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1. Summary of the work undertaken

The research work presented in this thesis has been developed to accomplish two fundamental objectives, namely:

> In the framework of the project in which this work is fitted in, tools for sewing parameter measurement and analysis were to be developed;
> The effect of needle penetration and the possibility of its automatic monitoring were to be studied.

To accomplish these two objectives, it was necessary to fulfil a series of tasks of different nature.

The development of the sewing test rig involved in the first place the cooperation with other researchers in the project. Support to the design of new measurement devices was provided, and these devices were added to the sewing test rig and integrated into its software. Processing tools, proposed by the project's researchers or suggested in the context of this work, were created and generally used by all researchers (in the analysis of presser-foot, thread tensions, stitch checking and thread consumption).

In the course of this work, the sewing test rig was extensively enhanced with new functions related to acquisition, analysis, graphical display, sensor calibration, file I/O and data management. The ease of use was greatly increased by these functionalities and by redesigns of the user interface. In the background, a constant evaluation and revision of the software code's structure allowed an ordered expansion of the system.

Finally, all the relevant processing tools were gathered and integrated into the test panels, allowing an automatic computation and quick display of a collection of parameters describing the efficiency of operation. During this development process, new functions beyond those already existing in the initial software versions were conceived.

The study of needle penetration, by its turn, involved in first place the study of the measurement set-up, with all effects involved in the needle-bar movement. A careful examination of needle-bar force signals led to the creation of a software application with which the measurement process could be simulated. This application would serve to study the accuracy of the processing methods used. Based on the results provided, the spectral filtering method was optimised.

The typical errors and noise values at different sewing speeds were determined, showing that the measurement is somewhat inaccurate. Other approaches, such as adaptive filters and wavelet-based filtering, were quickly evaluated, but it was not possible to find any advantage over the spectral filtering method.

The next attempt to increase measurement accuracy was to train a neural network to correct feature values extracted by the existing processing methods. The network was trained and tested with data generated by the simulation program. An objective evaluation of the result showed that accuracy in the corrected data was similar to the original, uncorrected data, in some features. In other features, results were worse. It was decided that the neural correction scheme would still be quickly evaluated in the experimental phase of this work.

Finally, an experimental plan was designed to study needle penetration forces related to various factors, and to evaluate the effectiveness of the measurement method. Although this experiment was specifically designed to evaluate needle penetration variables, the feeding system and stitch formation performance
could also be analysed. In the experiment, several factors were varied that also exert influence on these subsystems. Its study was found to be of great interest and was carried out using the work of [1] and [2] as a starting point.

In the next sections, a short review of the results of the experiment will be presented. The findings will then be examined in the context of possible practical applications and future developments.
2. Results

2.1. Feeding system

The results obtained with presser-foot displacement measurement are quite remarkable. Its extraordinary sensitivity allows the detection of very fine differences in sewing conditions, such as the amount of stretch that is given to the fabric during sewing. In combination with the presser-foot force control that is being developed [1][5], it is possible to try the automatic adjustment of the differential feed to enable an optimal adjustment of force and stretch of the material. This is a challenging task considering the complex behaviour of the fabrics and the sewing speed variations that occur in most of the sewing operations.

The information provided by this measurement clearly depicts the operation of the feeding system. Losses of contact may be easily recognised by comparing the displacement cycle with that of the reference cycle at low speed. The definition of Admissible Displacement Limits (ADL)[1] for the peak values is also an effective way of monitoring operation.

Sewing defects like folds or curling of the fabric at the edge are readily detectable by the ADL method or by monitoring the difference of displacement to its reference.

As has been shown, the definition of stitch cycle phases for the displacement signal is not straightforward, as the shape of the signal changes with speed. This aspect should be observed in more detail to allow the development of robust peak detection algorithms.

The presser-foot reference cycle provides a valuable measurement of fabric thickness that is used to predict thread consumption. It also reveals to some extent the behaviour of the fabrics under compression. This knowledge may be important for the characterisation of fabrics, namely for determining its sewability, or to tune control systems. Combined with the active presser-foot actuation from Silva, more complex measurement procedures for fabric compressibility are conceivable.

