Chapter I Introduction and Objectives

Index

1. TRENDS IN THE SEWING INDUSTRIES RELEVANT TO THE DEVELOPMENT OF HIGH-TECH SEWING MACHINES AND SYSTEMS 2

2. STATE-OF-THE-ART 4

2.1. PRESENTATION OF THE OVERALL RESEARCH PROJECT 4
2.2. BRIEF REVIEW OF OTHER RESEARCHER'S WORK 5
2.3. COMMERCIAL APPLICATIONS AVAILABLE 8
2.4. THE SEWING TEST RIG 9
2.4.1. Sensors 9
2.4.2. Conditioning hardware 11
2.4.3. Software – General description 11

3. OBJECTIVES OF THE PRESENT WORK 13

3.1. STUDY OF NEEDLE-BAR FORCE 14
3.2. DEVELOPMENT OF THE SEWING TEST RIG 14

4. STRUCTURE OF THE THESIS 16

5. REFERENCES 17

5.1. PUBLICATIONS WITHIN THE RESEARCH GROUP AT THE UNIVERSITY OF MINHO 17
5.2. OTHER PUBLICATIONS 19

1. Trends in the sewing industries relevant to the development of high-tech sewing machines and systems

The need for clothes and protection from cold has always compelled Man to seek for means of joining materials, natural or man-made, with greater efficiency.

At the beginning of the industrial era, naturally, many people were thinking about machines to perform sewing operations. The first experiences are credited to *Weisenthal*, around 1750 [42][43]. However, more than a century had yet to elapse until the sewing machine achieved some commercial success. This is due not only to the development time of mature mechanisms for various types of stitches, which could be used in different applications, but also to issues of social acceptance.

It can be assumed that all of the basic mechanisms for stitch formation had been developed until the end of the 19th century. The 20th century was the time to improve those mechanisms. Sewing efficiency and speed grew immensely as machine technology advanced. Mechanical and electronic add-on devices could raise efficiency in specific operations, and machines became specialised. Many operations have been partially or totally automated in respect to material handling.

In the 1960's, it was believed that garment construction could be totally automated. In a huge research and development effort, a German sewing machine manufacturer (PFAFF) developed the first fully automatic garment assembly plant. It could be configured to produce several types of products in a fully automatic way[1]. This approach, however, did not achieve the expected commercial success (although many of the solutions found were re-applied and are still used at present). Two factors had been critical:

a) Textile materials are flexible and as such very difficult to handle, when compared to stiff workpieces such as mechanical parts: As product styles changed, handling mechanisms had to be adapted, readjusted or even replaced;

b) The process of sewing itself had never been controlled: As the materials changed, the machines would have to be manually readjusted.

The fully automatic plant would therefore be applicable to large-scale production, in which longer set-up times between production runs have little significance. Textile production, however, has been moving away from mass production. Fashion, with a direct influence on consumer demands, imposes a great variety of styles resulting in very small production runs, so that machine set-up times are very important to be considered. In addition, the variety of materials and structures has permanently been increasing, which makes machine set-up even more difficult and time-consuming.

This tendency has brought to light the limitations of automated machines. They find applications in mass production, and in operations that do not substantially change from style to style, but the concept of a totally automated garment factory has been generally abandoned. The garment manufacturer relies on the flexibility and learning capability of the human operator.

---

[1] The plants consisted of several machines linked by a conveyor system. Generally, only simple products could be produced. Examples are pillow inlets, sheets, shirt front parts, etc.. These involved operations like folding, hemming, button holing, button sewing, pocket and label sewing.

The sewing process itself is still not sufficiently controlled to solve the problem of adjusting the machine more quickly when changing material. Several of the machine's subsystems have to be adjusted so that adequate levels of quality and functionality of the seams are achieved. Methods of adjustment are based on experience and trial-and error, and demand for a considerable level of know-how from the technicians and operators.

Moreover, if the machine is wrongly adjusted, or if some mechanical malfunction causes defects, only the human operator is able to detect this situation. Detection can happen with some delay, which can cause a significant amount of lower-quality garments with the financial loss associated.

Combining the trends for small-batch production and increasing variety of materials and structures, it is possible to conclude that the control of the process is of great importance in the sewing industry. Machines that can be quickly readjusted or even adapt automatically to sewing conditions and that detect defects and malfunctions autonomously, combined with CAE (Computer-Aided Engineering) software to configure and tune the process, would be a great advantage for the apparel manufacturer. In this way, costs associated to machine set-up and quality problems could be reduced, enhancing industry competitiveness.

Many other important advantages result from such a strategy. It would enable garment manufacturers to off-line engineer the process and store process data during operation. In this way, it would be possible to associate quantitative data to the final product, showing that it was manufactured according to defined standards. This kind of "quality documentation" is becoming more and more important in the framework of quality certification, for example for safety seams (airbags, safety belts, etc.).

Many researchers and manufacturers are still pursuing the objective of automating the sewing room. When speaking of automation, normally automated material handling is meant. Machines that eliminate human material handling in specific operations will always be useful in the industry. New concepts for material handling, also for specific applications, like 3-dimensional sewing, are also expected to transform the way sewing machines are built [44].

In the author's opinion, the most groundbreaking development will be the understanding of the process, to achieve automatic control and monitoring, as well as off-line process engineering. Regardless of the degree of automation of material handling, machine's performance and final product's quality depend on the following three interfaces:

- Material-needle
- Material-thread
- Material-machine

New-generation sewing machines should sense the material while sewing, and monitor and control themselves adequately through appropriate devices and software.

Prior to production, process planning and material testing should occur, in order to determine machine set-up and material properties and thus avoid problems during production, reduce set-up times, and provide the manufacturer with tools to control and assure quality.

The current work was developed in this context, aiming to provide a further advancement in this new type of technology.

2. State-of-the-art

2.1. Presentation of the overall research project

The work developed and presented in this thesis is integrated in a research project whose final objective is the automatic control of the sewing process.

By project a whole *line of investigation*, followed by various researchers within the same strategy, is meant. In fact, work on sewing process control reaches back to 1988 at the University of Minho.

The first major publication has been prepared by Ferreira in 1991[1]. In his work, a lockstitch machine was equipped with thread tension[2] sensors and conditioning hardware for both needle and bobbin threads. A data acquisition board in a PC, for which a simple acquisition software was created, acquired the signals. A first understanding of the measured waveforms, and conclusions about relations between upper and lower thread tensions, materials, and threads were drawn. Thread tension waveforms were found to display several peaks, related to the events of the stitch formation process. A quantitative relationship between the thread pre-tension and these peaks was drawn for a balanced stitch.

In 1996, Rocha published her PhD thesis [9]. This work added sensor set-ups for needle-bar and presser foot force measurement, as well as thread tension sensing to an overlock machine. The acquisition set-up was similar to the one used by Ferreira. Her work made it possible to evaluate the behaviour of the two other physical interfaces present in the process: material-needle and material-machine. In addition, tools were created for measurement of thread tension on another type of machine.

In these two studies, a basic understanding of the underlying sewing dynamics was achieved. This understanding created the basis to outline further investigation.

In 1996, Carvalho, M. published his MSc dissertation, in which the sewing test rig had been used to measure and study thread tensions on the overlock machine [12].

The equipment, however, needed a redesign of both hardware and software. The need for expansion, in order to accommodate more signal entries, and some control hardware, arose. Some of the sensors and in general, all of the conditioning hardware had to be improved in both reliability, accuracy and maximization of dynamic response, as the physical phenomena occurring during high-speed sewing are extremely fast.

