Adaptive Control of an Electromagnetically Presser-Foot for Industrial Sewing

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Abstract

This study describes some possibilities of setting up an adaptive control method for an electromagnetically actuated presser-foot in an industrial high-speed sewing machine. The control of fabrics feeding in sewing machines is difficult not only because of the complexity of relations between the intervening variables (material properties, sewing speed), but also because in many operations a varying number of material plies are crossed. This implies that the reference for the controller has to be adapted dynamically. Several methods, using PID and/or fuzzy logic control, have been tried and are described in this paper. A preliminary sewing test is able to provide data to tune the controller variables. With these adaptation techniques, the machine would be able to automatically adapt its feeding system according to the material being sewn.

1. Introduction and Objectives

1.1. Introduction

Gaining quantitative knowledge over the industrial process of joining flexible materials by sewing has become a major concern in the industrial manufacture of high-quality sewn products. Controlling the process is not only important in the traditional garment industry (where high-quality, flexibility and low set-up times have become even more important), but especially in the manufacture of technical textiles, in order to assure the correct function of the final product.

One important aspect of a sewing machine is the fabric feeding system. The objective of the study herein reported is addressed to the feeding system of an industrial overlock sewing machine for the design and

development of closed-loop controllers. This is a result of research work carried out by the authors and other team members in this area [1-4], to which researchers from three different departments at the School of Engineering have contributed.

This paper represents a further contribution towards the development of a new generation of sewing equipment integrating control systems designed to reduce set-up times, improve machine performance and increase flexibility in the production of high-quality sewn products.

1.2. Early studies in this area

For some decades now, the problem of sewing technology and its defects have been the basis for a regular research work. This research has been primarily undertaken in the universities and in 1961, Dorkin and Chamberlain [5], analyzed and discussed the relation of seam pucker (the effect of undulation of the fabric along the seam line) and its occurrence with the behavior of the feeding system. From this point on, many studies have been carried out regarding the following four major aspects:
• The study of seams quality [5, 6];
• The study of damage in sewing needles [7];
• The analysis of sewing threads tensions and its consumptions, related with the production of balanced seams [8-16] and its behavior during the sewing operation [17, 18], and
• The study of needle penetration and fabrics feeding system dynamics [8, 10, 14, 15, 19-41].

All these studies, and others not herein mentioned, have contributed essentially to a better scientific understanding of the sewing processes, performance and behavior of materials used, in order, on one hand, to solve the problems related with the process itself and, on

the other hand, to improve sewing machines and to enable the control of the sewing process. Some interesting solutions have been found and an active actuation system for the presser-foot, called "autodamp" [37], using an electromagnetic actuator with a "maglev" presser-foot controller was proposed [38]. An industry solution was also developed and implemented, using a linear motor to dynamically vary the pre-tension of the spring that exerts force on the presser-foot. This system, proposed and adopted by the German company PFAFF, is named SRP, the English acronym for "Speed-Responsive Presser-foot".

In 1992 however, based on a joint research effort between several researchers of the Department of Textile Engineering, at the University of Minho, and two researchers from the North Carolina State University (in the United States), a new research area has been undertaken, supported on a mechatronic research framework. Some of the findings and other achievements accomplished by the University of Minho team, which currently gathers several senior researchers from three different departments of the School of Engineering (Textile, Mechanical and Industrial Electronics), are summarized in the next topic.

1.3. Previous studies at the University of Minho

The feeding system of the overlock sewing machine comprises the following three components:
• A presser-foot;
• A throat plate, and
• A feed dog.

The throat plate is a smooth surface that supports the fabric being sewn with openings for the needle and the feed dog to pass. The presser-foot, with a helical spring working under compression in the presser-foot bar, is responsible for guaranteeing the required pressure to control fabrics feeding and to constrain their movement during needle penetration and withdrawal. The feed dog, made up by two teethed elements arranged in tandem (one in front of the needle and the other behind), is used to move (in a differential or uniform way) the fabrics a certain desired distance (called stitch length) between needle penetrations. During its movement, the feed dog rises above the throat plate to engage the fabric against the underside of the presser-foot before starting the advancing motion. Some of the problems in the sewing process rely on the interaction between the presser-foot and the feed dog, which results in an irregular stitch formation and other sewing defects (such as skip stitches and seam pucker).

