Differential Feed Control Applied to Corner Matching in Automated Sewing

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Abstract— **This paper presents a new method for independent feed control in an automated sewing cell. This is important to match the corners of the parts as well as to compensate for uncertain material characteristics and variations in the length of the parts. In this method, the feed speed for the two parts is controlled independently, based on measurements of the endpoints of the parts while keeping an equal sewing force in both parts. Different strategies for correcting errors are presented and experiments are shown to evaluate the different strategies. Possibilities for using the methods to match reference points during the sewing are discussed.**

I. Introduction

When automating sewing in manufacturing, many complex tasks have to be solved. Due to varying material characteristics and uncertainties in the handling of the materials, the system has to be highly flexible to ensure a good quality of the resulting assemblies. A combination of sensor systems and advanced control strategies is needed to achieve satisfying results. The literature shows that a common method to control a sewing operation is to use sensor-based feedback control for the tension in the parts as well as for controlling the seam allowance.

Gershon [1], [2] presents an automated sewing system that includes tension control and control of the seam allowance in real-time. A single robot is used for both handling and for the sewing operation.

Gottschalk and Seliger [3] present a sewing machine with rollers in front of and behind the needle, which is used for sewing of curved materials. By using different feeding speeds, different seam lengths can be matched.

Seliger and Stephan [4] present an overview of challenges in automated sewing with focus on material handling and sewing of 3D-shaped workpieces.

Kudo et al. [5] present a multi-arm robot control system for sewing. Two robots are used to guide a single piece of limb fabric on the table during the sewing operation. Force sensing is used to control the fabric tension while visual feedback is used to control the seam path. A task-oriented robot language with graphical user interface enables programming of complex motion.

Winck et al. [6] describe an approach for fabric control during a sewing process. The feed mechanism of the sewing machine used is replaced by a servo-controlled manipulator to both feed and control two sheets of fabrics individually. Position control is done using a vision system that tracks threads in the fabric.

Koustoumpardis and Aspragathos [7], [8] present several papers about an intelligent sewing cell. They use fuzzy logic and neural networks to control the sewing process. They estimate the properties of the material prior to the sewing operation and use this information for the fabric tension control. The goal is to be able to sew a wide range of materials with different characteristics.

Wetterwald et al. [9] present a sewing cell which is closely related to the sewing cell used in this project. It is used to sew two parts of similar shapes. Motion sensors and a triangulation-based edge sensor system are used to control a single robot that presses the parts together onto a table and moves them during the sewing operation.

Different part systems of the sewing demonstrator used in this paper have already been presented in other publications. These are the following:

- Preliminary experiments were presented in [10].
- The sewing cell hardware and the first version of the control system were presented in [11].
- [12] discusses the real-time behavior of the control loops. The delays in the system are analyzed and discussed.
- A method for corner matching was presented in [13].
- In [14], feed-forward velocity and setpoint generation based on a geometric model were presented.
- Material handling is presented in [15].

This paper addresses one challenge in automated sewing of two parts, which is to control the feed speeds of the two parts during the sewing operation such that the corners of the parts or other reference points match. To achieve this, the feed speed for the two parts is controlled independently, based on the distances between the gripping points and the needle, while the sewing force is kept constant.

II. Sewing Cell Description

This section describes the sewing cell in the current state. Detailed descriptions of the earlier versions can be found in [11], [13]. While the basic layout is similar, several improvements have been included in the current version. The sewing cell is shown in Fig. 1

A. Components

Sewing machine

The sewing machine used in the demonstrator cell is a standard industrial sewing machine with modifications that enable electronic control of the