The author proposed the development of this task and also to create a software package specifically designed for the application. This application would not only allow the user to quickly perform and display a series of tests, but should also be flexible and modular to integrate signal analysis functions to create in the future.

In 1998, the author concluded his MSc thesis, in which the sewing test rig was substantially enhanced [15]. A more detailed description of its functionalities is given in section 2.4.

---

[2] The sensor actually picks up thread forces and not tensions, as do the sensors used in this work. Tensions would have to be computed relating the force to the thread's cross-sectional area. Although linguistically imprecise, the term *tensions* will be maintained throughout the text, since it is the term commonly used in industry to describe all that is related to the tensioning of the threads.

Using this new system, Carvalho, M., began the study of the stitch formation system. A device for measuring the consumption of the three threads used by the overlock machine was added. Tools to classify thread tension adjustment and to detect sewing defects due to malformed stitches were found, based on features extracted from thread tension and consumption values [38].

Silva began his study of the feeding system, replicating the test rig on another machine, which he equipped not only with a sensor to measure presser foot force, but also with another sensor used to measure presser-foot displacement. After having studied the dynamic behaviour of the presser foot under various conditions, he proposed an active actuator set-up, based on an electromagnetic actuator, and methods to control presser foot movement in real-time [37].

The present work started in parallel with the latter two, with the objective of studying the needle penetration and methods of detecting incorrect needle choice, defective needles and sewing defects caused by the needle. Moreover, it should integrate the results of all the studied variables, and create tools specifically designed for the computation and analysis of sewing parameters.

In this sense, the work comprises the integration of the new sensors and hardware into the acquisition system providing other researchers with new tools to analyse and classify the relevant sewing parameters.

2.2. Brief review of other researcher's work

There are many publications on the research work that has been carried out to establish the relationships between fabric, needle, thread properties and sewing conditions with seam quality.

Many researchers have instrumented sewing machines with sensors to measure some of the sewing parameters, whilst others have concentrated on developing mathematical models to predict some of the variables of the process.

The first studies on seam quality were carried out by Dorkin and Chamberlain in 1961 [45]. The relation of seam pucker occurrence, a common quality problem, with the behaviour of the feeding system was presented. Moreover, the operation of the feeding system was described in a very detailed way.

In 1964, Chamberlain and Deery developed a method for measuring thread tension variation within the stitch formation cycle of a lockstitch machine [46]. The tension signals were analysed relating the occurring peaks to events in the stitch cycle, and analysing the values of the peaks. Also Greenberg presented another instrument for the same purpose [49].

These studies set the starting point for various research works concerning the sewing machine's feeding system performance, the stitch formation setup, namely the thread tensions during sewing, and the needle penetration process. Some authors studied these aspects separately, whilst others observed them in combination.

Based on Chamberlain and Dorkin's description of the feeding system [45], Johnson presented in 1974 a mathematical model for the movement of the presser-foot in a sewing machine, especially concerned on predicting the contact losses between presser-foot and feed-dogs [47]. The researcher would then present a simple experimental set-up to determine when and how long contact losses occurred. This was done with the machine operating without fabric. The main findings were that contact losses increase with sewing speed and decrease when presser-foot pre-tension is increased. Some experiments

carried out by stitching paper without thread provided additional results relating stitch density variation with speed and presser-foot pre-tension.

In the sequence of Johnson's results, Frank and Mo [48] developed an analysis of presser-foot "bouncing" and determined that the feeding system has critical operating points, exhibiting resonance-like behaviour at certain speeds, depending on presser-foot pre-tension. Once again, presser-foot bouncing (resulting in contact losses between fabric and presser-foot) could be related to the resulting deviation of stitch length from its nominal value. A pneumatic actuator was later introduced on a Union Special lockstitch machine and reported to improve the performance.

In the meantime, several studies were directed to the behaviour of thread tensions and its relations to seam quality. Jones and Munden describe the geometry and mechanics of the two-thread chainstitch, proposing a method for the measurement of both static and dynamic thread tensions [50][51]. Horino, Miura, Ando and Sakamoto [52], and later Kamata, Kinoshita, Ishikawa and Fujisaki [53], dedicated some studies to the thread tensions in lockstitch sewing machines. They examined the relationship between the needle and bobbin thread tensions, also observing the movement of the check spring, a component that is found in the needle thread path of lockstitch machines. Similar work was carried out by Onoue [54].

Mende would present in 1982 a more elaborate model to describe presser-foot movement and force. It was possible to this researcher to confirm the conclusions drawn by Johnson and Frank/Mo, and refine some results, namely the instants of contact losses and their relation to presser-foot pre-tension and sewing speed.

In 1988, Matthews and Little devised a sewing machine with sensors to measure force on the needle and presser-foot bars [56]. The studies focused mainly on the study of the feeding system, and the insights gained by Johnson, Frank, Mo and Mende could be experimentally confirmed. The researchers also applied FFT-transforms to the signals, in a first attempt to classify the feeding behaviour.

The same authors would later introduce with Clapp and Vass the fabric objective properties into this study, trying to relate fabric objective properties (measured by the Kawabata Evaluation System) and sewing conditions to the efficiency of material feeding [57][58].

Some of the results of their studies were materialised by Barrett into the concept of an active actuation system for the presser-foot, called "autodamp" [60], which used an electromagnetic actuator with a "maglev" presser-foot controller proposed by Barrett and Clapp [61].

Chmielowiec and Lloyd [61] equipped a Pfaff lockstitch machine with sensors measuring presser-foot force and displacement, thread tension and needle penetration force. They were able to detect the effect of "presser-foot bouncing", and some correlation between presser-foot compression force and seam pucker. Some experiments with limited results were carried out concerning needle penetration force.

Bühler and Hennrich developed measurement methods for thread tension and needle penetration force. The sensor for needle penetration force was integrated in the stitch plate, measuring the force with which the needle compressed the fabric against the plate. This method does not allow the measurement of needle withdrawal force. The authors mainly presented the results of the thread tension measurements, drawing important relations to sewing speed and sewn material, and pinpointing the typical shape of certain sewing defects in the obtained signals[63][64].

Alagha, Amirbayat, and Porat, discussed the relation between fabric objective properties and sewing conditions, with the contraction and consumption of sewing threads. This was done on a Rimoldi 401 double chainstitch machine, comparing the conventional with an experimental positive thread feeding system. The performance of the feeding system was also analysed by measuring vertical presser-foot displacement with a contactless arrangement using a Hall-effect sensor.

A series of publications by Stylios *et al* [67][68][69][70][71] [72][73][74][75][76] analysed several aspects of "intelligent garment manufacturing". In these papers, both the organisational as well as the technical aspects of the control of the sewing process are discussed. The concept of "the Sewability Integrated Environment" was introduced. A Pfaff sewing machine was equipped with sensors measuring sewing speed, thread tension, tension disk pressure, presser-foot pressure, feed-dog pressure and differential feed. An extensive experiment with a variety of fabric types was carried out, and a neuro-fuzzy control system was designed and trained to adjust presser-foot pressure and thread tensions. The network relied on only two inputs to compute the outputs: sewing speed and a fabric sewability factor computed on basis of the fabric's objective properties [74]. In another article, a mathematical model for needle penetration force in woven fabrics was presented. This work would later be taken up by Lomov, resulting in a "*qualitatively accurate and quantitatively reasonable*" model [78] for prediction of needle penetration force depending on several factors. The model is formulated for the "static penetration force", when the needle is moving at about 1 mm/s. This condition is far different from that occurring in industrial high-speed sewing.