In order to study the dynamics of the feeding process and to enable the control of the presser-foot, the sewing machine was instrumented with an LVDT (i.e. linear variable differential transformer) to measure the (vertical) displacement of the presser-foot and a miniature piezoelectric force transducer to measure the (compression) forces exerted on the presser-foot bar.

Fig. 1 highlights the transducers arrangement on an industrial overlock sewing machine.

The system built around the machine is composed of sensor conditioning hardware and actuator drivers connected to a Multifunction Data Acquisition Board plugged in a PC. The software, developed in Labview, provides hardware drivers, acquisition, display, storage and analysis functions [4]. It has also been used to prototype the closed-loop controllers.

Fig. 2 depicts two waveforms for different sewing speeds, measured in stitches per minute [spm], obtained with the standard presser-foot system equipped with a helical compression spring. This graph plots the displacement of the presser-foot bar over the machine's rotation angle. It can be observed that several contact losses between the presser-foot and the fabrics occur at high sewing speeds. This "bouncing", as mentioned, results in sewing defects.
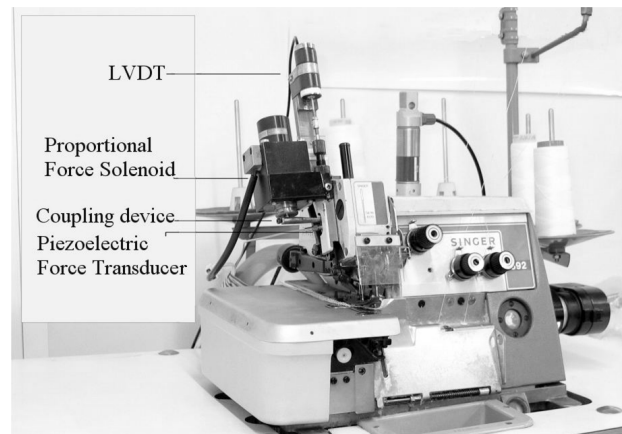

Figure 1. Industrial overlock sewing machine equipped with transducers and with a proportional force solenoid placed sideways to the presser-foot bar.
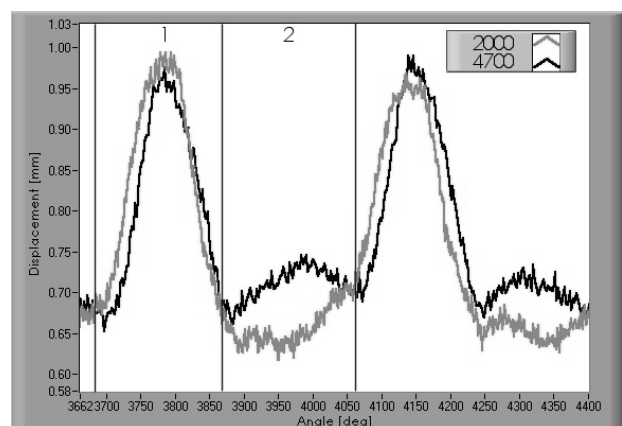

Figure 2. Presser-foot bouncing observed for two different tested sewing speeds: 2000 and 4700spm (phase 1 – fabrics feeding, and phase 2 – needle penetration and withdrawal/stitch formation).

To improve the feeding process, an electromagnetically actuated presser-foot (using a proportional force solenoid) was designed and implemented on a similar sewing machine. (Fig. 1 also highlights the adopted actuation system set-up.) This actuator presents inherent advantages over the traditional spring-hinged system. First tests showed that even using constant force, the behavior of the feeding system is much improved after the introduction of the solenoid.

The next step was to vary the force applied on the presser-foot, according to the sewing conditions.

1.4. Purpose and objectives of this study

The objective of this study is to develop a control system to vary force according to current operating conditions and adapt its reference point when the number of fabric plies varies.