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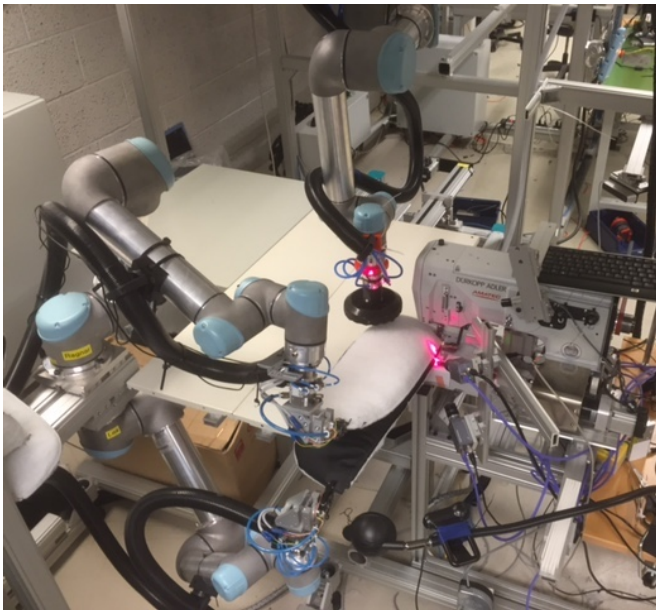

Fig. 1. The sewing cell demonstrator consists of a sewing machine and three robots that handle the parts during the sewing operation. Sensor systems are installed to measure the force in the parts and the edge position in front of the needle.

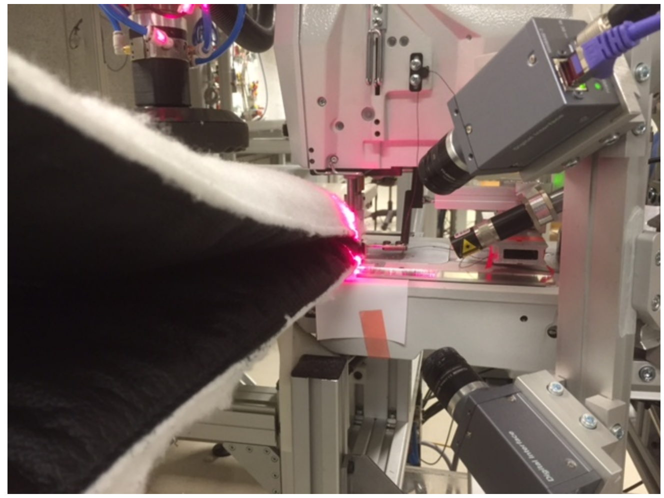

Fig. 2. The edge sensor system consists of two cameras and a laser that projects a laser line directly on the lower part. A mirror is used to project the laser line on the upper part.

functions needed in the sewing operation as for example lifting the sewing foot or cutting the thread. The feeding mechanism can be controlled from the PC, Both the upper and the lower stitch length can be controlled independently as well as the sewing frequency. Additionally, the sewing machine can be opened which makes it possible to feed the parts into the sewing machine using the robots.

Robots
: Two Universal Robots UR-6-85-5-A are used to control the parts during the sewing operation. The robots are real-time-controlled with a cycle time of $125\,\mathrm{Hz}$. Pincer-like grippers are attached to the robot tool holder to grip the parts. A third robot is installed in the cell and is used for material handling. The gripper for this robot is a soft pad which can press the part to the table and move them around. This robot is also used to control the last part of the seam, since the control robots have to release the parts about $10\,\mathrm{cm}$ in front of the sewing machine to not collide.

Force sensors
: Force sensors are installed on the sewing robots to be able to measure the sewing force during the operation.

Edge sensor
: An edge sensor system is installed in the sewing cell based on two cameras, a line laser and a mirror. It is used to measure the edge position a few centimeters in front of the needle. The sensor system, shown in Fig. 2, is based on laser triangulation.

Movable table
: A movable table is installed to support the part during the sewing operation. Due to the limb nature of the parts, without support, the parts would sag which leads to high friction at the sewing machine. To prevent this, the table supports the lower part, and is moved synchronously with the robot tools towards the sewing machine. The upper part is supported by the lower part.

Control PCs
: Three control PCs are used using mainline Ubuntu with lowlatency kernel. The control system is based on ROS and is mainly programmed in Python and C/C++. Different ROS nodes in the control system are used to connect the control software with the hardware components. An overview of the different elements of the control system is shown in Fig. 3.

B. Control System

To guide the parts during the sewing operation, two robots are used that grip the parts in the corners and lead them towards the sewing machine. Each of the robots operates on a different virtual sewing plane, as shown in Fig. 4. This is to ensure that both parts can move freely and that the robots do not collide with each other. A feed forward velocity with corrections from an edge controller and a force controller are used to generate the paths of the robot. Fig. 5 shows how the robot movement is generated. The force controller generates a movement away from or towards to the needle based on the force measured in the tool. The force setpoint is typically set to $2\,\mathrm{N}$. The edge controller generates a rotation around the needle based on the measured edge error a few centimeters in front of the needle.