Gotlith had some months earlier proposed another model for penetration force, also based on fabric objective properties. The model was tested with a sewing machine operating at 450 spm (stitches per minute). Little details are given about the measurement method used. The experimental values were found very different from those predicted by the model, leading Gotlith to propose some modifications to the model.

Later, Malllet and Du proposed the use of finite element modeling techniques to predict penetration forces into fabrics. Some success was achieved with this numerical technique, being the values within an 11% margin of those measured by a strain gauge applied to the needle. The simulation used simplified models of the needle and a plain weave fabric. It is very interesting to note that Mallet was able to predict the profile of the needle penetration force waveform that has been observed by the University of Minho research team. (Figure I- 1)

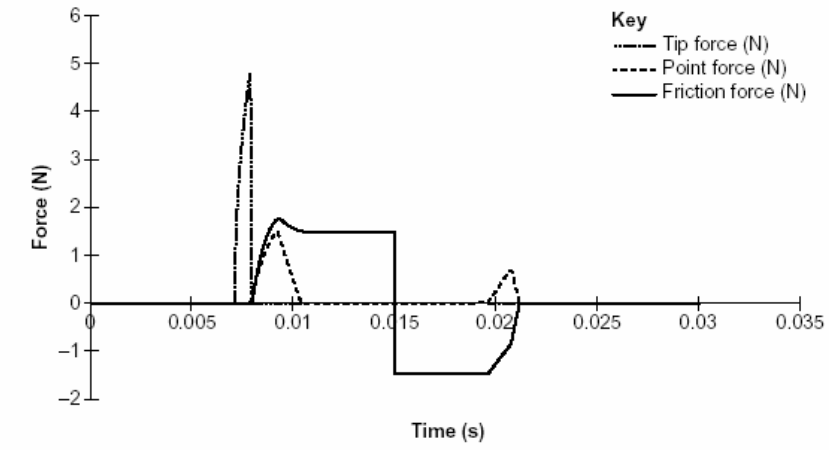


Figure I- 1 Needle penetration force profile predicted by Mallet with its FEM

With this technique, Mallet also simulates the deformation caused to the fabric and its recovery after penetration.

Stjepanovic and Strah proposed an expert system for supporting the choice of an adequate needle size for a specific seam[79]. Fabric material, mass per unit area and density (yarns/cm), as well as sewing thread linear density, composition and stitch type were used as inputs for a "learn-by-example" regression tree. 193 examples were used to train the machine-learning technique implemented on Retis software [82][83]. The application was found to present answers with an error margin of ±5 Nm, a good value, although the authors indicate a margin of ±1 Nm as a desired error.[3]

The phenomenon of needle heating during high-speed sewing, particularly important in the sewing of synthetic materials, is also a subject that has been studied by several researchers. Recently Liasi *et al* presented a series of publications [80][84][85] concerning the problems arising from this behaviour .

2.3. Commercial applications available

Despite the extensive work carried out by several researchers, the sewing process is still not sufficiently understood to allow a broad range of industrial applications.

The only known commercial machine that uses some of the technologies presented is the *Pfaff Doku-System*. This system monitors the seams produced in the assembly of car seats in which side airbags are integrated.

The sewing machine is equipped with a thread tension sensor of Pfaff's own design and uses a PC with a data acquisition board and software to monitor the side seam under which the airbag is concealed. This seam is supposed to be broken by the airbag when inflated, and it is thus very important to monitor the conditions under which it is produced. Thread tension is monitored and tested against pre-defined limits. Additionally, a proximity sensor monitors the backtack lever of the sewing machine. This is also very important, because if the operator introduces a backtack into the seam by mistake, the seam strength is tripled at this point: The airbag may not be able to break the seam, failing its function.

The Pfaff Docu-System monitors this process and provides numerical data about the seam that can be printed and attached to the car seat as an additional quality control document. It rejects any seam failing to comply with the limits or in which a backtack operation was detected.

In 1999, Pegasus, a japanese sewing machine manufacturer, presented at the JIAM sewing Machine Trade held in Tokyo, a prototype of an overlock machine equipped with stepper motors allowing the controlled adjustment of thread tensions and presser-foot force. The basic concept of this prototype was to allow a quick adjustment of these variables; it was then possible to store the settings in the controller's memory and recall them later if the same style and fabric was to be produced again. No feedback of sensor information, and thus no kind of control was performed.

The lack of industrial applications shows that research has not yet been able to find all the knowledge necessary for the development of monitoring and control systems in a broad sense. In this work, a contribution to this development will be given with the creation of new tools for sewing parameter analysis. The starting point is the system created in 1998 [15] and the following section gives a brief

[3] Nm: Metrical numbering system, needle shaft diameter x 100

description of its development state before the beginning of the present work. (An extensive description is presented in Annex B)

2.4. The sewing test rig

The sewing test rig set up by Rocha in 1996 was composed of

- A three-thread, differential bottom-feed overlock machine;
- Sensor set-up for thread tension measurement;
- Sensor set-up for presser foot compression and needle-bar force;
- Basic signal conditioning hardware;
- A PC with a data acquisition board (National Instruments Lab-PC+);
- A basic MS-DOS based software package with acquisition, display and file I/O functions.

In his MSc thesis [15], the author carried out a total redesign of the equipment, improving its accuracy, reliability, ease of use and functionality. The test rig structure after this redesign is shown in Figure I- 2.

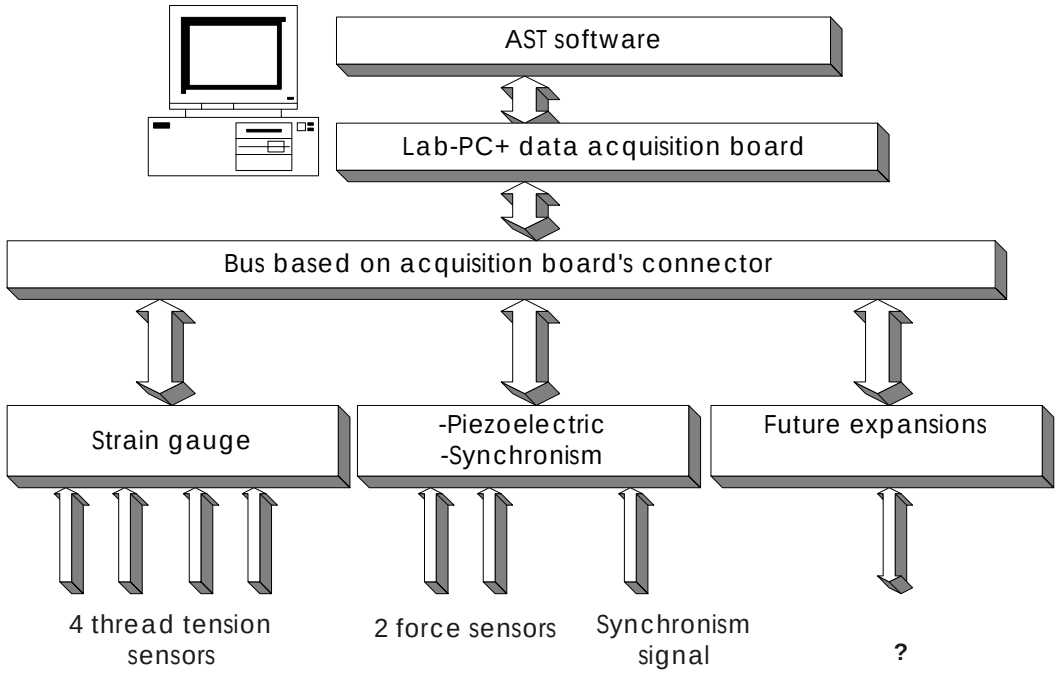


Figure I- 2: Structure of the sewing test rig (1998)