2. Controller Design

2.1. Speed-dependent control

The first approach was a simple and cost-effective speed-dependent control, in which force was varied according to sewing speed (see Figs. 3 and 4). This is a commercial solution already available from one sewing machine manufacturer (albeit not using the same actuation system).
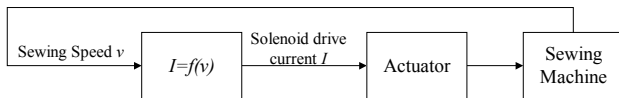
Figure 3. Speed-dependent open-loop control implemented according to the control curve example presented in Fig. 4 for a rib fabric.

Although this solution is simple and represents an interesting advancement, there is no monitoring of the output variable itself (presser-foot displacement), meaning that abnormal situations are not detected. Ideally, the system should be able to detect defect situations, which can only be achieved with a closed-loop control using presser-foot displacement as feedback variable.

2.2. PID closed-loop control

The first implementation of a closed-loop controller uses PID control, as detailed in [42] and [43]. The force applied to the fabric is varied depending on the error computed between the maximum presser-foot displacement values measured and the reference value. Fig. 5 shows the set-up that was used for first experimentation.
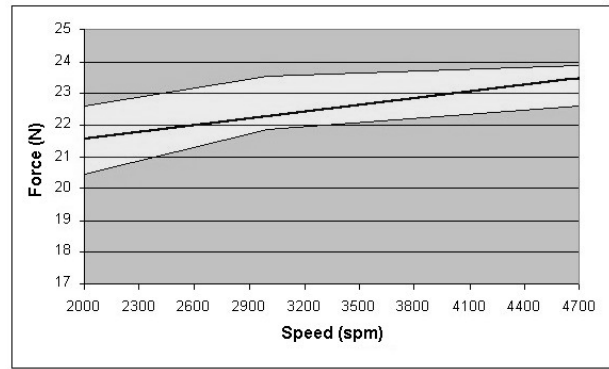
Figure 4. Ideal range for presser-foot force (using a rib 1×1 fabric) obtained by laboratorial testing.
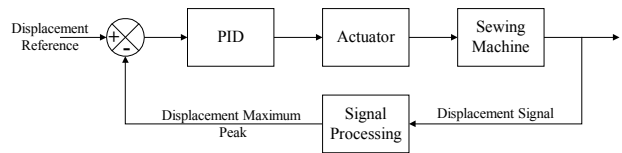
Figure 5. Closed-loop control block diagram.

This controller was found to be quite suitable for the application. Fig. 6 shows the behavior of the control system during a low-to-high speed transition (approx. 2000 to 4700spm), following a 0.9 mm maximum displacement reference. After 4 to 5 stitches, the system is able to reestablish the presser-foot height to the reference point. Considering the limited dynamic response of the actuator (about 50 ms response time to a current step), this is a truly interesting performance. But in terms of feeding efficiency, the end result depends mainly on the setting of the displacement reference point, which has to take into consideration the fabrics being sewn and the number of plies.
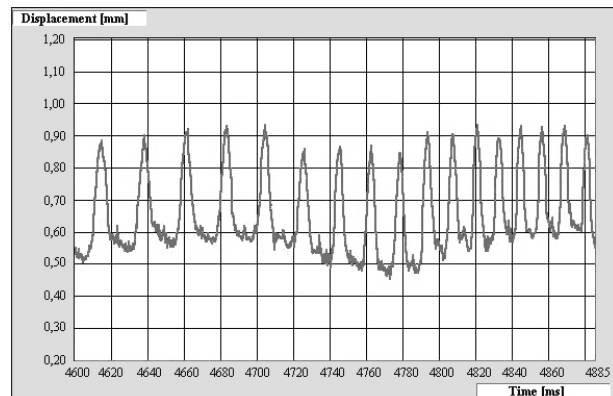
Figure 6. Presser-foot displacement waveforms obtained from low-to-high speed transitions.

The fact that, in many operations, the number of fabric plies varies during the seam, presents an additional challenge. The solutions presented in the next sections were designed to overcome this difficulty.