The synchronization between the two robots is presented in Section III.

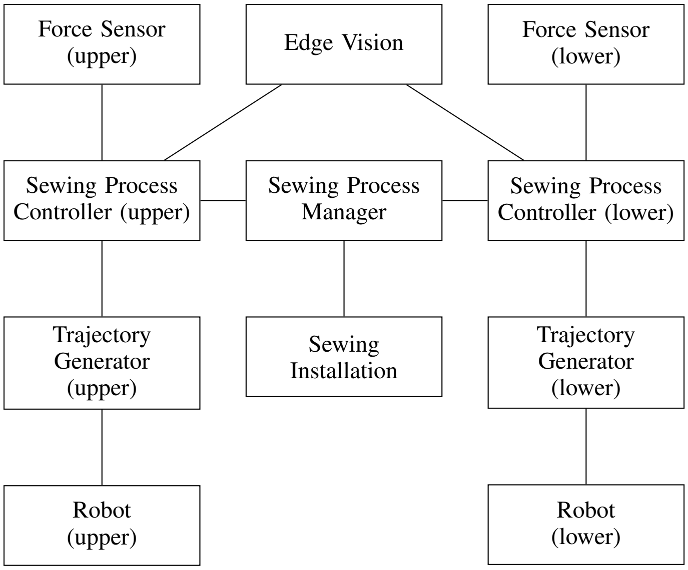

Fig. 3. Overview of the components in the system.

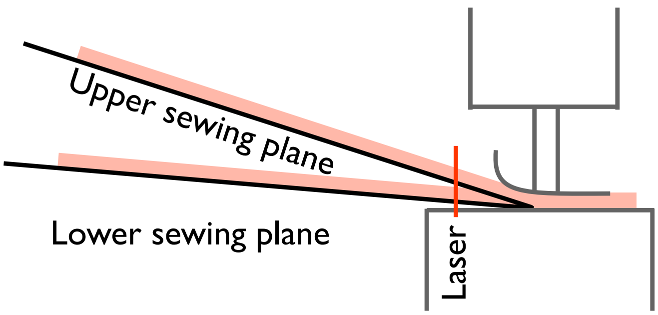

Fig. 4. Different virtual sewing planes are used for the two robots to prevent collisions and to ensure that the parts can move freely.

Since the robots grip the parts in the corners, they have to release the parts about 10 cm before the seam is finished in order to not collide with the sewing machine. A third robot which is located beside the sewing machine is installed in the sewing cell to control the parts in the last part of the seam.

III. Differential Feed Control

A challenge in automated sewing is matching the corners of the parts after the sewing operation. Due to different material characteristics and physical effects, the feed speed of the upper and the lower part can mismatch. In this case, there may be an offset at the end of the seam as shown in Fig. 6. Another reason for the offset may be that the lengths of the edges that have to be matched are not initially equal. In other cases it may be desirable to match different length of material which can be beneficial in order to achieve a desired shape of the assembly.

A method for corner matching was presented in [13]. In this method, both robots are commanded to keep the same distance between the gripping point and the needle. The robots are free to rotate around the needle while keeping the constant distance in order to compensate errors using the

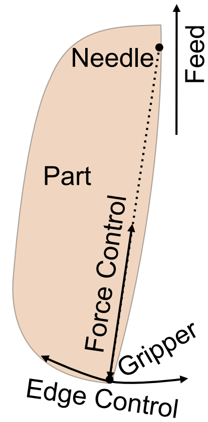

Fig. 5. The control concept of the robot for edge and force control. The two controllers work independently.

