

Article

Realization of an Automated Vertical Warp Stop Motion Positioning

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Abstract: The tension in the warp yarns is a critical variable in the weaving process. If the warp tension is too high or too low the weaving process will be interrupted. A parameter that directly affects the warp tension is the vertical warp stop motion position. The position of the warp stop motion must be set for every produced new article. The setting procedure is performed completely manual. In this paper we present a mechatronic modification of an air jet-weaving machine to adjust the vertical warp stop motion position with the help of actuators. The parameters for the automated movement are determined and an open loop control, which uses a PLC, is proposed.

Keywords: weaving; stepper; warp stop motion

1. Introduction

Weaving is one of the oldest manufacturing technologies known to mankind. Woven fabrics are described as a rectangular crossing of so-called warp and weft yarns. Woven fabrics are produced on weaving machines or so-called looms [1]. The principle of a weaving machine is shown in Figure 1.

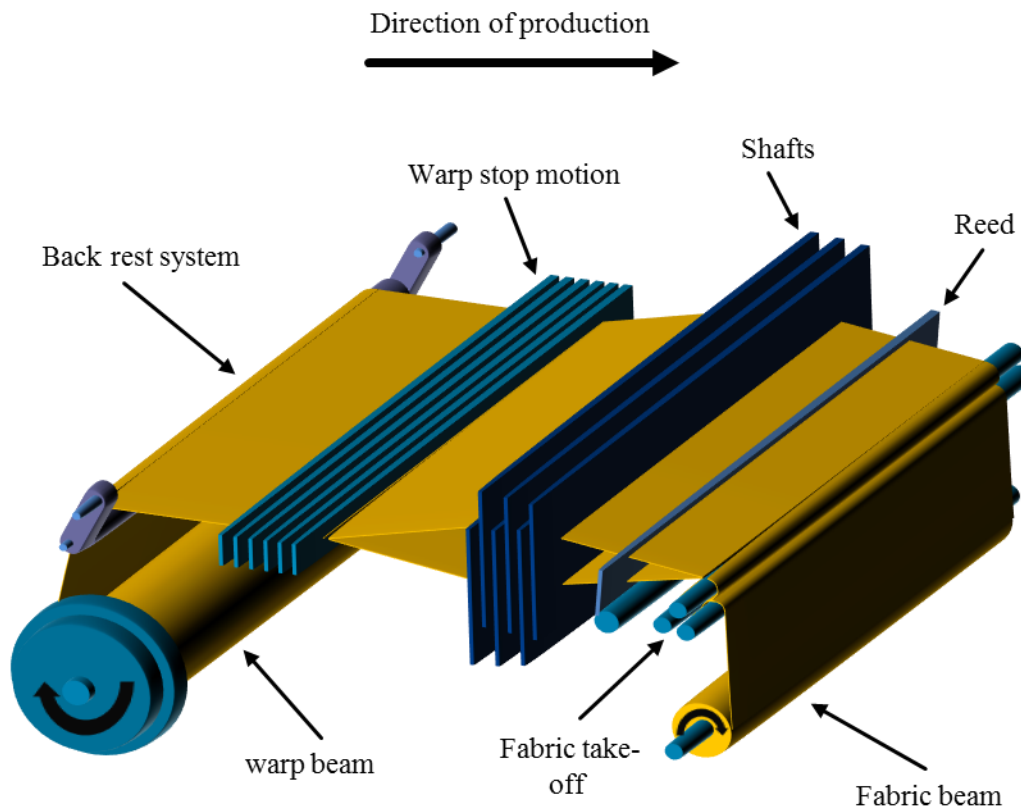


Figure 1. Principle of a weaving machine (loom).

The so-called warp yarns are delivered by the warp beam and redirected by the back rest system. The yarns are led through the warp stop motion. The warp stop motion redirects the warp yarns and detects breaks of the warp yarn. A part of the warp yarn is led through a shaft. The up and down motion of the shafts creates the shed, in which the so-called weft yarn is inserted rectangular to the warp yarns. The reed strikes the inserted weft yarn to the fabric edge and the position of the shafts change. The produced fabric is taken off and rolled onto the fabric beam [1].

Modern looms process a high number of diverse yarns and fiber materials to various fabrics. Examples are cotton webs for the apparel industry or technical webs made from polyamide for parachutes or carbon for lightweight products. Every combination of yarn and produced article requires its own setting of the loom. The position of all yarn-guiding elements and many process parameters are adjusted for every new fabric. There are over two hundred parameters that can be varied on a modern loom. One important parameter is the vertical position of the warp stop motion, which effects the tension in the warp yarns and the appearance of the fabric.

In the past, the Institut für Textiltechnik der RWTH Aachen University, Aachen, Germany successfully atomized several factors of modern weaving machines. Within the AutoWarp concept, an active back rest system was developed using simulation of the warp tension and a genetic optimization algorithm [2]. Also a control for the fabric weight during weaving was developed using an x-ray sensor and a control loop with a smith predictor [3]. In this paper an essential setting parameter of the loom, the vertical warp stop motion position, is automatized and therefore significantly decreases the changeover time when producing a new fabric.

