other two types of sample, among which the CW cut lace samples have the lowest quality and the cut quality is inconsistent, as indicated by the standard deviation value.
Lace edge quality assessment

![Standard design](image1.png) ![Checked design](image2.png)

Fig. 13 Lace designs for the trial

Table 4 Edge quality trial sample numbering

<table>
<thead>
<tr>
<th>Set number</th>
<th>Design type</th>
<th>Sample number</th>
<th>Cutting method</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Checked</td>
<td>1</td>
<td>Pulsed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Mechanical</td>
</tr>
<tr>
<td>B</td>
<td>Checked</td>
<td>1</td>
<td>Pulsed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Mechanical</td>
</tr>
<tr>
<td>C</td>
<td>Standard</td>
<td>1</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Mechanical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Pulsed</td>
</tr>
<tr>
<td>D</td>
<td>Standard</td>
<td>1</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Mechanical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Pulsed</td>
</tr>
</tbody>
</table>

4 USER TRIAL METHOD

In addition to the quantitative methods described above, a lace edge quality assessment trial based on a user trial method was also carried out, aiming to assess the edge quality of lace samples scalloped with different methods. The trial involved asking a number of volunteers to rate the softness of the lace edges and then assessing the lace edge quality according to the scores given by the volunteers. The higher the score a lace sample gets, the better the edge quality of the lace sample.

4.1 Test set-up

A number of volunteers (20) were asked to rate the edge quality of lace samples produced by mechanical and laser cutting. Two designs of lace were selected, which formed four sets of samples. Sample sets A and B were for the standard design and sets C and D were for the checked design, as shown in Fig. 13. Each set of samples consists of one mechanically cut sample, one CW laser cut sample, and one pulsed laser cut sample. The laser cutting parameters for both the CW cut and pulsed cut are the same as previous ones used for contact measurement tests, i.e. the 240 W CO₂ laser with 0.2 mm spot size and 0.1 ms pulse duration for the pulsed cut. The samples within each set were randomly numbered as shown in Table 4. The scores given to each lace sample ranged from 0 to 5, where 0 means the quality is very bad and 5 means very good.

4.2 Test results

The scores for each lace sample from all 20 volunteers were summed together and an overall score and an average score were obtained. A summary of the scores for each lace sample is shown in Table 5.

The results clearly showed that the mechanically cut sample was the softest, with average scores of 4.00 and 3.38 for the standard design and checked design respectively. The CW laser cut lace with scores of 1.95 and 1.59 for the standard design and checked design respectively was the least soft of the samples. With scores of 3.20 and 3.05, which are close to the score of the mechanically cut sample, the 0.1 ms pulsed laser cut sample was perceived to be much softer than the CW sample. As the standard deviations of all assessments are around 1, the assessment results were considered consistent. The samples of the checked design were rated slightly more consistently than the samples of standard design. The results are shown graphically in Fig. 14.

From the results shown in Fig. 14, it is clear that the mechanically cut lace is the softest, which indicates that it has the best edge quality. This is consistent with the test results obtained from the previous experiments. The pulsed sample was deemed to be softer than the CW cut sample, which showed that the pulsed sample has a clear improvement in edge softness over the CW samples.

5 MICROSCOPIC METHOD

Another assessment method employed by the authors is to inspect the lace edge purls under a microscope. When the lace purls are overexposed to or inaccurately targeted by the laser beam during the cutting process, some small bubbles, invisible to the naked eye, will be formed. However, with the aid of a microscope, these small bubbles can be clearly seen, as shown in Fig. 15.

It is the bubbles that cause the skin irritation and therefore degrade the overall lace edge quality. From this point of view, the lace edge quality can be assessed and categorized by observing and classifying these bubbles.
5.1 Test set-up

Three lace samples, the same as those used in previous tests, were selected for the microscopic investigation test, including mechanically cut, CW cut, and pulsed cut (0.1 ms pulse duration). These samples have the same pattern as shown in Fig. 16.

As inspecting the lace purl under a microscope one by one is time consuming, two pattern repeats of each sample are selected for the inspection, which is considered to be enough for representing the whole lace edge quality. As each repeat contains 14 purls (only true for the lace pattern shown in Fig. 16), totally 28 purls of each lace sample will be inspected and classified as good, neutral, or bad quality according to the severity of the thermal damage caused during the cutting process.

The quality of a purl is classified as ‘good’ only when no thermal damage or bubbles can be seen under the microscope. The purl will be considered as ‘bad’ or ‘neutral’ quality depending on the position and degree of the thermal damage. Figure 17 shows four examples of purls of different quality.