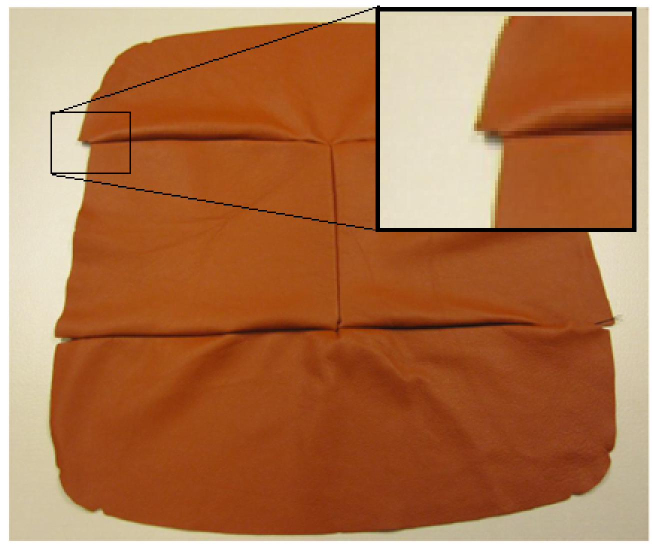

Fig. 6. Without velocity synchronization, the corners of the two parts are not ensured to match.

edge controller. The force in both parts is measured using the force sensors attached to the robots tools and while the robot with the lower sewing force is in force control mode and seeks to keep a constant sewing force of typical 2 N, the robot with the higher force measurement is in distance control mode and is holding the same distance to the needle as the force-controlled robot. Doing this, the force measured at the distance-controlled robot may be several times larger as the intended sewing force, depending on the reason for the mismatch. This higher sewing force results in a reduced feed speed for the part, but may influence the quality of the sewing. Another drawback of this method is that a higher tension along the edge of the part may influence the edge measurement. This is due to changes in the shape of the part edge in the image of the vision system, which can lead to inaccuracies in the edge detection. This is especially a problem if the gripping point is not in the corner of the part or if the edge of the part is curved.

The new method proposed in this paper addresses the drawbacks of the method shown in [13]. It was already mentioned in [10], but first implemented in the current state of the sewing cell. Instead of controlling the robots to the same tool-needle-distance while ignoring the sewing force mismatch in one of the robots, the new method controls the distance by changing the feed speed directly in the sewing machine. This is possible due to independent feeding mechanisms in the sewing machine for both parts. The feed speeds are mechanically adjustable and controlled by servo motors.

The method works by measuring the sewing force in both robot tools as well as the tool-to-needle distance for both robots. Both robots are controlled to keep a constant sewing force of $2\,\mathrm{N}$ which prevents wrinkling or overstretching, which both can result in faulty edge measurements. At each time of the sewing operation, a desired setpoint for the tool-to-needle difference is generated by a geometric model, typically $0\,\mathrm{mm}$ for identical parts. If the measured distance difference mismatches, the differential feed speed for the two parts is altered to compensate the difference.

Different strategies can be:

- Minimize the error as fast as possible
- Compensate the error linearly and monotonous over the whole seam length
- Compensate the error over a certain desired part of the total seam

The third strategy can for example be used to place the compensation in a wanted part of the material, not necessarily in the beginning or the end of the seam

Another scenario is in case of sewing parts that should be used to generate curvatures. In this case, the two materials can be designed to have different initial length which are not seen as error, but the same strategies can be applied to this case. Furthermore, reference points in the geometric model of the parts can be defined to indicate which positions on the two parts have to be matched. During the sewing operation these points are aligned using the differential feed control.

As mentioned before, the desired distance difference for identical parts is $0\,\mathrm{mm}$ during the whole sewing operation. In the beginning of the sewing operation, an initial force control is performed before the sewing machine is started. In case of a initial distance difference, a strategy is chosen, typically to compensate the error over the whole seam length, which ensures that also the center of both parts is matched instead of only the corners. However, if two different parts are sewn, it may be desirable to match different positions of the edge with each other, which can be done by a different setpoint generation for the controller.