2. State of the Art

2.1. Importance of the Warp Stop Motion Position

The main function of the warp stop motion is to detect breaks of the warp yarns. If a break of any warp yarn is detected, the weaving machine stops immediately. The weaver can repair the warp yarn break before the open end of the broken yarn gets stuck in moving machine parts. Beside this security feature, the warp stop motion redirects the warp yarns. The position of the warp stop motion therefore influences the appearance of the produced web and the tension in the warp yarns. Figure 2 shows a schematic weaving shed and that the elongation of the warp yarns in the different shed positions is different, depending on the vertical warp stop motion position.

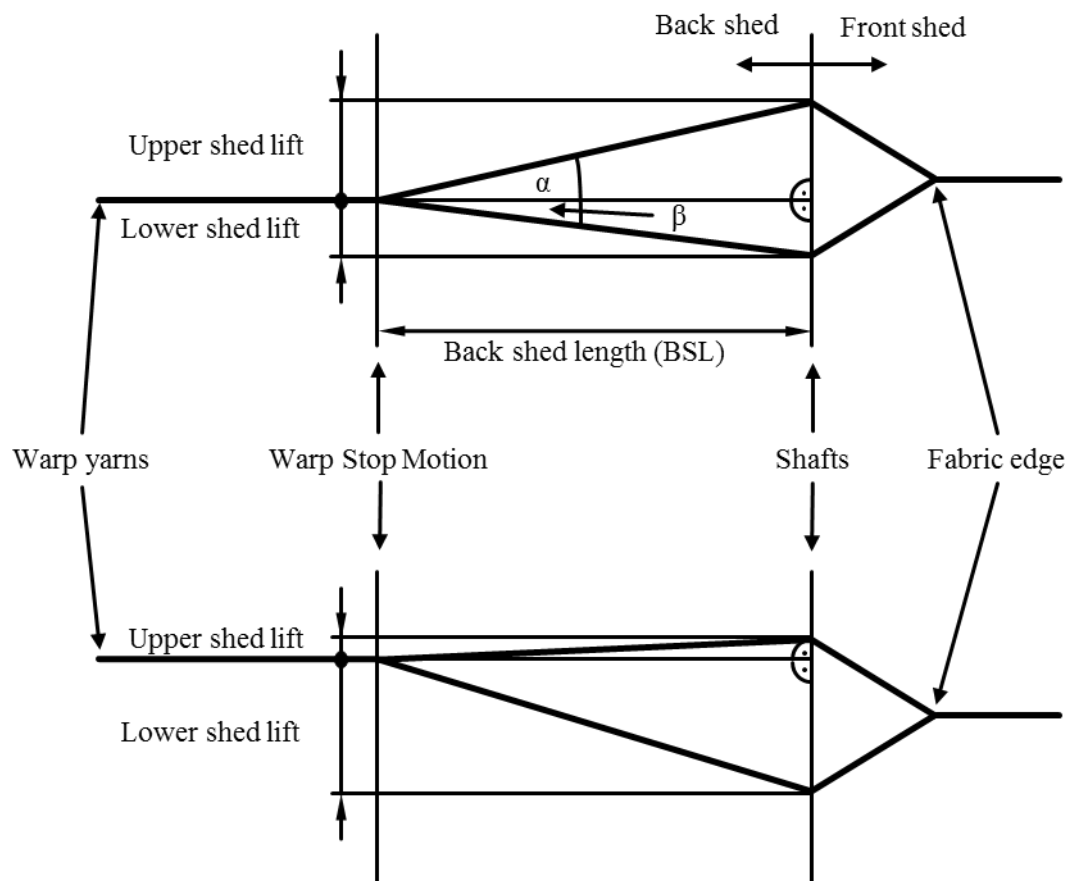


Figure 2. Two schematic weaving shed geometries.

The amount of yarn delivered by the warp beam is equal for all warp yarns. Between the warp beam and the warp stop motion, the yarn length of all yarns is the same. Depending on the position of the warp stop motion the warp yarns get elongated differently between the warp stop motion and the shafts. In the upper weaving shed geometry in Figure 2, the angle α is greater than the angle β .

$$\alpha > \beta \quad (1)$$

The different length of the warp yarns between the warp stop motion and the shafts can be described using the back shed length (BSL) and the angles α and β .

$$\frac{BSL}{\cos \alpha} > \frac{BSL}{\cos \beta} \quad (2)$$

The elongation of the warp yarns in the different shed positions is therefore different. Hooke's law states that the tension σ depends on the E modulus and the elongation ε [4].

$$\sigma = E * \varepsilon \quad (3)$$

As the E modulus of the yarn is constant, the different elongation of the yarns directly effects the tension in the yarn. As the shafts change their position with every new weft insert, the result is a constant change of the tension in the warp yarns. Figure 3 shows the effects of a wrong tension in the warp yarns.

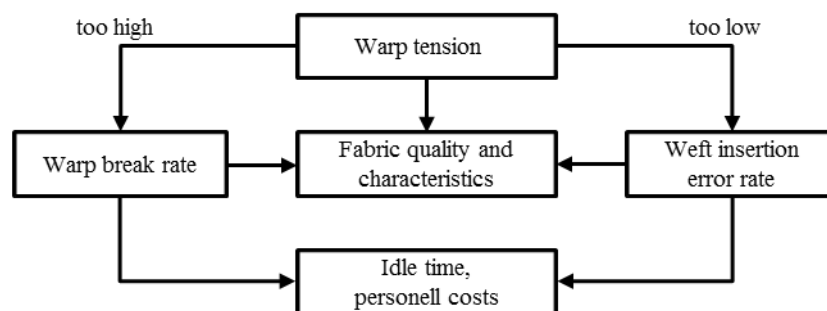


Figure 3. Effects of the warp tension [5].