Some useful information is also provided by the harmonic distortion of the displacement signal, but in other cases, misleading interpretations are possible. This results mainly from the fact that the ideal presser-foot signal is not a sine wave; more specific harmonic distortion factors may be an alternative.

Presser-foot force measurement confirms the observations that are made with the displacement signals. The observation of the force signals may provide some additional insight for research work. However, the parameters provided by the automatic processing tools do not add any additional monitoring information.

The computation of force amplitude has supplied some interesting results, but in many situations, variations have been observed that cannot always be explained by the sewing conditions. A further examination should be carried out to determine if these might result from the current measurement set-up or from a computation error.

With regard to the harmonic distortion factors, conclusions were similar to those drawn in the analysis of displacement. Although some interesting results were found, in some situations the indications are ambiguous.

2.2. Stitch formation

The observations made on the variables associated to stitch formation have also
supplied very satisfying results.

As far as the experiment design allowed, it has been shown that thread consumption measurement and prediction is a very effective tool to evaluate correct stitch formation regarding tension adjustments. Not only stitch balance, but also the overall tensioning of the seam can be assessed by comparing predicted and measured values.

However, the current consumption measurement device only provides average information for a complete seam, impairing stitch-by-stitch monitoring. The device under development will eventually allow an improvement of measurement resolution. In any case, an accurate stitch-by-stitch evaluation is not expected possible, because the thread is pulled in a discontinuous way by the sewing machine.

For the detection of localised defects, parameters obtained from the thread tension signals are a valid alternative. Some thread tension peaks clearly show the occurrence of skipped stitches and other, less evident faults. Safer detection margins for these faults are obtained with peak ratios.

Moreover, some correlation between tension adjustments and these ratios has been observed, just as with the Stitchcheck parameter used by [2]. The use of tension ratios would present the advantage of not requiring consumption measurement. Additional research work is planned to examine the possibility of automatic tension adjustment on basis of peak ratios or the Stitchcheck value.

The definition of stitch cycle phases is even more difficult than for displacement signals, because phases are in this case narrower, i.e. the measured effects are closer in time. Just as in displacement signals, the angles delimiting these effects slightly change with factors as sewing speed and tension adjustment, making a universal phase definition difficult. Future work is also focused on alternative peak detection algorithms that can safely extract the peaks regardless of its instant of occurrence. This may be possible with strategies already proposed by the author for the detection of “relative peaks”, as proposed in [4].

2.3. Needl e penetration

As already described in other chapters, the forces related to needle penetration forces are the most demanding variables to measure. Great care has been put in the development of tools to perform this task as accurately as possible. Nevertheless, this measurement is partially affected by other parameters and errors in the acquisition process. Nevertheless, results can be considered as estimates that proved to be effective for the analysis of needle-fabric interaction. The errors result mainly from the filtering process, that

> does not eliminate the motional forces completely, whilst

> distorting the useful signal.

In an actual industrial situation, in which the machine is used with thread, thread forces add another effect, but it has been observed that the first peak of penetration force is not significantly influenced by those forces.

The two different processing methods used (spectral filtering and referenced subtraction) provide qualitatively similar results in most cases, but quantitatively different. The correction of results using neural networks has been found not to unveil any new information.

Still, good results have been obtained.
It is possible to detect different needle sizes and draw the relation of penetration forces to needle size for a particular fabric, in a comparative analysis. This relation is different from fabric to fabric and can be linked to its sewability.

The same comparative analysis can be made to compare differently finished fabrics. It has also been possible to distinguish damaged from new needles, but the differences produced are small considering that the needles tested were strongly damaged. The error and spread of the measurement makes the detection of fine differences difficult.