The distance difference l_{diff} is defined as

$$l_{\text{diff}}(x) = l_{\text{upper}}(x) - l_{\text{lower}}(x) \tag{1}$$

where l_{upper} is the tool-needle-distance for the upper robot and l_{lower} is the tool-needle-distance for the lower robot, which depend on the needle position on the part edge. x is a parameter which indicated the needle position on the part edge. x is defined to be between 0 at the start of the seam and 1 at the end of the seam. The distance error is calculated as follows:

$$l_{\text{err}}(x) = l_{\text{diff}}(x) - l_{\text{set}}(x) \ . \tag{2}$$

l_{set} is here the distance difference setpoint. The generation of l_{set} would be as follows in the case of an initial distance difference error which has to be compensated over the whole seam:

$$l_{\text{set}}(x) = l_{\text{err,init}} \cdot (1 - x) \tag{3}$$

The stitch length $l_{\text{stitch,upper}}$ and $l_{\text{stitch,lower}}$ for the two feeding mechanisms are then calculated by

$$l_{\text{stitch,upper}}(x) = l_0 - k_{\text{p}} \cdot l_{\text{err}}(x) \tag{4}$$

and

$$l_{\text{stitch,lower}}(x) = l_0 + k_{\text{p}} \cdot l_{\text{err}}(x) \tag{5}$$

where k_{p} is the control constant of the resulting proportional controller. l_0 is the average desired sting length, typically around $5\,\mathrm{mm}$. An upper threshold is set for $k_{\text{p}} \cdot l_{\text{err}}$.

With a constant sewing frequency of $10\,\mathrm{Hz}$, the resulting feed speeds can be calculated:

$$v_{\text{feed,upper}}(x) = l_{\text{stitch,upper}}(x) \cdot 10\text{Hz} \tag{6}$$

$$v_{\text{feed,lower}}(x) = l_{\text{stitch,lower}}(x) \cdot 10\text{Hz} \tag{7}$$

In comparison to the previously presented method, the new method gives a better control over how the error is compensated, and enables model-based generation of distance difference setpoints l_{set} such that different points on the two part can be matched with each other. This can be used to generate different shapes of the assembly.

IV. Experiments

In order to test the new corner matching method, experiments were conducted. As discussed previously, the two main reasons for undesired corner mismatch are initial different length of the materials or different material characteristics and mechanical effects. To demonstrate the new method, a series of experiments has been conducted with parts of the same length as well as with parts of different length to generate an initial error. This introduced error of $3\,\mathrm{cm}$ is believed to be larger than the errors that would occur in a usual seam caused by varying material characteristics such as varying stiffness and thickness of the materials and mechanical effects such as friction.

For both cases, the following three strategies were tested:

- The differential feed controller is disabled.
- The differential feed controller compensates the error as fast as possible.
- The differential feed controller compensates the error linearly over the whole seam.

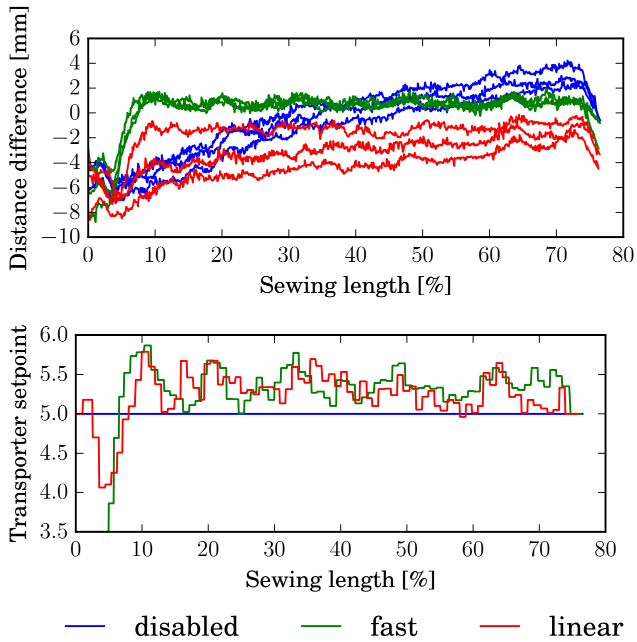

Fig. 7. Distance differences and transporter setpoints for sewing of two similar parts with different strategies.