If the warp tension is too high the warp yarns will break, if the tension is too low the warp yarns sag into the weaving shed. The weft yarn then collides with the warp yarn during the weft insertion. Both errors stop the machine immediately and have negative effects on the quality and the mechanical properties of the produced fabric. The fixing of broken warp yarns or the removal of a not correctly inserted weft yarn takes time in which the weaving machine is not producing. The correct setting of the warp tension and for this reason also the vertical warp stop motion position is crucial for the effectiveness of the weaving process.

2.2. Setting of the Warp Stop Motion Position

Currently the setting of the warp stop motion position is done manual in several working steps. If a weaver produces a new article, it usually takes a number of tries until a setting is found that allows a stable weaving process. Therefore the changeover time of the weaving machine can be significantly reduced if the vertical warp stop motion position is automatized. Figure 4 shows the construction to adjust the vertical warp stop motion position on an OmniPlus 800 air jet-weaving machine from Picanol NV, Ieper, Belgium. The construction is used on either side of the machine.

The locking nuts on each side of the machine secure the vertical warp stop motion in its position. To adjust the vertical warp stop motion position, the locking nuts need to be released. The male thread of the locking construction is connected to the warp stop motion and builds a jack screw together with the threaded rod. If the threaded rod is rotated the warp stop motion moves up or down depending on the direction of rotation. The scales assure an exact, even vertical position of the warp stop motion if the same setting is used on both sides of the weaving machine. Concluding the securing nuts get tightened again.

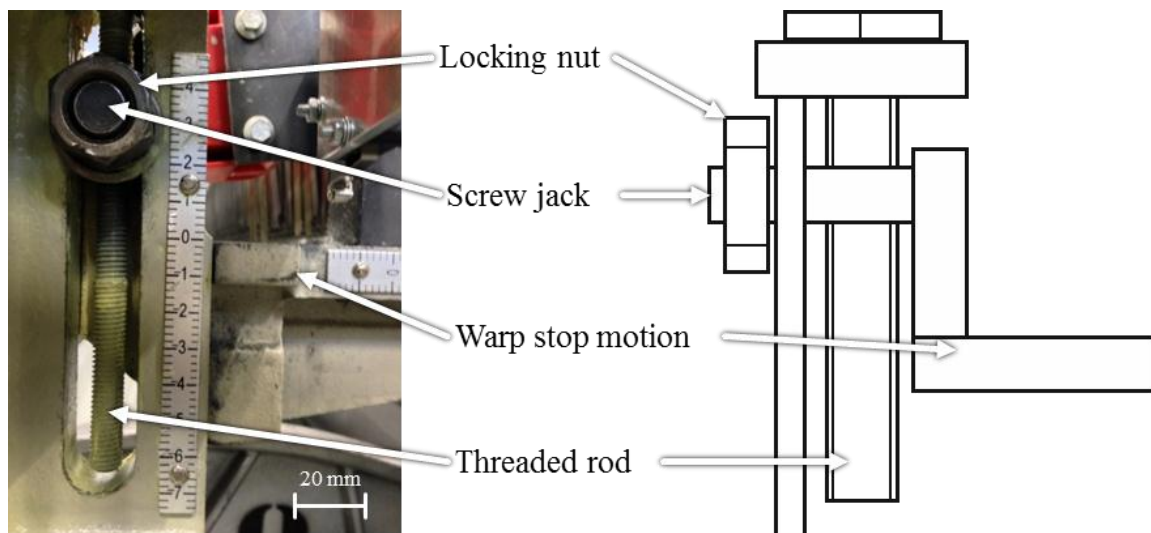


Figure 4. Vertical warp stop motion adjustment on an OmniPlus 800 air jet-weaving machine from Picanol NV, Ieper, Belgium.

2.3. Motivation

As described in Section 2.2, the process of manually adjusting the vertical warp stop motion position is time consuming and reduces the production time of a weaving machine. The Institut für Textiltechnik der RWTH Aachen University developed the AutoWarp concept in the past, which also enables a quick change of the shed geometry [2]. Deficit of the AutoWarp concept was the high price for the electric engines and the complicated redesign of the shed adjustment mechanisms. As the prices for electric drives have dropped in the last decades it is now possible to automatize the weaving shed geometry at reasonable prices. An automated adjustment of the vertical warp stop motion position would reduce the changeover time of a weaving machine significantly.