2.4.1. Sensors

The sensor set-up for presser foot and needle-bar forces developed by Rocha was not changed. It uses commercial piezoelectric sensors that are introduced in the presser foot and needle bars as shown by the following principle schemes:

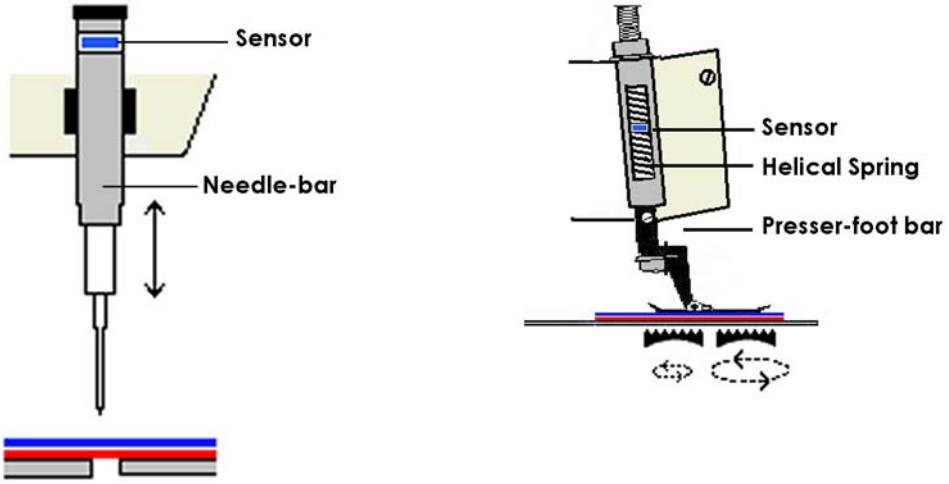


Figure I- 3: Sensor set-up for needle and presser foot bar force measurement

This sensor set-up was considered satisfactory, although the positioning of the needle-bar force sensor at the top of the needle-bar creates some problems that will be analysed in later chapters.

Figure I- 4 shows a picture of the sewing machine with the piezoelectric sensors. Only the presser foot force sensor is visible, since the needle-bar is concealed within the sewing machine.

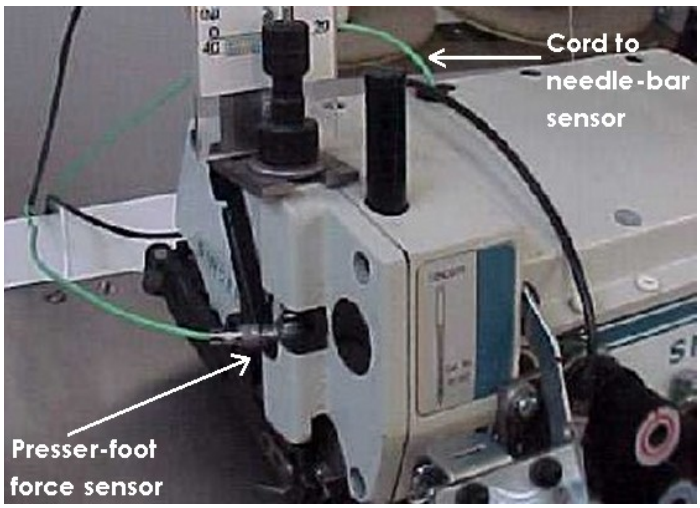


Figure I- 4: Piezoelectric sensors fit to the machine

A major improvement was made on the thread tension sensors. A deep study of the requirements for these sensors made it possible to exactly specify the desired characteristics. A Czech R&D institute with some experience in the construction of these types of sensors (Petr Skop) supplied a new sensor, based on semiconductor strain gauges, which has shown very satisfactory performance in all aspects. Figure I- 5 shows the new thread tension sensors.

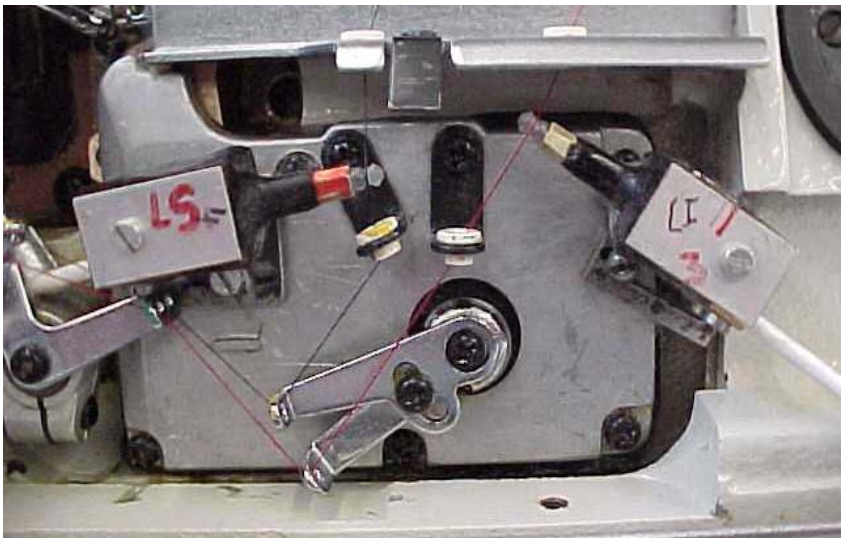


Figure I- 5: New thread tension sensors

2.4.2. Conditioning hardware

Conditioning hardware for the piezoelectric and strain-gauge based sensors, as well as for a digital signal providing a synchronism to the acquisition (to be analysed later on), was totally redesigned by Andrade and the author [15][22]. Two signal conditioning boards were developed.

The first board, designated as *piezoelectric type,* features two channels for piezoelectric sensors and a CMOS to TTL conversion with isolation for a digital synch signal from the machine's motor. The second board, designated as *strain-gauge type*, supplies 4 strain gauge conditioning channels. Both boards are equipped with software controlled variable gain and several functions for sensor calibration purposes. With the development of these two boards, the level of measurement accuracy and reliability could be significantly raised.

2.4.3. Software – General description

The development of a new software package was perhaps the greatest investment made in the reshape of the system.

One of the most fundamental premises established for the development of the system was that of being modular and thus expandable. This was particularly important for the software, because many enhancements were to be added in the future, as has actually happened.

LabView was chosen as the development environment for this new program. This application, produced by National Instruments, has been customized for the design of measurement and automation software. It provides tools to build a measurement application in a quick and straightforward way, integrating seamlessly with the National Instruments hardware, as is the case of the Lab-PC+ board.

The resulting program surpassed the functionality of all of the services delivered by its predecessor (acquisition, display and file I/O), and added some other important tools. These allowed visual and mathematical analysis of the acquired signals to be done much more easily, replacing the flexible but burdensome standard spreadsheet programs. The new application had a standard Windows interface and delivered the following tools:

- Data acquisition;
- Powerful signal display;
- File I/O;
- Sensor Calibration;
- Conditioning hardware driver, configuration and test modules;
- General purpose signal processing tools;
- A basis for process-specific signal processing algorithms.