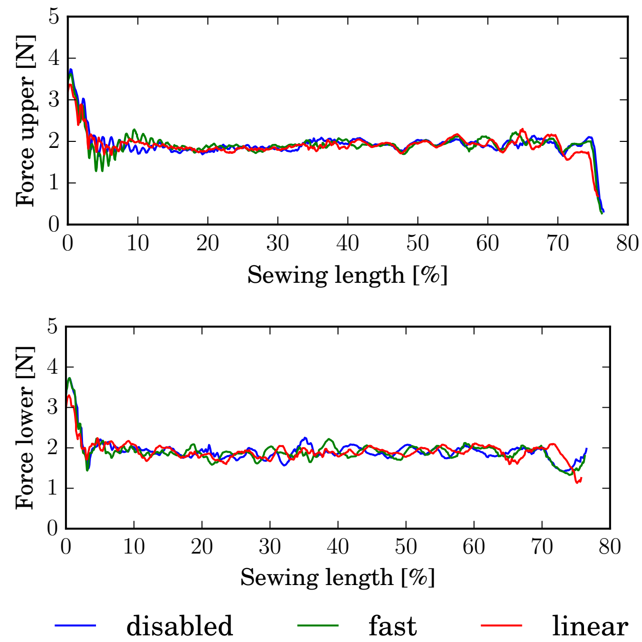

Fig. 8. Sewing forces for sewing of two similar parts with different strategies.

Finally, as a proof of concept, an experiment was conducted implementing a strategy where the error is compensated in a defined region of the seam, between $30\,\%$ and $60\,\%$ of the seam.

For all cases, the distance differences l_{diff}, the transporter setpoint for the feed mechanism, and the sewing forces for both robots were recorded. The relation between this setpoint and the stitch length is approximated to be linear. Due to the constant sewing frequency, the feed speed is proportional to the stitch length. In the following plots, only the upper transporter setpoints are shown. The plots for lower setpoints would correspond to a mirrored version of the shown plot, mirrored around a transporter setpoint of $5\,\mathrm{mm}$.

Fig. 7 shows the distance difference for parts with similar length, as well as the transporter setpoint for the upper feed mechanism for one of the experiments for each strategy. It can be seen that there is an initial error in all of the data series. The explanation for this is that due to the inclined sewing plane for the upper part, gravity pulls the robot towards the sewing machine. This does not happen for the lower part which is supported by the sewing table.

For the case of the disabled controller, the distance difference increases from about $-6\,\mathrm{mm}$ until about $2\,\mathrm{mm}$. The bend that can be seen in the last part of the plot is due to a stopping trajectory for the robots before they release the parts. This behavior is present in all experiments, but does not influence a real sewing operation since then the third robot takes over the control of the parts while the control robots release the parts before they are stopped.

In the second strategy, it can be seen that the controller compensates the error in the first $10\,\%$ of the seam, while in the third strategy, the error is compensated over the whole length. In the beginning of the sewing process, the distance difference is changing quite fast, before the typical behavior for the strategy can be seen. This is the case for all experiments and happens in the starting phase of the seam and may be due to different startup behavior for the controllers and the robot movements. Mechanical effects may also contribute.

The plot for the transporter setpoint shows a larger change in the stitch length for the fast compensation strategy as expected. It can be seen that there is an oscillation in the controller. Further investigations have to be done to see whether this effect is due to a non-desired coupling with the edge controller or if it is due to delays in the control system.

Fig. 8 shows the sewing forces for the upper and the lower robot. It can be seen that after the startup phase, and before the parts are released, the sewing forces are between about $1.5\,\mathrm{N}$ and $2.5\,\mathrm{N}$. This is a considerable advantage to the control method described in [13].

Fig. 9 shows the distance difference for parts with different length, as well as the transporter setpoint for the upper feed mechanism for one of the experiments for each strategy. As for the first series of experiments, the initial measurement for the distance difference is smaller than the expected one, here about $20\,\mathrm{mm}$ instead of $30\,\mathrm{mm}$. The effects for the different strategies are much more clear than in the first experiment. Here, one can see that some overshooting occurs in the controller. Notable is that the controller first seems to control in the wrong direction. One can see that the start force for the lower part is larger than the force for the upper