3. Concept for the Vertical Warp Stop Motion Variation

3.1. Drive and Transmission

To adjust the vertical warp stop motion position on a modern loom as the OMNIplus 800 by Picanol NV, Ieper, Belgium the threaded rod shown in Figure 5 must get actuated with sufficient torque. The concept for actuating vertical warp stop motion position includes a drive train consisting of the following three components:

- Motor
- Planetary gear
- Clutch

The drive train is connected to the threaded rod with the screw jack. The single components are shown in Figure 5. Figure 6 shows the mounted drive train on the weaving machine. Stepper motors are chosen as suitable motors for the following reasons. Suitable stepper motors are available at prices below \$100. Additionally stepper motors have the technical advantage of a compact and light structure that can be integrated into the weaving machine without greater support constructions. In a non-slipping operation,

every step made by the motors is equal to a proportional travel distance. Therefore additional sensors to detect the position of the warp stop motion are unnecessary. The exact same positioning on both sides of the weaving machine is guaranteed if both stepper motors make the same amount of steps. The holding brake, available for stepper motors, secures the position of the warp stop motion if it is not moved [2].

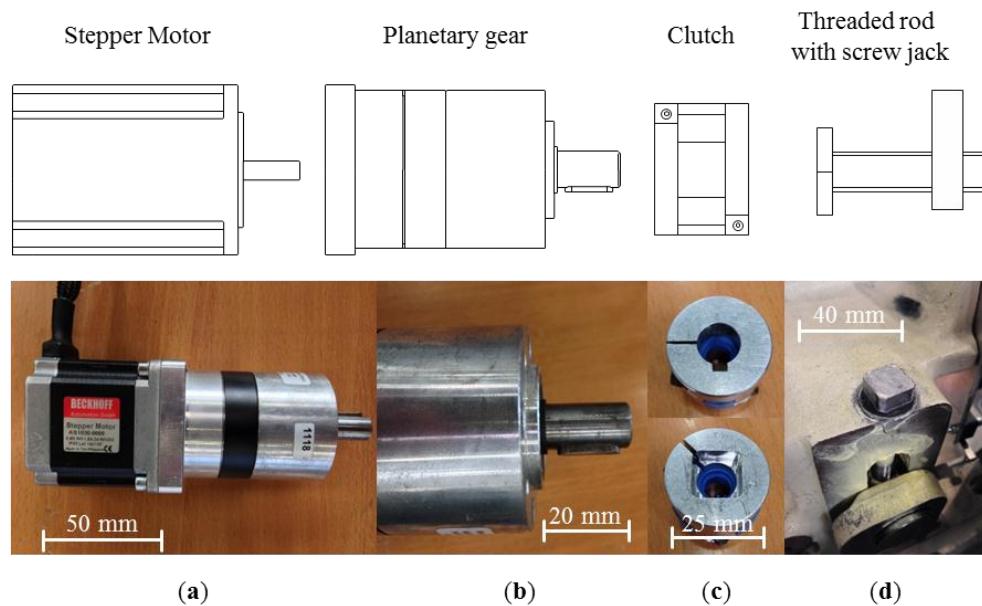


Figure 5. Drive train of the automatized vertical warp stop motion positioning consisting of (a) stepper motor, (b) planetary gear, (c) clutch, and (d) threaded rod with screw jack.

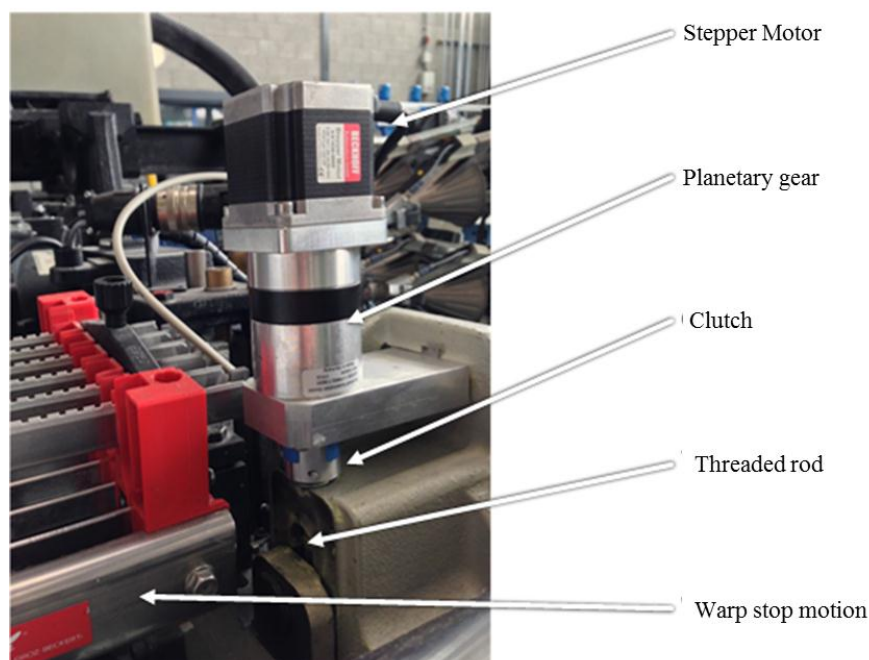


Figure 6. Mounted drive train on the weaving machine OMNIplus 800 by Picanol NV, Ieper, Belgium.

For the envisaged task, the stepper motor AS1030-0000 by Beckhoff Automation GmbH, Verl, Germany are chosen. The technical data of the stepper motors is shown in Table 1.

Table 1. Datasheet of the AS1030-0000 stepper motor by Beckhoff Automation GmbH, Verl, Germany [6].