The application was called *Advanced Sewability Tester* (AST). Although at that the time it was just an acquisition and general-purpose analysis tool, the name revealed the aim of refining and creating tools for actual sewability testing.

Standard signal processing tools were included, like DFT/FFT-processing and digital filtering, that would be later very useful for certain signal evaluations.

The application also introduced the concept of **stitch cycle phases**, a specific method for the analysis of the sewing process. In this method, an angle scale is calculated for the signal and phases of the stitch cycle are defined. These phases are related to events that occur during the cycle. Subsets of the signal can then be retrieved and analysed.

The starting version of the present work (version 1.1) only included functions for peak detection in the signals subsets. Results were delivered in text tables that could be exported to a file compatible with spreadsheet programs and other applications.

3. Objectives of the present work

Keeping in mind the objectives of the overall project in which this work is integrated, it is important to begin by outlining its two main objectives:

- Developing support tools for sewing machine set-up and sewability[4] testing;
- Developing the basis for dedicated controllers as add-on kits for sewing machines.

The central piece to fulfil both objectives is the continued development of the software. All of the methods found to classify seam quality on basis of the acquired signals are to be built into the software, so that they can be tested and improved. Prototypes for control and/or monitoring algorithms are to be developed and tested in the software, before they lead to dedicated devices.

In this way, the sewing test rig serves not only as a research and development tool, but also as a support tool that can be used both for off-line process planning/controller tuning as well as for material testing (sewability testing). It should acquire the ability to diagnose faulty situations, assist optimisation of the machine's settings, and report about suitability of the materials in terms of sewability.

The present work can be divided into two main tasks:

- The study of the signals of needle-bar force;
- The development of the software and hardware of the test rig.

Whilst the first task is dedicated specifically to one of the three fields of study presented before, the second has a much wider role and objective. It represents the integration of all of the knowledge acquired by the team in a single software application that materializes the core of all of the potential spin-offs attained in the project. Figure I- 6 shows this interaction, with the tasks assigned to the present work highlighted in grey shading.

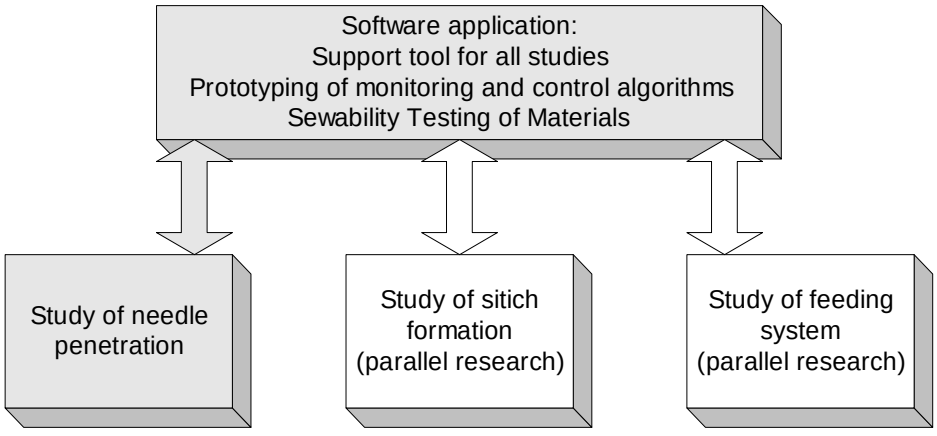


Figure I- 6: Interaction between tasks, with tasks assigned to the present work marked with a grey shade

[4] Sewability: Ability of a material to be sewn without quality problems. This term will be detailed in later chapters.

3.1. Study of needle-bar force

As stated earlier, the project within which this work is developed can be divided into three fields of study. It is the aim of this work to study one of them, namely the material-needle interface, that can be evaluated by measuring the force exerted on the needle-bar during sewing.

In order to measure the force on the needle-bar a piezoelectric sensor was inserted into the needle-bar [9]. In this way, it is possible to measure the interaction between the needle and the fabric during sewing. However, this sensor picks up not only this interaction, but also the forces applied to the needle-bar necessary to produce motion and the forces applied by the threads.

Bearing in mind that one of the final, long-term objectives of the project is to develop real-time controllers for sewing machines, and taking into account that the existing methods still implied some manual steps to process the signals, new processing algorithms are needed.

The first aim of this task is to find automatic signal processing routines able to extract the features relevant to the characterisation of the needle penetration process.

The next step is the classification of quality issues associated to the needle, based on the calculated features. Besides searching for methods to detect defects on-line, the processing algorithms should also enable the user to quantify by some means the fabrics in respect to their sewability, regarding, in this case, the needle penetration process. Such a tool would also be used, for example, to support the choice of needle types and widths for each material.

3.2. Development of the sewing test rig

In this work, the results already obtained are to be taken up and refined, to provide guidelines to the design of real-time controllers and monitoring systems. Moreover, a software package will be developed to support the development of these systems by providing tools to quantify the efficiency of machine operation in terms of quality.

The stitch formation process is studied by measuring and observing thread tension signals and thread consumption values in varying situations. Appropriate relations and values, as well as features calculated on the signals, have shown to be able to indicate correct and incorrect thread tension adjustment and stitch formation faults.

Feeding system behaviour is evaluated by measurement of presser foot compression force and vertical displacement. Inefficient feeding behaviour has shown to be detectable on both parameters.

Needle penetration is characterised by the signals obtained with a sensor measuring forces exerted on the needle-bar. Signal processing schemes are to be developed to extract the relevant features related to penetration.

Needle penetration is in principle, a process on which actuation cannot be exerted. Nevertheless, it is very important to attain monitoring, in order to detect inadequate materials, defective or worn-out needles, and defects produced by the needle. Furthermore, off-line support tools for needle choice and material testing are in this regard very valuable.

The task of software development can be considered as a higher-level task that provides support to all of the studies being carried out. The sewing test rig that has been developed will be continuously enhanced with additional functionality, both in hardware and software.

All hardware, devices proposed and developed to measure additional process variables have to be integrated into the system.

All this work leads to better tools for an integrated evaluation of all sewing variables, bringing the research closer to the objectives of control system prototyping and tuning, as well as sewability testing.

4. Structure of the thesis

This thesis is divided in 7 chapters and 4 annexes.

Chapter I presents a review of the work produced within the research team and by other researchers. The sewing test rig developed [15] is the starting point for this work; a brief description of its structure and functionalities is given. The objectives of the work are defined and justified.

In **Chapter II**, some fundamental concepts about the operation of sewing machines is described. Some issues related to seam quality are analysed.

Chapter III describes all the developments introduced into the sewing test rig, which includes several aspects related to the software's user interface, structure, acquisition, and analysis tools. The implementation of processing routines for sewing efficiency assessment will be specifically analysed in the chapters IV and V**.**

Chapter IV analyses the subsystems of the machine and presents the results of experiments from which a set of parameters for sewing efficiency quantification can be outlined. An analysis of signal processing tools for the measurement of needle penetration forces is also presented.

In **Chapter V**, the actual implementation of the sewing efficiency test tools and its integration in the sewing test rig is scrutinized.