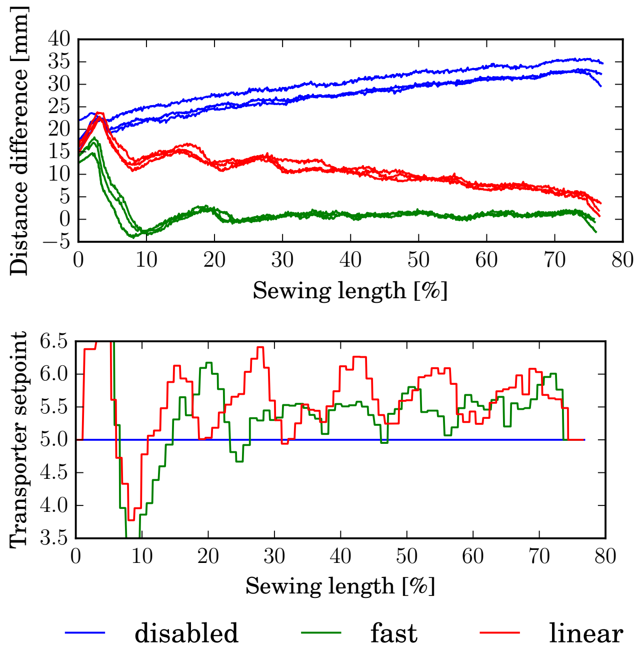

Fig. 9. Distance differences and transporter setpoints for sewing of parts with different edge lengths with different strategies.

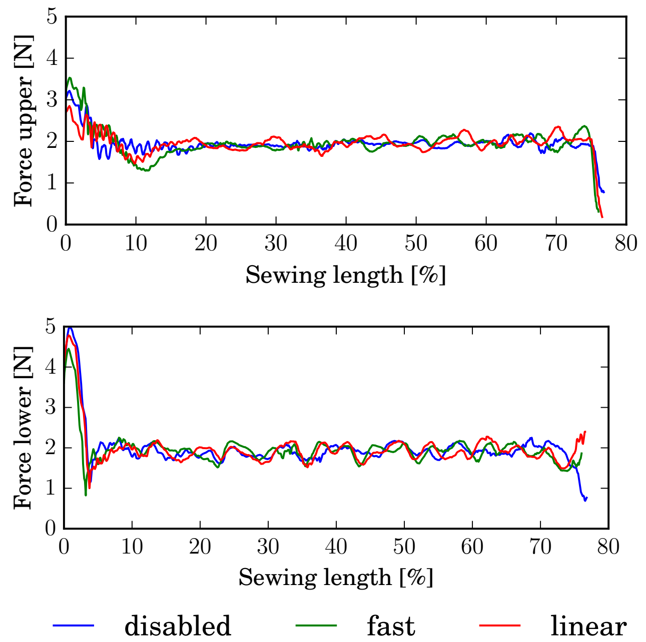

Fig. 10. Sewing forces for sewing of parts with different edge lengths with different strategies.

part. The result of that is a faster movement of the lower robot in the direction of the sewing machine. Since the force controller is faster than the distance controller, this leads to a temporary increase of the distance difference. The plot for the transporter setpoint shows for the case of the fast control scheme that the stitch length is increased to the maximum in the first $7\,\%$, while in the same region in the distance difference plot, the value increases. Afterwards, when the force controller has regulated the sewing force towards $2\,\mathrm{N}$, the distance controller catches up and the transporter setpoint decreases.

Regarding the experiments, it has to be noticed that the introduced error is much larger than in a real scenario where the parts can be designed to fit and variations are much smaller.

When the tools release the parts, the sewing machine is stopped to be able to visually inspect the result. This inspection shows that the initial difference is compensated as seen in the plots.

Fig. 10 shows the sewing forces for the upper and the lower robot. Like in the previous experiment, it can be seen that after the startup phase, and before the parts are released, the sewing forces are between about $1.5\,\mathrm{N}$ and $2.5\,\mathrm{N}$.

Fig. 11 shows the distance difference and the transporter setpoint for the special case where all the compensation is intended to happen between 30 and $60\,\%$ of the seam. One can see an overshooting in the beginning. As seen in the other experiments, the difference first increases due to a higher sewing force for the lower part at the start of the operation. The initial setpoint for the difference is set to the starting value before it decreases linearly between 30 and $60\,\%$. The measured difference follows this behavior. The experiment shows that the desired behavior works as intended, but that some further tweaking of the controller is necessary to obtain a behavior without overshooting.

Fig. 12 shows that the also the sewing forces for this experiment lie in the range between about $1.5\,\mathrm{N}$ and $1.5\,\mathrm{N}$ for the main part of the seam.