2.3. Combined PID/Fuzzy logic controller scheme – reference switching

The first attempt to provide adaptation to a varying number of plies is schematically depicted in Fig. 7.
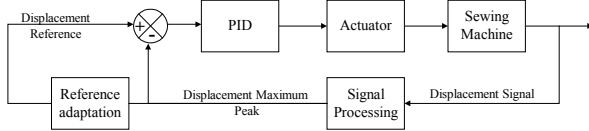

Figure 7. Adaptation based on predefined reference values.

The fuzzy logic controller herein proposed compares the measured displacement with fabric displacement ranges defined previously. If the displacement matches a predefined displacement range (a specific number of plies) a new reference value will be set. If displacement is not within the range expected for the individual segments of the seam, over a number of stitches, a sewing defect can be indicated (example: fold or seam missing the fabric).

Fig. 8 shows a test result of this solution. In this test, a rib 1x1 fabric was sewn at a low constant speed (approx. 200spm) for testing the recognition of different fabrics and number of plies. The seam begins with the presser-foot "climbing" to 4 plies of fabric, crossing over to 2 plies and finally leaving the fabric behind. The graph represents the displacement error, the displacement, the force control signal and the reference setting.

The reference is switched according to predefined displacement ranges, and it can be observed how this reflects on both the error as well as on the force output, that behave more or less as expected. Some abrupt variations are present in the force control signal, at the points at which the reference is switched. The displacement does not reflect these peaks, as the actuator is not fast enough to turn them into actual force.
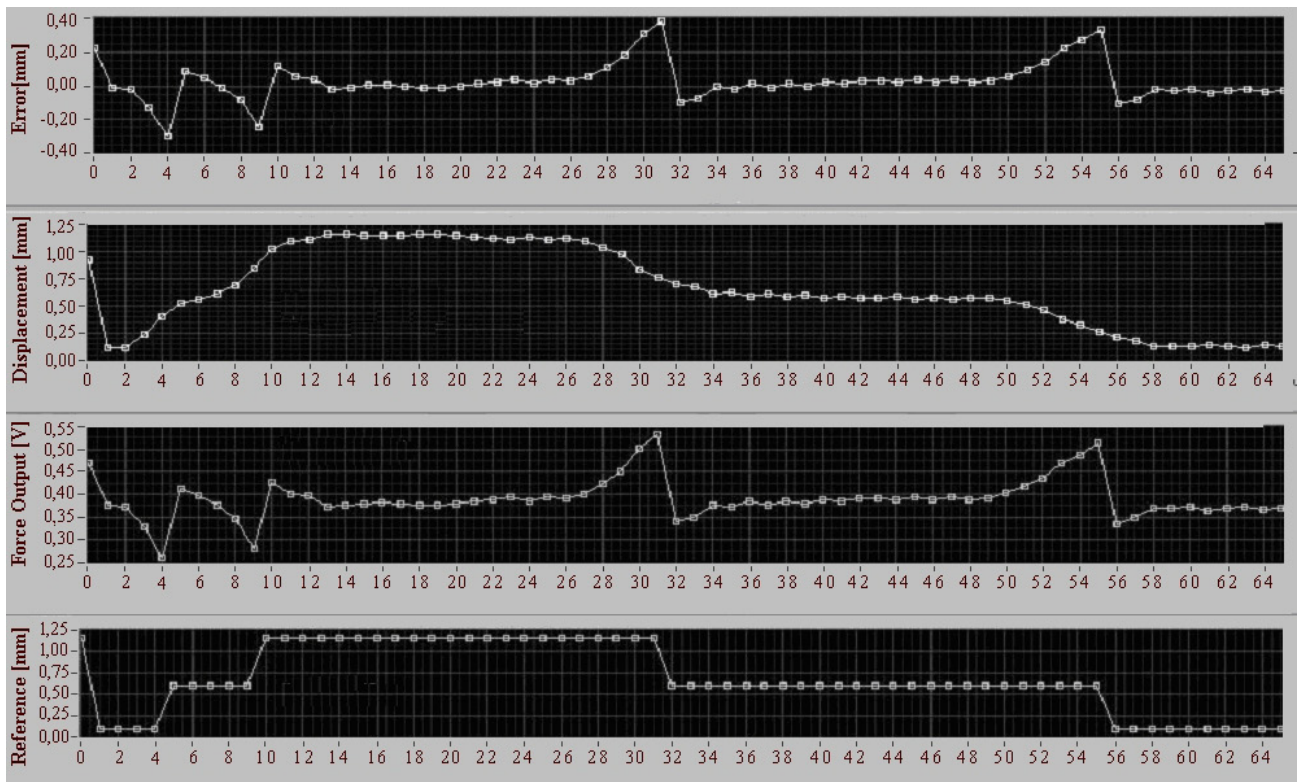