The main factor influencing the penetration value indicated by the system has been found to be sewing speed. A comparative analysis between signals at different speeds is not possible, considering that the same needle produces very different values when speed changes. The increasing value of measured penetration forces with speed is partially due to the higher impact energy between needle and fabric, but it results mainly from the residual mechanical noise still present after the filtering process.

The effort to find a ratio of peak penetration values that would be more independent of sewing speed has not led to an effective result. The value of the ratio peak2/peak1 has shown to decrease in some cases when sewing conditions get worse (thicker needles), but this tendency could not be confirmed in other situations. Furthermore, this peak ratio also varies with sewing speed.

Another parameter expected to be able to provide some description of the process was the spread of values. Although interdependency is found in isolated cases, it is not possible to draw a general relation between the efficiency of the needle penetration process and the spread of values.

A particular situation occurring during the experiment drew attention to the detection of localised faults. Specifically, with the dyed fabric and using the machine without thread at 3500 spm, a clear defect situation occurred due to excessive needle heating. Unfortunately, it has not been possible to detect this progressive needle heating in any of the measurements.

The results obtained show that the measurement of needle penetration forces in the current configuration is not fit for industrial applications in production, in which sewing speed varies in most operations. The design of a monitoring system for constant-speed operations is conceivable. However, only the average value of penetration forces over a series of stitches contains useful information; it is likely that some localised defects would pass unnoticed. In an industrial application, the system can be used unthreaded prior to production, to study important parameters regarding the fabric characteristics (including finishing), appropriate needle and suitable speed of operation.

A significant improvement to this measurement would be obtained if the force sensor would be placed nearer to the needle, thus reducing the motional forces applied to the sensor. This configuration will be tried in future work.

It is important to emphasize that the measurement showed to be useful for comparative analysis in a laboratorial environment, considering both research and textile testing purposes. The creation of reference values for needle penetration force has to define a standard sensor set-up and signal pre-processing method, as well as to take in account sewing speed. This task will be significantly eased with an alternative sensor set-up.
3. Applications and perspectives for future work

Very few commercial products exist that provide process monitoring capabilities. One of the few examples is the Pfaff Doku-Seam system. It is used in airbag manufacturing to monitor thread tension during certain critical seams. Additionally, it monitors the backtack\(^1\) lever on the machine to assure that the seam never contains a backtack. The system is based on a PC and is able to supply all quantitative data about the seams produced.

Nevertheless, the development of systems for process control is not necessarily limited to specific machines as the Pfaff Doku-System. The experience and results collected by the research team suggest that other applications of diverse complexity are conceivable.

It is possible to conceive devices devoted to monitoring/controlling a single variable. If developed on the premise of modularity, machines may be upgraded with optional sensors and acquisition systems according to the end user's needs. Modules may be connected and integrated into a higher-level information structure, in which they receive control data according to the product, and provide process data to a central quality management system.

The immediate applications are the monitoring of the sewing variables. A monitoring system should consist of a sensor and hardware with conditioning, acquisition and signal processing capabilities. A simple keyboard/display would serve as input for reference values and tolerances. If the system were complemented with communication capabilities, automatic exchange of process data would be possible.

This kind of approach is suitable for the monitoring of presser-foot displacement, using either the ADL method or the comparison with a reference cycle. A monitoring algorithm can be developed to indicate a fault when one or a number of consecutive stitches are out of the defined tolerances. The same method can be applied to monitoring of thread tension peaks or peak ratios and, if operating at constant speed, of needle penetration values.

The next step would be the control of sewing variables.

In the case of thread tensions, the first step is the use of tensioner compression force sensors in the machines. A low-cost sensor for this purpose is currently under development within the research team. It measures the force exerted by the tensioner's disks on the thread, a force that can be related to the static thread tension presented in this work. The existence of this sensor, with conditioning and display, would allow a quantitative adjustment of thread tensions.

The optimal values for static thread tension would be determined using, for example, predicted thread consumption. A completely equipped sewing test rig would supply these values off-line, at the time of sample making. The operator would then quickly set the machine to these values, or the value could be transferred via network.