Chapter VI presents the execution of an extensive experiment to evaluate the usefulness of the test tools created. The effectiveness of the developed processing methods, in all of the sewing variables that the system is able to measure, is analysed. The complete results of the experiment are presented in **Annex A.**

Finally**, in chapter VII** an analysis of the applicability of the results is made, considering its practical application in specific devices for sewing machines and software support tools. Future work perspectives are also proposed.

Annexes B, C and D present a complementary description of the work that has been carried out as well as more detailed information on several aspects. In **Annexes B and C**, the sewing test rig and its development are explained in more detail. **In Annex D** the work carried out in the attempt to find the optimal tools for needle penetration measurement is described.

5. References

5.1. Publications within the research group at the University of Minho

[1] Ferreira, F. N., A Study of Thread Tensions on a Lockstitch Sewing Machine, PhD thesis, University of Leeds, 1991.

[2] Araújo, M., Little, T. J., Rocha, A. M., Vass, D., Ferreira, F. B. N., Sewing Dynamics: Towards Intelligent Sewing Machines, NATO ASI on Advancements and Applications of Mechatronics Design in Textile Engineering, Side - Turkey, 5-16 April, 1992.

[3] Rocha, A. M., Sousa, E. J., Lima, M., Araújo, M., Estudo da Dinâmica do Processo de Costura numa Máquina de Corta-e-Cose, Journal "Revista de Robótica e Automatização", Nº. 9, October, 1992, pp. 12-17.

[4] Rocha, A. M., Lima, M., Sousa, E., Araújo, M., Evaluation of Sewing Performance and Control of Sewing Operation, 2nd International Clothing Conference, University of Bradford, UK, June, 1992.

[5] Ferreira, F. N., Harlock, S. C., Grosberg, P., A Study of Thread Tensions on a Lockstitch Sewing Machine (Part I), International Journal of Clothing Science and Technology, Vol. 6, Nº. 1, pp. 14-19, MCB University Press, U.K, 1994.

[6] Ferreira, F. N., Harlock, S. C., Grosberg, P., A Study of Thread Tensions on a Lockstitch Sewing Machine (Part II), International Journal of Clothing Science and Technology, Vol. 6, Nº. 5, pp. 26-29, MCB University Press, U.K, 1994.

[7] Ferreira, F. N., Harlock, S. C., Grosberg, P., A Study of Thread Tensions on a Lockstitch Sewing Machine (Part III)): Further Stitch Formation Analysis, International Journal of Clothing Science and Technology, Vol. 6, Nº. 5, pp. 39-42, MCB University Press, U.K, 1994.

[8] Rocha, A. M., Lima, M., Ferreira, F. N., Araújo, M., Developments in Automatic Control of Sewing Parameters, Textile Research Journal, 66 (4), pp. 251-256, 1996.

[9] Rocha, A. M., Contribuição para o Controlo Automático dos Parâmetros de Costura: Estudo da Dinâmica da Penetração da Agulha e da Alimentação do Tecido", PhD thesis, University of Minho, 1996.

[10] Rocha, A. M., Ferreira, F. B. N., Araújo, M., Monteiro, J., Couto, C., Lima, M., Mechatronics in Apparel: Control, Management and Innovation on the Sewing Process, Proceedings of the Mechatronics'96 Conference, Vol. II, pp. 109-114, Universidade do Minho, September 1996.

[11] Project report: PRAXIS XXI, Nº: PRAXIS/2/2.1/TPAR/2078/95, "Controlo, Gestão e Inovação no Processo de Costura" - Part B, 1996.

[12] Carvalho, M. A. F., Estudo das Tensões nas Linhas na Máquina de Costura Corta-e-Cose, MSc thesis, University of Minho, 1996.

[13] Carvalho, M. A. F., Ferreira, F. B. N., Study of Thread Tensions in an Overlock Sewing Machine, Proceedings of the ViCAM - Vision and Control Aspects of Mechatronics, pp. 223-226, University of Minho, September, Portugal, 1996.

[14] Carvalho, H., Monteiro,J., Ferreira, F.N., Measurements and Feature Extraction in High-Speed Sewing; Proceedings of the ISIE'97 (IEEE International Symposium on Industrial Electronics),Vol.3, pp 961-966; Universidade do Minho, Guimarães, July 1997

[15] Carvalho, H., Medição e Análise de Parâmetros em Máquina de Costura Industrial, MSc Thesis, University of Minho, 1998

[16] Carvalho, H., Silva, L. F., Medição de Parâmetros de Costura em Máquina Industrial, 2as Jornadas Têxteis e do Vestuário, University of Minho, pp. 22-23, April 1998.

[17] Silva, L. F., Lima, M., Couto, C., Ferreira, F., Rocha, A. M., Carvalho, H., Estudo do Mecanismo do Calcador de uma Máquina de Costura Corta-e-Cose, FIMEC'98, Jornadas de Engenharia Mecânica, University of Minho, pp. 24-26, May 1998.

[18] Silva, L. F., Lima, M., Couto, C., Ferreira, F. N.,Study of the Behaviour of the Presser Foot Mechanism on an Overlock Sewing Machine, Proceedings of the 3rd International Conference of Textile Science – TEXSCI'98, pp. 459-460, Technical University of Liberec, Liberec, Czech Republic, May 1998.

[19] Ferreira, F.N., Rocha,A.M., Monteiro, J.L. , Carvalho, H., Carvalho, M. Development of a Sewing Machine Control System, TEXSCI'98, Proceedings of the 3rd International Conference of Textile Science, Vol.2, p.397, Liberec, Czech Republic, May 1998

[20] Silva, L. F., Lima, M., Couto, C., Ferreira, F. N., Andrade, D., Ferreira, L. P., Study of the Feeding System of an Overlock Sewing Machine, Proceedings of the 6th UK Mechatronics Forum International Conference –Mechatronics'98, pp. 733-738, University of Skövde, Skövde, Sweden, September 1998.

[21] Carvalho,H., Monteiro, J., Ferreira, F.N., Rocha, A.M., A Sewing Rig with Automatic Feature Extraction, Proceedings of the 6th UK Mechatronics Forum International Conference (Mechatronics'98), pp 727-732, Skovde, September 1998

[22] Andrade, D.F., Sistema de Condicionamento para Sensores em Máquina de Costura Industrial; Final Project for the course of Industrial Electronics Engineering, University of Minho, Portugal, 1998;

[23] Lima, M., Silva, L. F., Couto, C., Coelho, J., Ferreira, F. N., Alternativa Mecatrónica para o Mecanismo do Calcador de uma Máquina de Costura Industrial, 1º. Simpósio de Electrónica Industrial – SEI'98, University of Minho, December 1998.

[24] Silva, L. F., Lima, M., Couto, C., Coelho, J., Ferreira, F. N., Rocha, A. M., Mechatronics Approach for a Controlled Actuation of the Presser Foot Mechanism on an Industrial Sewing Machine, Proceedings of the First International Conference on Advanced Engineering Design – FICAED'99, Czech Technical University in Prague, Prague, Czech Republic, May 31-June 2, 1999.

[25] Silva, L. F., Lima, M., Ferreira, F. N., Andrade, D., Ferreira, L. P., Couto, C., Mechatronic Approach to the Feeding System of an Overlock Sewing Machine, Mechatronics Journal, Vol. 9 / Issue 7, pp. 817-842, September, 1999.

[26] Silva, L. F., Lima, M., Ferreira, F., Coelho, J., Couto, C., Development of a Mechatronic Controlled Actuation on the Presser Foot of an Overlock Sewing Machine, Proceedings of the 44th International Scientific Colloquium – 44.IWK.99, Vol. 2, pp. 116-121, Technical University of Ilmenau, Ilmenau, Germany, 20-23 September, 1999.