Figure 8. Test results of controller based on switching of the reference through fuzzy logic. Rib 1x1 fabric. From top to bottom: Displacement error [mm], displacement [mm], force control output [V] and reference [mm].

2.4. Combined PID/Fuzzy logic controller scheme – Fuzzy reference switching and force offset control

An alternative to the approach presented in the previous section is the one depicted in Fig. 9.
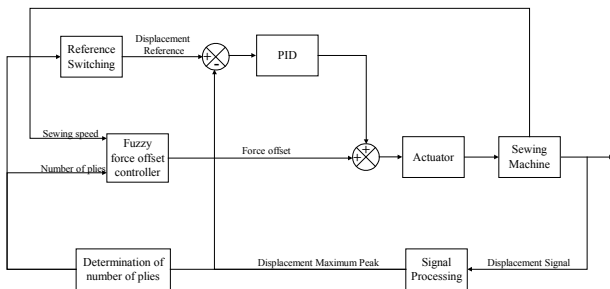

Figure 9. Alternative reference switching controller with fuzzy logic force offset control.

In this case, the adaptation of the reference is complemented with an adaptation of the force offset, depending on the number of plies and sewing speed. This controller is expected to behave as illustrated in Fig. 10, when the number of plies is varied. The definitions of the fuzzy interference set for the combined PID/fuzzy logic controller can be observed in Fig. 11, while the implemented rules are listed in Tab. 1.
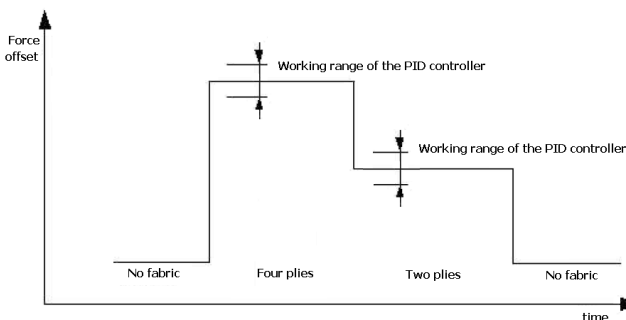

Figure 10. Behavior expected for force offset and reference switching controller.

Practical tests have shown that this controller's action is very similar to the simple reference switching solution. It has been noticed that the force output signal does not suffer the same abrupt variations at reference switching points. This is due to the fuzzy force offset control, that is able to anticipate the force needed for a new number of plies or sewing speed.

Although the behavior of these new control solutions have shown to be most interesting, the actual value in terms of fabric feeding efficiency (and thus stitch quality) is still dependent on a correct determination of references for each fabric, number of plies and sewing speed, to tune the fuzzy logic blocks. In the cases presented, they were established by careful laboratorial