Model	AS1030-0000
Rated supply voltage	24–50 V DC
Rated current (per phase)	1.5 A
Standstill torque	0.6 Nm
Winding resistance (per phase)	0.8 Ω
Winding inductance (per phase)	3.8 mH
Rotor moment of inertia	0.21 kg cm ²
Dimensions (radius \times length)	56 mm \times 53 mm
Resolution	1.8° = 200 full steps/revolution

The stepper controller described in Section 3.2.1 creates 64 micro steps per full step. The amount of steps for a full revolution of the motor therefore is:

$$i_{stepper_motor} = 200 \frac{full\ steps}{revolution} * 64 \frac{microsteps}{full\ step} = 12.800 \frac{microsteps}{revolution} \quad (4)$$

The required torque to move each threaded rod was measured to:

$$T_{required} \geq 2\ Nm \quad (5)$$

To obtain the required torque a planetary gear AG1000 by Beckhoff Automation GmbH, Verl, Germany is used. The planetary gear has a transmission of [6]:

$$i_{gear} = 6.75 \quad (6)$$

Therefore the stepper motor must deliver a minimum torque of

$$T_{motor_min} = \frac{T_{required}}{i_{gear}} = \frac{2\ Nm}{6.75} = 0.296\ Nm \quad (7)$$

to move the warp stop motion. A safety factor of 1.5 is used to ensure that the warp stop motion can be moved safely. Therefore, the setting of the stepper motor must be chosen in a manner that a torque of

$$T_{motor_min, S=1.5} = T_{motor_min} * 1.5 = 0.296\ Nm * 1.5 = 0.444\ Nm \quad (8)$$

Figure 7 shows the torque graph for a voltage of 24 V and a current of 1.5 A.

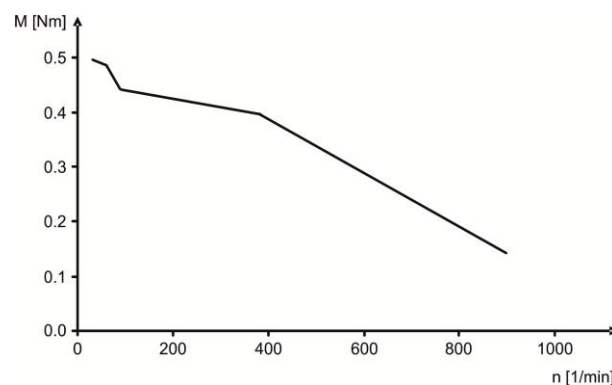


Figure 7. Torque graph of the stepper motor AS1030-0000 by Beckhoff Automation GmbH, Verl, Germany [7].

A consequence of Equation (6) and Figure 7 is that the maximum used speed of the stepper motor is.

$$n_{max} = 90 \frac{1}{min} = 1.5 \frac{1}{sec} \quad (9)$$

The gear shaft uses a feather key. The end of the threaded rod has a square head. To connect the gear shaft and the threaded rod, a suitable clutch is used. The clutch is shown in Figure 6.

The threaded rod has a M10 thread and uses a screw jack to convert the rotatory movement of the stepper motor into a translational movement of the warp stop motion. The screw jack drive ensures high axial forces that are capable of moving the warp stop motion against gravity and the force of the warp yarns [8]. The pitch of the thread equals the transmission of the movement.

$$i_{rod} = 1.5 \frac{mm}{revolution} \quad (10)$$

The required number of steps to move the warp stop motion one millimeter up or down consequently is:

$$\begin{aligned} i_{total} &= i_{motor} * i_{gear} * \frac{1}{i_{rod}} = 12.800 \frac{microsteps}{revolution} * 6.75 * \frac{1 revolution}{1.5 mm} \\ &= 57.600 \frac{microsteps}{mm} \end{aligned} \quad (11)$$

End switches limit the movement of the warp stop motion. The secured position of the limit switches is also used to reference the motors.

3.2. Controllers

3.2.1. Hardware

To ensure good driving properties special stepper controllers are necessary (see Figure 8). The controllers operate the magnetic coils of the drive.

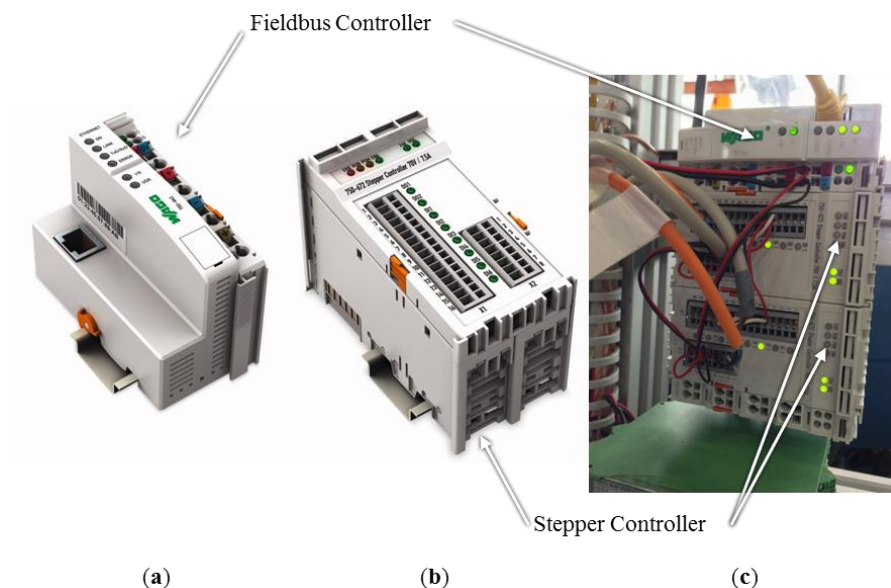


Figure 8. (a) Fieldbus Controller 750-842 [9], (b) stepper controller 750-672 (middle) [10] by WAGO Kontakttechnik GmbH & Co. KG, Minden, Germany and (c) mounted combination on the loom.