5.2 Experimental result

By inspecting and classifying the purls one by one, the number of purls with a different quality for each sample can be counted as shown in Table 6. The overall lace edge quality of the lace sample is determined by calculating the percentage of ‘good quality’ purls out of all the purls.

Table 6 and Fig. 18 clearly show that the mechanically cut lace sample has the best overall edge quality without any thermal damage. The edge quality of the pulsed cut lace sample is close to that of the mechanically cut sample, while the CW lace sample has the lowest edge quality. Lace samples of other types (checked design and floral design) cut by different cutting systems are assessed as well using the microscopic method and the same conclusion can be drawn.
6 DISCUSSION

6.1 Lace edge quality assessment methods

Three methods of lace edge quality assessment have been presented. Although these methods are different in terms of principle and process, the conclusion drawn from each assessment method is the same, which states that mechanical cut lace samples have the best edge quality while the edge quality of lace samples cut by a CW laser is the lowest. Unfortunately, it is not possible at this stage to benchmark the proposed assessment techniques against any other methods because they simply do not exist.

The contact measurement method assesses lace edge quality by recording the resistance forces caused by sliding the lace edge against the tight material. Based on this principle, the method is further divided into two separate methods, called tube abrasion and sheet abrasion. The lace edge quality can be distinguished by analysing test data obtained during the experiments. This method is considered more reliable, objective, and time-effective than the other two assessment methods, i.e. the user trial and microscopic methods. Assessing lace edge quality using the user trial and microscopic methods takes a long time, making them not feasible for online lace edge quality assessment. However, the contact measurement method has the potential for assessing lace edge quality in real time, especially when it is combined with a machine vision system.

<table>
<thead>
<tr>
<th>Lace sample</th>
<th>Good</th>
<th>Neutral</th>
<th>Bad</th>
<th>Total</th>
<th>Percentage of good (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanically cut</td>
<td>28</td>
<td>0</td>
<td>0</td>
<td>28</td>
<td>100</td>
</tr>
<tr>
<td>CW cut</td>
<td>3</td>
<td>3</td>
<td>22</td>
<td>28</td>
<td>11</td>
</tr>
<tr>
<td>Pulsed cut</td>
<td>21</td>
<td>2</td>
<td>5</td>
<td>28</td>
<td>73</td>
</tr>
</tbody>
</table>
6.2 Lace cutting methods

The lace samples used for the assessment experiments in this research are cut by three different cutting systems, namely mechanical, CW laser, and pulsed laser systems. According to the conclusion of each lace edge quality assessment, mechanical cut lace samples have the best edge quality. However, the mechanical cutting process has limitations, as outlined in reference [22], in terms of speed and labour requirements, both of which produce a bottleneck in the cutting process. The mechanical lace cutting process is slow and fairly inaccurate, requiring constant operator attention. Although there is no thermal damage caused to the lace being cut, the cutting inaccuracy always leaves the cut lace hairy or miscut. The mechanical lace cutting system also suffers from the inability to deal with closely interlocked lace patterns, known as centre cutting. These must be cut by hand using scissors, resulting in corresponding throughput and cost disadvantages.

The combination of machine vision and a laser system appears to be a feasible substitute to the mechanical cutting system. The CW laser cutting system [8-10] can cut lace with a cutting speed up to 10 m/s automatically. However, the lace edge quality cut by the CW laser system is not good enough for some demanding markets due to the thermal damage introduced by the laser energy. However, the pulsed laser cutting system [11] is able to cut lace with the resulting edge quality close to that cut by the mechanical cutting system. Currently, the authors are continuing to carry out the lace cutting research project, aiming at further improving the edge quality by investigating the lace handling issues. It is speculated that a pulsed laser cutting system capable of automatically producing high-quality lace is achievable in the near future.

7 CONCLUSION AND FUTURE WORK

In this paper, three lace edge quality assessment methods have been described in detail and some tests have been carried out to compare the edge quality of lace samples cut with different cutting systems. The assessment methods are then compared and contrasted, which identifies that the contact measurement method is more reliable and objective and has shown potential for future development. The comparison of the three different cutting systems reveals that the pulsed laser system is a promising solution to the lace cutting problem.

Future work will be focused on improving the contact method, as user trial and microscopic methods are both time consuming and subjective. Machine vision technology could be incorporated to enable each purl of the lace edge to be assessed, which makes it possible to assess the lace edge quality in a more local scale. It is expected that this contact solution could even be implemented for online assessment in real time.

REFERENCES