testing. In industry, however, this testing would be too time-consuming, representing an overhead that would significantly limit the possibilities of practical use. A solution to this issue is the "teach-in" method described in the following section.
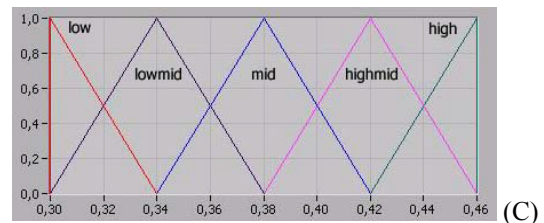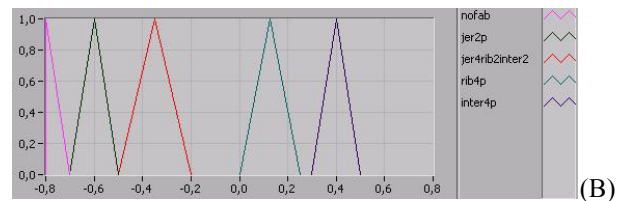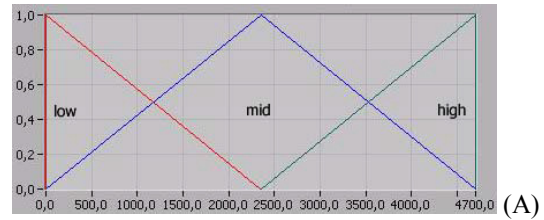

Figure 11. Fuzzy interference set for the combined PID/fuzzy logic controller: Antecedence (A) Sewing speed and (B) Presser-foot displacement range; Consequence (C) Force on the presser-foot.

Table 1. Implemented Rules for the combined PID/fuzzy logic strategy.

Rule No.	IF speed	AND displace	THEN force
1	low	nofab	low
2	low	rib2p	mid
3	low	inter2p	mid
4	low	rib4p	high
5	low	inter4p	highmid
6	mid	nofab	low
7	mid	rib2p	mid
8	mid	inter2p	mid
9	mid	rib4p	high
10	mid	inter4p	highmid
11	high	nofab	low
12	high	rib2p	mid
13	high	inter2p	mid
14	high	rib4p	high
15	high	inter4p	highmid

2.5. Controller tuning by "teach-in" procedure

In order to define the parameters for the controllers, some tests were carried out varying the sewing speed and the force output independently.

The displacement of the presser-foot was measured during these tests, for a range of sewing speeds and presser-foot forces. Fig. 12 and Fig. 13 display the outcome for two different fabrics (rib and interlock respectively). The graphs show how displacement varies with force and speed, while sewing just two plies of each fabric. Based on these data, almost all the parameters for controller tuning can be extracted automatically. Using signal processing techniques developed in [4], it is possible to determine the point at which presser-foot bouncing ceases to occur.
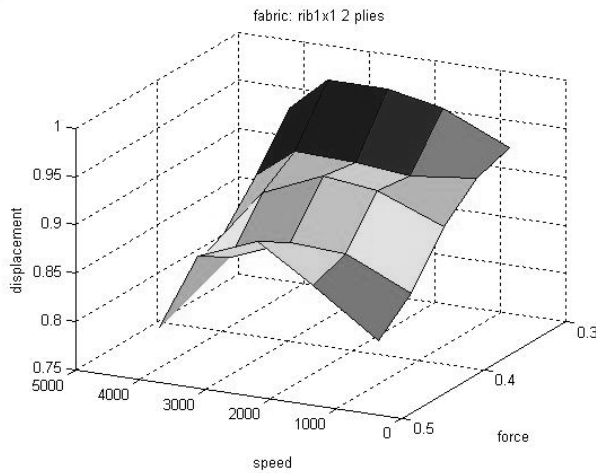

Figure 12. 3D chart obtained for two plies of a rib fabric (displacement [mm] vs speed [spm] vs force signal applied to the driver of the presser-foot bar actuator [V]).
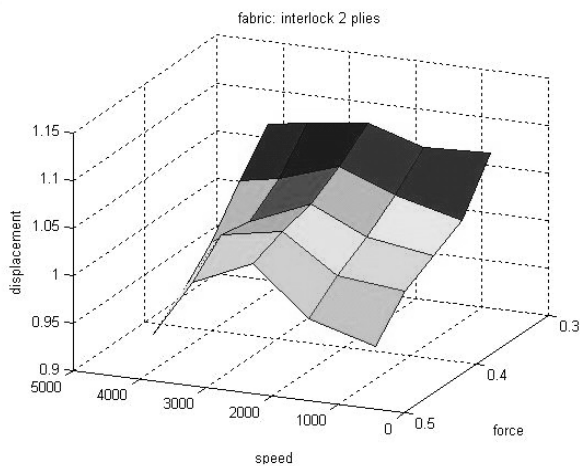

Figure 13. 3D chart obtained for two plies of an interlock fabric (displacement [mm] vs speed [spm] vs force signal applied to the driver of the presser-foot bar actuator [V]).