For every stepper motor a stepper motor controller 750-672 by WAGO Kontakttechnik GmbH & Co. KG, Minden, Germany is used (see Figure 8b). The model can control two phase stepper motors up to 70 V and 7.5 A. The Controller uses 64 micro steps per full step. Micro steps avoid resonance-induced loss of steps (slipping) and ensure a positioning with a high resolution [11].

The user enters the desired warp stop motion position into the user interface of a programmable logic controller (PLC). The PLC communicates with the stepper controllers over a fieldbus terminal. The stepper controllers translate the commands of the user into currents on the two phases of each stepper motor. A 750-842 fieldbus terminal by WAGO Kontakttechnik GmbH & Co. KG, Minden, Germany is used (see Figure 8a). The fieldbus terminal and the PLC communicate using the modbus protocol. The modbus protocol is very reliable because every transmission is confirmed by the recipient. Errors are easily identified because there will either be no answer, the wrong answer or an answer with an error code [12].

3.2.2. Settings

The chosen stepper controllers provide 65 setting parameters. Beside the parameters that adjust the controllers to the technical motor data, most of the parameters modify the movement of the stepper motors for the specific moving task [11].

The energization of the motors can be modified for the phases acceleration, drive, deceleration and stand still. For the specific moving task, it is important that the full torque of the stepper motors is available in every phase of the movement. This also includes the stand still of the motor. During the stand still the holding brake of the motor is used to secure the position of the warp stop motion. Therefore the energization of the motors is set to 100% for all moving phases.

The desired moving speed of the stepper motors transmitted by the PLC is translated by the stepper controllers into an internal pulse frequency in steps per second. The pulse frequency f_p is calculated as following:

$$f_p = \frac{Speed_Mult}{Speed_Div} * \frac{80}{Freq_Div} * Speed \quad (12)$$

The parameters *Speed_Mult*, *Speed_Div* and *Freq_Div* are set in the configuration table of the stepper controllers and allow that the variable *Speed* can be provided in a user defined unit different from the pulse frequency (e.g.: mm/sec). The controller then converts the speed setting into the correct pulse frequency for the specific moving task [11].

In this case the conversion of the speed into the correct pulse frequency is done by the used PLC independent from the stepper controllers. Therefore the parameters *Speed_Mult*, *Speed_Div* and *Freq_Div* must be set in a manner where they don't influence the variable *Speed*, which is provided in the process image of the PLC. Concluding these Parameters are set as following:

$$Speed_Mult = Speed_Div = 1 \quad (13)$$

$$Freq_Div = 80 \quad (14)$$

As described in Section 3.1, the used stepper motors make 200 full steps per revolution and the stepper controllers generate 64 micro steps per full steps. Therefore the number of revolutions of the motor shaft is calculated by [11]:

$$n = f_p * \frac{1}{200 * 64} = Speed * \frac{1}{12.800} \quad (15)$$

Using equation (7), the maximum allowed value for the variable *Speed*, which is provided in the process image of the PLC, is:

$$Speed_{max} = n_{max} * 12.800 = 19.200 \frac{1}{sec} \quad (16)$$

The acceleration *a* is converted by the stepper controllers as well using the following equation:

$$a = Acceleration * \frac{Acc_Fact}{Freq_Div} \quad (17)$$

As the acceleration should not be converted by the stepper controllers, the parameter *Acc_Fact* is set as following:

$$Acc_Fact = Freq_Div = 80 \quad (18)$$

Analogous considerations lead to the setting of the paramters *Pos_Mult* and *Pos_Div*, which convert the provided position:

$$Pos_Mult = Pos_Div = 1 \quad (19)$$

The acceleration mode defines the velocity profile of the stepper motors in acceleration and deceleration phases of the movement. There are three main acceleration types that can be set using the parameter *Acceleration_Modes* of the stepper controllers [11]:

- constant acceleration
- linear acceleration
- \sin^2 acceleration

Using a constant acceleration will lead to jolts at the beginning and end of an acceleration or deceleration phase. This might lead to a significant loss of steps and therefore non-exact positioning. Such acceleration should only be used, if the moved system does not have a high moment of inertia compared to the provided torque of the stepper motor and when highest acceleration rates are necessary. In a linear acceleration, the acceleration rises and falls linearly in each acceleration or deceleration phase. The induced jolt into the mechanical system is reduced, but still measurable. A linear acceleration should be used if there is only a slight chance of losing step. In a \sin^2 acceleration, the acceleration or deceleration follows a \sin^2 graph. The induced jolt is minimized. The risk of a loss of steps is minimal [11]. In this scenario an exact positioning is very important. Therefore \sin^2 acceleration is used. The acceleration time is set to 500 ms. In a deceleration phase, the friction in the screw jack connection supports the deceleration. The risk of a loss of steps is reduced. The deceleration time is therefore set to 300 ms.