As a next step, it is desirable to replace the traditional tensioner by an active device, for instance using stepper motors to adjust spring tension, or using a controllable electromagnetic actuator. This would allow an automatic

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\(^1\) A backtack is when sewing direction is reversed for a couple of stitches to reinforce the seam at a specific point. In side airbags, where the seam is supposed to break when the airbag is inflated, a backtack, incorrect tension or other kind of defect may impair the function of the airbag.
adjustment of tensions. Combined with dynamic thread tension sensors, the process can be monitored and controlled centrally or locally. The possibility of sparing thread consumption measurement, at least at the local controller, would be an economical advantage.

New possibilities for adaptive control open up with this solution, like in-process variation of thread tensions. Combined with presser-foot displacement measurement, different tension can be adjusted when material thickness increases; an optimal solution when different numbers of layers are crossed in one seam, for example in trouser back cross seams.

Feeding system control can use several implementations. The first is an open-loop control in which linear motors vary presser-foot compression force with speed ("SRP-Speed responsive Presser-Foot", a technology developed by Pfaff). In [1] the replacement of the traditional spring-hinged system by a proportional force solenoid is proposed. In both cases, if force is to be varied with speed, the exact dependency between them is dependent on the sewn material, and can be determined by the off-line process planning tool. The next stage is a closed-loop control, in which force is adjusted according to the ADL’s [5] or reference cycles of the presser-foot.

In all cases of control, an adequate dynamic response of the actuators is vital to the success of the application. With the current actuator used on the presser-foot, response times are too large for a stitch-by-stitch control. Faster actuators or techniques to increase control resolution should thus be found.

The sewing test rig should serve both as a process planning tool, to determine monitoring and control parameters, as well as a sewability tester, to test materials before production. In the current state, the rig is configured as a research tool, but many enhancements are desirable to streamline the definition of control parameter values.

If the system is devised with actuators to vary thread tensions and/or presser-foot force, it is possible to design automatic procedures to aid in further experimentation. An example can be the automatic generation of combinations of thread tension adjustments and their immediate classification in terms of stitch adjustment (by means of thread consumption and/or tension peak ratios). The relations between thread tensions on different threads, found in [2], could in this way be confirmed and fine-tuned. Another possibility is that of setting sewing speed automatically and determine the ideal force setting for each sewing speed on a specific fabric (an “SRP tuning system”).

These automatic procedures can then be adapted to controller tuning procedures, whose exact implementation depends on the results found. Other applications include testing the compressibility behaviour of the fabric, and the determination of needle penetration references for ranges of sewing speed. Some of the described controller tuning methods may be regarded as “teach-in” procedures.

The use of neural networks to classify sewing parameters is also a very worthwhile alternative to follow in future work. The sewing situations created by the previously described automatic experimentation procedures can be fed into a neural network designed for pattern classification. It is possible that the neural network is able to determine when an undesirable sewing situation is occurring. This may be especially useful in the classification of the features related to needle penetration, which are to some extent blurred by noise and errors.

The exact physical implementation of the control devices depends on functional and especially economical factors. In low-end machines, low-cost sensors and hardware have to be developed. However, in high-end machines in which the cost of the acquisition system is low when compared to the cost of the machine,
the current configuration is appropriate at least for monitoring applications; it may not be able to keep up with the timing restrictions of a closed-loop controller. After the validation of the proposed algorithms with the software running on a PC, these may be transposed to embedded systems for specific applications, with all the advantages of processing efficiency, robustness and low price.

Two final suggestions are considered fundamental. The first is to apply all the developed techniques on a different type of machine, which is already been undertaken within the team, on a lockstitch machine. It is very important to learn if the analysis techniques developed are generally applicable, or to what extent they have to be modified.

The second suggestion is to set up a test rig in an industrial environment, collecting data from sewing operations occurring at the daily industrial routine. Only this data can confirm the effectiveness of the developed techniques. The first step could be the analysis of operations at constant speed, as are performed by most automatic machines.
4. References