This marks the upper limit of the admissible displacement. The lower limit is obtained using the highest force that can be exerted by the actuator. One way of defining the displacement reference can then be the average of these two values. This setting may then be readjusted by the user, or the user can determine the best setting by performing a simple test to determine the maximum force that can be exerted by the presser-foot without damaging the fabric or otherwise producing undesirable results. This may be accomplished very easily at low speed, by producing a seam starting with a very low and ending in a very high force.

Once the ideal displacement is defined, the corresponding force will be used as force offset for a specific number of plies and sewing speed.

The displacement ranges for recognition of the number of plies are then set as margins around the displacement references previously determined. The correct setting of these margins is fundamental for a proper operation of the system. The ranges are defined by the maximum and minimum displacements determined previously, for each number of plies. If these ranges do not overlap, they can be set as reference switching margins. If they do overlap, the detection margins have to be narrower. In this situation, it is possible that the number of plies may be misinterpreted by the controller. However, this would only happen in extreme situations that most probably result from defect situations.

According to this principle, unknown fabrics can be easily defined and saved in a database for future usage. The PID controller has a much less important role in this control system, only compensating for small differences. It is possible that its control parameters can be the same for all situations without affecting the overall performance of the controller, but this has to be confirmed in further testing.

Ultimately, the PID controller can be completely eliminated, basing all of the control on the fuzzy block, as shown in Fig.14.

The development of procedures and software to perform this automatic sewing test are under way. If well-succeeded, they may result in totally adaptive controllers, which can be tuned in one or two minutes and at the expense of a small sample of fabric.
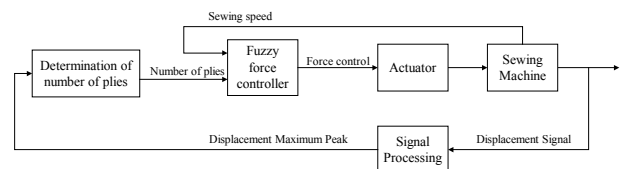

Figure 14. Controller architecture based on fuzzy blocks.

2.6. Summary of developments

Several controllers have been designed, prototyped and tested to control the feeding system.

The efficiency of the speed-variable force control depends on the correct adjustment of the speed-force relationship. From this point of view, the PID controller presents a clear advantage, in which the force applied by the presser-foot is varied depending on the error computed between the maximum presser foot displacement values measured and the reference value. The measurement of presser-foot displacement also enables monitoring of the sewing process, providing the detection of sewing defects, such as wrinkles or folds.

A combined PID/Fuzzy logic controller has been proposed, to provide a reference and force offset adaptation to the number of plies and sewing speed.

Finally, the latest developed controller also includes a "teach-in" procedure to tune the controller's parameters while varying sewing speed and the force output independently.

3. Conclusions and Future Work

Controllers based on a combination of PID/Fuzzy logic control were tested and seem to perform as expected. An exact evaluation of the ideal architecture, in terms of the final seam quality, will be undertaken in future work. This study should also include the possibility of a controller entirely based on fuzzy logic.

Another important aspect is the development of procedures for preliminary sewing tests ("teach-in" procedures) and quality. Future work will be focused on these two aspects.

In all cases, the control system is still somewhat limited due to the dynamic response of the actuator. Future developments in the field of actuators will certainly allow a further improvement of the feeding system behavior.

The developments carried out on the design of specific controllers for the sewing process represent a further step towards more efficient sewing machines. Although other steps are needed to accomplish the team's full objectives, this work is a very significant contribution to eliminate *trial-and-error* tuning of the sewing machine, towards a highly flexible and controlled operation.

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