4. Open Loop Control of the Vertical Warp Stop Motion Position

4.1. Program Structure

A program, using an open loop control to set the warp stop motion position, is designed. Figure 9 shows the structure of the program and communication of the individual program tasks. The whole communication between the PLC and the stepper controllers is performed by the specific task *stepper communication*. Every command for the stepper controllers is written into a control process image, which is sent to the controllers. The successful processing of a command leads to a change in the status process image of the stepper controller. The stepper communication writes the current control process image and the reads the current status process image of the stepper controller in every cycle of the PLC. The control process image is delivered by the currently active task. The status process image is supplied to all other tasks.

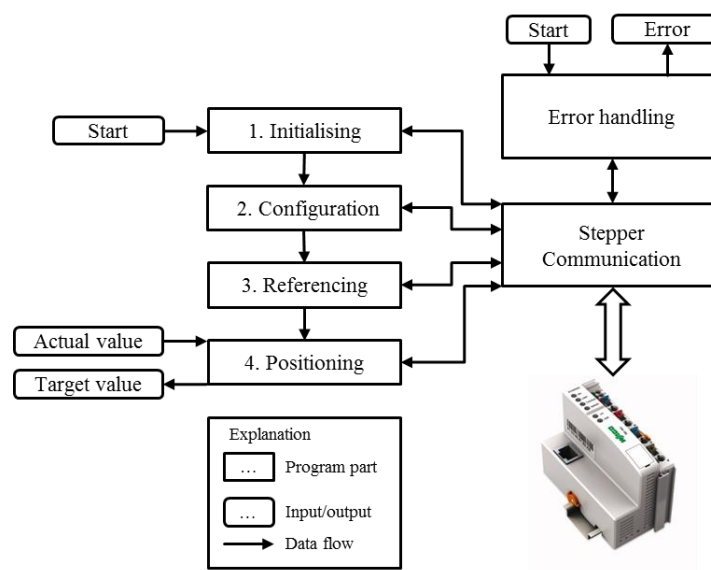


Figure 9. Structure of the programmable logic controller program.

An unwanted interference of the control process images of the individual tasks is prevented by the following prioritization between the tasks.

1. Error handling
2. Initializing
3. Configuration
4. Referencing
5. Positioning

This order ensures that the control process image generated by the most important task, the error handling, is never displaced by another task. The other tasks are handled in their logical order.

The communication between the PLC and the stepper controllers is based on the modbus protocol. If a task is active and sends a control process image to the stepper communication task the function code 23 (read/write multiple registers) is used. The control process image is written into the stepper controller

and the status process image is read. Otherwise just the process image is read by using the modbus function code 3 (read holding registers).

At the beginning the stepper controllers are initialized. The initializing task confirms old errors and resets and starts the energization of the stepper motors.

After the initializing process the configuration of the stepper motors is started automatically. The configuration memory of the stepper controllers is set back to the default values after every reset of the controllers. Therefore this task must run on every start of the program. The configuration task uses the so-called mailbox function of the stepper controllers, which allows splitting up a complex command into several separate control process images. The stepper controller detects the context of the process images. This allows the user to set a lot more configuration parameters than it is possible to write in the twelve-byte process image. The configuration task writes the values described in Section 3.2.2 into the controllers. After the configuration is successfully completed, the stepper controllers are able to accept driving commands.

The proposed actuator system does not use a position sensor. The actual position of the warp stop motion is calculated by the number of steps the motors made and the safe assumption that the movement happens without a significant loss of steps. At the beginning of the positioning process it is necessary to drive the warp stop motion to a known position to initially set the correct position. From then on, all other positions can be calculated by the number of steps the motors have made. To do so, the reference mode of the stepper controllers is used. The upmost position of the driving range is limited by an end switch. During the reference mode the stepper control drives the warp stop motion as long in the upward direction until the end switch is triggered. The position of the end switch is known and written into the stepper controllers during the configuration. After the warp stop motion has reached the end position the controller sets the position of the end switch as the actual position. This reference procedure also ensures an absolute even positioning of the warp stop motion. If the accuracy of positioning system is sufficient, the use can skip the referencing process. After the reference procedure is completed or skipped, the positioning task starts. As soon as the desired position is unequal to the actual position the positioning task creates the process image to command the stepper controllers to drive the warp stop motion in the correct position.

In the case of any error the program task error handling enables the user to read the error code from the stepper controller. After the removal of the error cause, the error state can be confirmed and the program switches back to the positioning mode.

4.2. Functional Validation

The described system was implemented on a OMNIplus 800 loom by Picanol NV, Ieper, Belgium at the technical center of the Institut für Textiltechnik der RWTH Aachen University. The program tasks of the PLC run reliable and are executed safely after each other.