[27] Silva, L. F., Lima, M., Couto, C., Coelho, J., Ferreira, F. N., Rocha, A. M., Mechatronics Approach for a Controlled Actuation of the Presser Foot Mechanism on an Industrial Sewing Machine, Acta Polytechnica – Journal of Advanced Engineering Design, Special Issue, Vol. 40, No. 4/2000, pp. 35-43.

[28] Carvalho, M., Ferreira, F. N., Seam Qualification and Control of Parameters in an Overlock Sewing Machine, Proceedings of The Fibber Society Technical Meeting - Spring 2000, pp. 89-92, University of Minho, Portugal May, 2000.

[29] Carvalho,H., Rocha,A.M., Ferreira, F.N., Monteiro, J., The Development of Support Tools for Sewing Machine Setting, Monitoring and Control, Intelligent Automation and Control - pp 188-194, TSI Press, Maui, USA; June 2000

[30] Silva, L. F., Lima, M., Ferreira, F. N., Rocha, A. M., Carvalho, H., Couto, C., A New Electromagnetic Actuated Fabric Feeding System for Sewing Machines, Proceedings

of The 7th Mechatronics Forum International Conference – Mechatronics'2000, Georgia Institute of Technology, Atlanta, Georgia, USA, September 2000.

[31] Carvalho, H., Rocha, A.M., Monteiro, J., Research on Process Monitoring and Control in the Sewing Room: A Novel Approach Proceedings of the 4th Portuguese Conference on Automatic Control, Universidade do Minho, Guimarães, Portugal; October 2000

[32] Silva, L. F., Lima, M., Ferreira, F. N., Rocha, A. M., Carvalho, H., Couto, C., New Electromagnetic Presser Foot Actuation and On-Line Monitoring of Feeding Efficiency in a High-Speed Sewing Machine, Proceedings of the Second International Conference on Advanced Engineering Design – SICAED'2001, pp. 213-218, University of Glasgow, Scotland, 24-26 June, 2001.

[33] Carvalho, M., Ferreira, F. N., On-Line Seam Qualification and Control in a Sewing Machine, Proceedings of the IFAC Workshop on Manufacturing, Modeling, Management and Control - MIM 2001, Prague, Czech Republic, August 2001.

[34] Carvalho, H., Rocha, A.M., Monteiro, J. Operation Diagnosis and Real-Time Control of Industrial High-Speed Sewing Machines, Proceedings of the IASTED International Conference Measurement and Control 2001 , pp 68 -73, IASTED/ACTA Press, ISBN 0-88986-279-6, Pittsburgh, Pennsylvania, USA, May 2001

[35] Carvalho, M., Ferreira, F. N., Automatic Seam Control and Qualification on Sewing Machines, Proceedings of the IASTED International Conference Measurement and Control 2001, pp. 16-18, IASTED/ACTA Press, Pittsburgh, Pennsylvania, USA, May 2001.

[36] Carvalho, H., Rocha, A.M., Monteiro, J., Measurement and Processing of Sewing Variables towards Real-Time Control and Off-line Process Planning, Proceedings of the International Conference on Information Processing and Management of Uncertainty in Knowledge-Based Systems, , Annecy, France, July 2002

[37] Silva, L. F., Estudo de Mecanismos Alternativos de Controlo do Sistema de Alimentação de Máquinas de Costura Industriais, PhD thesis, University of Minho, Portugal, 2002

[38] Carvalho, M., Estudo das relações entre os parâmetros de controlo, propriedades dos materiais e condições de regulação numa máquina de costura corta-e-cose, PhD thesis, University of Minho, Portugal, May 2003

[39] Silva,L.F., Lima,M., Carvalho,H., Rocha,A.M., Ferreira,F.N., Monteiro, J. Couto,C., Actuation, Monitoring and Control of Fabrics Feeding during High-Speed Sewing, Proceedings of the International Conference on Mechatronics (ICOM 2003), pp 471-476, International Engineering Publishing, ISBN 1-86058-420-9, Loughborough, UK, 19-20 June 2003

[40] H. Carvalho, A.M. Rocha, J. Monteiro, Process Control in Next-Generation Sewing Machines - A Project Overview, Proceedings of the International Conference on Mechatronics (ICOM 2003), pp 203-208, International Engineering Publishing, ISBN 1-86058-420-9, Loughborough, UK, 19-20 Junho 2003

[41] H.Carvalho, P.Ferreira, A.M.Rocha, J.Monteiro, Signal Feature Extraction for Sewing Analysis using Non-Linear Techniques, Proceedings of the 2003 IEEE International Symposium on Industrial Electronics (ISIE), IEEE, ISBN 0-7803-7912-8, Rio de Janeiro, Brasil, 9-11 Junho 2003

5.2. Other publications

[42] Renters, W., Die Naehmaschine in Schule und Haus, 2nd Edition, Werkschriften-Verlag GmbH, Heidelberg, 1958;

[43] Renters, W., Der Naehmaschinen Fachmann, Band 1, 8th Edition, Bielefelder Verlagsantalt, Bielefeld, 1957;

[44] Moll, P., Integrated 3D sewing technology and the importance of the physical and mechanical properties of fabrics, International Journal of Clothing Science and Technology, Vol. 9 No. 3, pp. 249-251, MCB University Press, 1997

[45] Dorkin, M. C., Chamberlain, N. H., Seam Pucker: Its Cause and Prevention, Clothing Institute, Technological Report Nº. 10, June, 1961.

[46] Deery, F. C., Chamberlain, N. H., A Study of Thread Tension Variations during the Working Cycle in a Lockstitch Sewing Machine, Technological Report Nº. 15, Clothing Institute, July, 1964.

[47] Johnson, E. M., Some Factors Affecting the Performance of High Speed Sewing Machines, Clothing Research Journal, Vol. 1, Nº. 1, pp. 3-35, 1973

[48] Frank, T. F. P., Mo, E. S. M., A Simple Test for Assessing Presser Foot Bounce, Clothing Research Journal, Vol. 2, Nº. 2, pp. 81-84, 1974.

[49] Greenberg, N. G., An instrument for measurement of thread dynamic tension characteristics during the sewing operation - Part 2, Clothing Research Journal, 3, Nº 2, pp. 77, 1975

[50] Jones, R. J. R., Munden, D. L., A Study of the Mechanics and Geometry of the 2-Thread Chainstitch - Part 1 - An Instrument for Measuring Static Needle and Looper Thread Tension, Clothing Research Journal, 1980. –

[51] Jones, R. J. R., Munden, D. L., A Study of the Mechanics and Geometry of the 2-Thread Chainstitch - Part 2 - The Development of an Apparatus for the Measurement of Dynamic Thread Tension, Clothing Research Journal, 1980.

[52] Horino, T., Miura, Y., Ando, Y., Sakamoto, K., Simultaneous measurements of needle thread tension and check spring motion of lockstitch sewing machine for industrial use, J. Text. Mach. Soc. Japan, vol. 2, pp. T30-37, 1982.

[53] Kamata, Y., Kinoshita, R., Ishikawa, S., Fujisaki, K., Disengagement of needle thread from rotating hook, effects of its timing on tightening tension on an industrial single needle lockstitch machine, J. Text. Mach. Soc. Japan, vol. 30, n. 2, 1984.