V. Conclusion

This paper presents a new method for independent feed control of the two parts which can be used for corner matching and matching of reference points during the sewing operation. Different strategies are presented and demonstrated for compensation of error introduced by uncertain material characteristics, mechanical effects or initial length differences. Furthermore, methods are presented how the same strategies can be used to intentionally match different reference points on the part edges or to compensate errors in specific regions of the seam. Experiments were conducted showing that the proposed methods work in a demonstrator cell. The behavior of the control system has been discussed. The experiments show promising results and show that the sewing force is considerably lower than in the previously presented method. Different strategies have been tested and work as intended. Some areas for improvement have been identified, for example an overshooting behavior if large deviations from the setpoint are present.

VI. Future work

The experiments have shown that tweaking of the control parameters is necessary to achieve better results in the case of large errors.

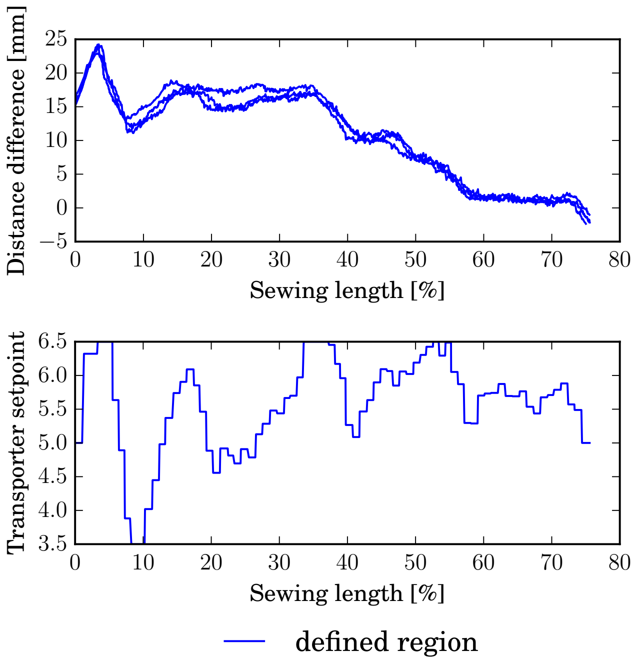

Fig. 11. Distance differences and transporter setpoints for sewing of parts with different edge lengths. The initial error is compensated in a defined region, between 30 and 60 % of the seam.

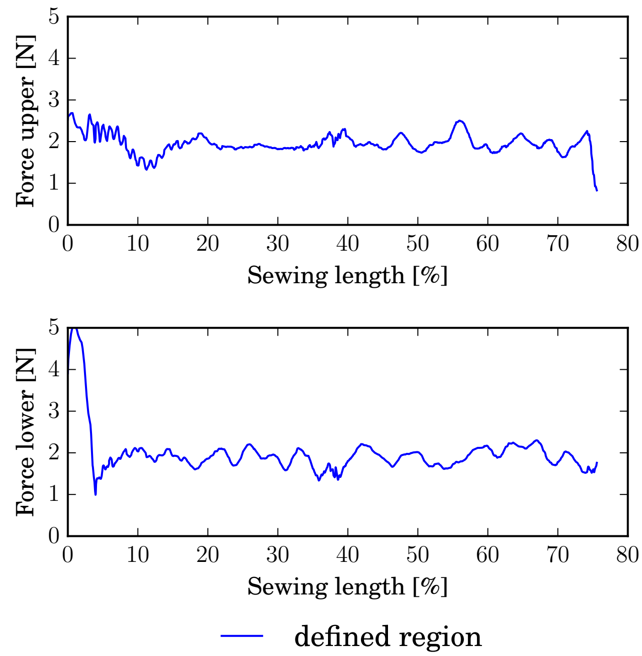

Fig. 12. Sewing forces for sewing of parts with different edge lengths. The initial error is compensated in a defined region, between 30 and 60 % of the seam.

In order to match reference points other than the corner of the part, the geometric model of the parts in the control system has to be extended. Additionally, the sensor system could be extended to sense markings on the edge which can be used to update the geometric model.

The current version of the system does not take into account that the parts may be slightly curved. Right now, the part edges are seen by the controller as straight edges. Using a geometric model of the parts can enable the system to increase the accuracy for curved parts. Additionally, it could be possible to use other gripping points, not only the corners.

Acknowledgements

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