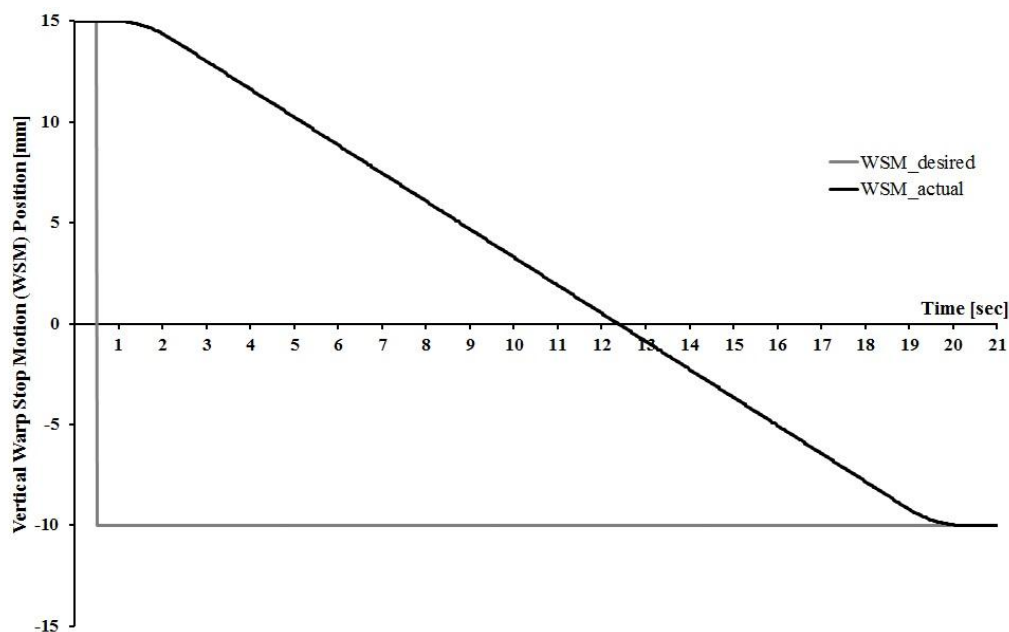
Table 2 shows the frequencies for the specific PLC tasks were used during the test procedure.

Table 2. Repetition frequencies of the PLC tasks (1 Hz = 1 repetition per second).

Task	Repetition Frequency
Initializing	50 Hz
Configuration	50 Hz
Referencing	20 Hz
Positioning	50 Hz
Error readout and acknowledge	2 Hz
Stepper Communication	50 Hz

The initializing and configuration of the stepper controllers took 8.8 s after the start of the PLC program. It is possible to further reduce the time needed for initializing and configuration by increasing the task frequencies for those tasks and the stepper communication task, if the PLC is only used for the positioning of the warp stop motion.

Figure 10 shows the behavior of the actuator system after a rapid change of the desired vertical warp stop motion position from +15 mm to −10 mm after 0.5 s during the test procedure.

**Figure 10.** Desired and actual warp stop motion position during the test procedure.

As visible in Figure 10 the development adjusts the vertical warp stop motion to the desired position within less than 20 s. A manual adjustment was made as a benchmark. Including the loosening and tightening of the locking nuts the manual adjustment of the vertical warp stop motion position for the same range as in Figure 10 on both sides of the weaving machine took 188 s. This implies that a complete start of the PLC, initializing and configuring the stepper controllers and driving the warp stop motion to a new position is more than 6.5-times quicker than one manual adjustment. In a standard-setting with 1200 rpm the weaving machine can produce 3.8 m² web in the saved time [3]. Furthermore the warp stop motion position can now be changed without stopping the machine due to the holding brakes of the stepper motors. This reduces the time needed for an adjustment even more. The pursued aim of this project is therefore achieved.

5. Conclusions

In this paper, we have presented the realization of an automated warp stop motion positioning on a modern weaving machine. The vertical warp stop motion position is crucial for the weaving process. It directly affects the tension in the warp yarns and therefore the appearance of the produced web as well as effectiveness of the weaving machine. The position has to be set for every new article. If a weaver produces a new article, it takes several tries until a good setting is found. An actuated warp stop motion therefore significantly decreases the setup time of a weaving machine.

Stepper motors were used as suitable actuators. Based on the mechanical properties the maximum speed of the stepper motors was determined to 90 revolutions per minute. Special controllers were used to drive the stepper motors. The setting parameters of the controllers were set for the envisaged moving task. A \sin^2 -acceleration is used to avoid significant slipping of the motors.

An open loop control of the warp stop motion position was realized by a programmable logic controller. At the start of the control, the PLC references the stepper motors. From the reference point on the actual position is calculated based on the number of steps made by the stepper motor.

The automated warp stop motion positioning was validated successfully on an air jet-weaving machine. The time needed for an adjustment of the vertical warp stop motion position is reduced from 188 s to 20 s. Furthermore, the vertical warp stop motion position can now be changed without interrupting the weaving process. In the future, the positioning system can be used for weaving applications in which a quick adjustment of the vertical warp stop motion position is necessary, like weaving mills producing small lot sizes. Beyond that, an application for the actuated warp stop motion is a self-optimizing weaving machine using multi parameter optimization routines.

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Author Contributions

Thomas Gries and Yves-Simon Gloy developed the major ideas and supervised the project. Yves-Simon Gloy selected and supervised the integration of the stepper motors and revised the manuscript. Frederik Cloppenburg designed the PLC program, performed the functional validation and wrote the article.

Conflicts of Interest

The authors declare no conflict of interest.

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