[54] Onoue, M., Influences of the sewing conditions of the lockstitch sewing machine for industrial use on the needle thread tension, J. Soc. Fib. Sci. Tech., Japan, vol. 10, pp. T395-401, 1984.

[55] Mende, S., Untersuchung des Zusammenwirkens von Transporteur / Nähgut / Nähfuß / Stichplatte bei Industrienähmaschinen, Textiltechnik, 32 (5), pp. 291-294, 1982.

[56] Matthews, B. N., Little, T. J., Sewing Dynamics, Part I: Measuring Sewing Machine Forces at High Speeds, Textile Research Journal, 58, July, 1988, pp. 383-391.

[57] Clapp, T. G., Little, T. J., Thiel, T. M., Vass, D. J., Sewing Dynamics: Objective Measurement of Fabric/Machine Interaction, International Journal of Clothing Science and Technology, Vol. 4, Nº. 2/3, pp. 45-53, 1992.

[58] Vass, D., Sewing Dynamics: Analysis of Variance of Sewing Variables and Correlation of Sewing Variables with Fabric Objective Measurement, Msc Thesis, North Carolina State University, June, 1992.

[59] Little, T. J., Matthews, B. A., Vass, D., Carrere, C. G., Sewing Dynamics: Influence of Fabric Properties and Sewing Machine Settings on Fabric Feeding, Proceedings of the First International Conference on Textile Objective Measurement and Automation in Garment Manufacturing, University of Bradford, July, 1990.

[60] Barrett, G. R., Sewing Dynamics: The Autodamp Technology for the Elimination of Presser Foot Bounce, North Carolina State University Leaflet, 7/92, 1992.

[61] Barrett, G. R., Clapp, T. G., Coprime Factorization Design of a Novel Maglev Presser Foot Controller, Mechatronics Journal, Vol. 5, No. 2/3, Elsevier Science Ltd, pp. 279-294, 1995.

[62] CHMIELOWIEC, R., LLOYD, D. W., The Measurement of Dynamic Effects in Commercial Sewing Machines, Proceedings of The 3rd Asian Textile Conference, Vol. II, pp. 814-828, 1995

[63] Bühler, G., Hennrich, L., Control "On-Line" de la Formación de las Costuras, Punto Técnica y Moda, 11, Nº. 4, pp. 239-242 e 244, 1993

[64] Bühler, G., Hennrich, L., Control "On-Line" de la Formación de las Costuras, Punto Técnica y Moda, 12, Nº. 1, pp. 42-46 e 51, 1994

[65] Amirbayat, J., Alagha, M. J., Porat, I., Factors Affected by Machine Settings and Fabric Properties in Knitwear Production Part I: Seam Shrinkage and Thread Consumption, J. Textile Inst., 86, Nº. 1, pp. 110-118, 1995

[66] Alagha, M. J., Amirbayat, J., Porat, I., A Study of Positive Needle Thread Feed During Chainstitch Sewing, J. Textile Inst., 87 Part 1, Nº. 2, pp. 389-395, 1996

[67] Stylios, G., Prognosis of Sewability Problems in Garment Manufacture Using Computer Based Techniques, Proceedings of the IEEE International Conference on Systems Engineering, 9-11 August, Pittsburgh, PA, USA, 1990.

[68] Stylios, G., Fan, J., An Expert System for Fabric Sewability and Optimisation of Sewing and Fabric Conditions in Garment Manufacture, Proceedings of the 1st International Clothing Conference on Textile Objective Measurement and Automation in Garment Manufacture, 9-11 July, 1990.

[69] Stylios, G., Fan, J., Sotomi, J. O., Deacon, R., Introducing a New Concept in Garment Manufacture, The Sewability Integrated Environment Incorporating Automatic Objective Measurement Systems, 2nd International Clothing Conference, July, 1992 and International Journal of Clothing Science and Technology, Vol. 4 Nº 4, 1992.

[70] Stylios, G., Sotomi, J. O., Automatic Settings of Optimum Sewing Machine Conditions for the Manufacture of High Quality Garments Made of Lightweight Synthetic Fibre Fabric, Proceedings of the 21st Textile Research Symposium on Basic Properties of Fibres and Fibre Assemblies, Performance and Design of New Fibrous Materials, 7-9 August, Japan, 1992.

[71] Stylios, G., Sotomi, O. J., Zhu, R., Katsugias, G., Xu, Y. M., Deacon, R., Intelligent Garment Manufacture, Proceedings of The International Conference Textile Science'93, pp. 563-570, September 14-16, Liberec, Czech Republic, 1993.

[72] Stylios, G., Sotomi, O. J., Zhu, R., Xu, Y. M., Deacon, R., The Mechatronic Principles for Intelligent Sewing Environments, Mechatronics Journal, Vol. 5, No. 2/3, Elsevier Science Ltd, pp. 309-319, 1995.

[73] Stylios, G. and Xu, Y.M. (1995), An investigation of the penetration force profile of the sewing machine needle point, Journal of the Textile Institute, Vol. 86 No. 1, pp. 148-63.

[74] Stylios, G., Sotomi, J. O., A Neuro-fuzzy Control System for Intelligent Overlock Sewing Machines, International Journal of Clothing Science and Technology, Vol. 7, Nº. 2/3, pp. 49-55, 1995.

[75] Stylios, G., Sotomi, J. O., Thinking Sewing Machines for Intelligent Garment Manufacture, International Journal of Clothing Science and Technology, Vol. 8, Nº. 1/2, pp. 44-55, 1996

[76] Stylios, G., The Principles of Intelligent Textile and Garment Manufacturing Systems, Assembly Automation, Vol. 16, Nº. 3, pp. 40-44, 1996

[77] Gotlih, K., Sewing Needle Penetration Force Study, International Journal of Clothing Science and Technology, Vol. 9 Nº 3, pp. 241-248, 1997, MCBUniversity Press

[78] Lomov, S.V., A predictive model for the penetration force of a woven fabric by a needle, International Journal of Clothing Science and Technology, Vol. 10 No. 2, 1998, pp. 91-103.MCB University Press

[79] Stjepanovic, Z., Strah,H., Selection of suitable sewing needle using machine learning techniques, International Journal of Clothing Science and Technology, Vol. 10 No. 3/4, 1998, pp. 209-218, MCBUniversity Press

[80] Liasi, E., Du,R., Bujas-Dimitrejevic,J., Liburdi,F., An experimental study of needle heating in sewing heavy materials using infrared radiometry, International Journal of Clothing Science and Technology, Vol. 11 Nº 5, pp. 300-314,1999 MCBUniversity Press

[81] Mallet, E.,Du, R., Finite element analysis of sewing process, International Journal of Clothing Science and Technology, Vol. 11 Nº 1, pp. 19-364,1999 MCBUniversity Press.

[82] Karalic, A., Retis – Users' Manual, Jozef Stefan Institute, Ljubljana, 1991.

[83] Karalic, A., Machine learning of regression trees from incomplete data, MSc dissertation, Slovene, University of Ljubljana, 1991.

[84] Li, Q., Liasi, E., Zou, H., Du,R., A study on the needle heating in heavy industrial sewing: Part 2: finite element analysis and experiment verification, International Journal of Clothing Science and Technology, Volume 13, No. 2, 2001

[85] Li, Q., Liasi,E., Simon,D., Du,R., A study on the needle heating in heavy industrial sewing: Part 2: Finite element analysis and experiment verification, International Journal of Clothing Science and Technology, Volume 13 No. 5; 2001