Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Development of a Solution for Monitoring and Recording the State of a Sewing Machine

Master's Final Degree Project

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Supervisor

Kaunas, 2025

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Mechatronics (6211EX017)

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Task of the Master's Final Degree Project

Given to the student – Paulius Stražinskas

1. Title of the Project

Development of a Solution for Monitoring and Recording the State of a Sewing Machine

(In English)

Siuvimo mašinos būsenos stebėjimo ir surinkimo sprendimo kūrimas

(In Lithuanian)

2. Aim and Tasks of the Project

Aim: to create a solution for monitoring and recording the state of sewing machines.

Tasks:

1. to compare different type of sensors for machines state sensing;
2. to select optimal placement positions of these sensors;
3. to evaluate and compare collected data from sensors;
4. to provide design of final solution;
5. to estimate the cost of provided solution of data collecting.

3. Main Requirements and Conditions

Machines data collection must be done locally with an option to send in to the server; need to use sensors, Raspberry Pi micro-computer or other small electronic devices; provide schematical design of solution.

4. Additional Requirements for the Project, Report and its Annexes

Not applicable

Project author	Paulius Stražinskas		07-03-2025
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Paulius Stražinskas. Development of a Solution for Monitoring and Recording the State of a Sewing Machine. Master's Final Degree Project, supervisor researcher dr. Marius Gudauskis; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: sewing machine, process automation, data collection, data monitoring, sensors comparison.

Kaunas, 2025. 56 p.

Summary

During this work an in depth analysis of existing data collection and recording solutions have been made. The analysis includes methods used in the manufacturing industry to collect information, and how they can be implemented in the sewing industry. The structure of a PFAFF 951 lockstitch sewing machine has been analysed to better understand the working principles of the sewing machine and existing solutions of sewing machine state monitoring have been reviewed. The acquired knowledge of the structure of a lockstitch sewing machine and possible monitoring solutions applied in the industry have been combined in effort to create a simple, yet versatile monitoring and recording system for sewing station data collection. In effort to select the most compatible sensors that would provide the monitoring and recording system with the most representative data, a sensor analysis and comparison has been done. The found sensors have been integrated into a monitoring system and verified by a higher or equal accuracy class instrument to prove their accuracy and reliability of the retrieved data. To integrate recording capabilities into the created monitoring system a Raspberry Pi 3B+ micro-computer has been implemented as the main data collection server. The collection of different sensor data retrieved from the Raspberry Pi 3B+ has been analysed and compared on the same real-time axis. The comparison consists of different action recognition from the retrieved data. It has been found that the most appropriate sensors to depict sewing machine state are current sensors. The possibility of integrating a non-complex data collection system into an existing sewing machine, could allow smaller scale manufacturers to implement big business methods such as LEAN and 6σ to increase efficiency of their production process.

Stražinskas Paulius. Siuvimo mašinos būsenos stebėjimo ir surinkimo sprendimo kūrimas. Magistro baigiamasis projektas, vadovas mokslo darbuotojas dr. Marius Gudauskis; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: siuvimo mašina, procesų automatizacija, duomenų surinkimas, duomenų sekimas, jutiklių palyginimas.

Kaunas, 2025. 56 p.

Santrauka

Šio darbo metu buvo atlikta nuodugni esamų duomenų rinkimo ir registravimo sprendimų analizė. Analizė apima gamybos pramonėje naudojamus informacijos rinkimo metodus ir jų pritaikymą siuvimo pramonėje. Siekiant geriau suprasti siuvimo mašinos veikimo principus, buvo išanalizuota PFAFF 951 rakinančio dygsnio siuvimo mašinos struktūra ir apžvelgti esami siuvimo mašinos būklės stebėjimo sprendimai. Įgytos žinios apie dygsnio siuvimo mašinos sandarą ir galimi pramonėje taikomi stebėjimo sprendimai buvo sujungti siekiant sukurti paprastą, tačiau universalią stebėjimo ir registravimo sistemą siuvimo stoties duomenų rinkimui. Siekiant parinkti labiausiai suderinamus jutiklius, kurie stebėjimo ir registravimo sistemai pateiktų reprezentatyviausius duomenis, atlikta jutiklių analizė ir palyginimas. Rasti davikliai buvo integruoti į stebėjimo sistemą ir patikrinti aukštesnės arba lygiavertės tikslumo klasės prietaisu, siekiant įrodyti jų tikslumą ir gautų duomenų patikimumą. Norint integruoti įrašymo galimybes į sukurtą stebėjimo sistemą, kaip pagrindinis duomenų rinkimo serveris, įdiegtas Raspberry Pi 3B+ mikrokompiuteris. Įvairių jutiklių duomenų, gautų iš Raspberry Pi 3B+, rinkinys buvo išanalizuotas ir lyginamas toje pačioje realaus laiko ašyje. Palyginimas susideda iš skirtingų veiksmų atpažinimo iš gautų duomenų. Nustatyta, kad tinkamiausi jutikliai siuvimo mašinos būsenai pavaizduoti yra srovės jutikliai. Galimybė integruoti nesudėtingą duomenų rinkimo sistemą į esamą siuvimo mašiną leistų smulkesniems gamintojams įdiegti stambaus verslo metodus, tokius kaip LEAN ir 6σ, kad padidintų savo gamybos proceso efektyvumą.

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Introduction

In today's times, the worlds population is growing exponentially, and as the human population grows, it needs more basic consumer items [1]. The textile industry is largely affected by this situation due to the larger consumption of clothing and textile products such as heavy duty transportational bags for various goods [2]. To meet the arising requirements companies such as JUKI, Brother, and Singer develop new and more efficient sewing equipment for manufacturing companies to buy and use [3]. The main issue emerges while trying to implement new technology as the inevitable increase in the cost of new equipment. Not only is new equipment expensive but it also adds to the consumerism problem in the world, by replacing old functional equipment with new equipment is not only expensive but also ecologically unfriendly. Looking at these factors it can be deducted that the textile industry is dominated by the companies who have the newest technology and due to the price hurdle of achieving new equipment the smaller companies will not have a decent fighting chance to stay financially afloat, to counteract such a problem a solution is needed to upgrade existing equipment with additional newer features allows better optimization of the whole sewing process. Looking at the newest scientific papers on the sewing industry there is a commotion with sewing automation using multi-axis robots and artificial intelligence [4]. The field of sewing automation is promising but still requires a lot of work because of a vast number of variables that make it extremely difficult to fully automate the process [5]. The previously mentioned factors bring attention to an existing technological gap between the traditional method and fully automated method that requires transitional technology to fill the gap. As seen in other industries process data collection allows to analyse and understand the process more deeply, thus providing the ability to eliminate existing bottlenecks in the manufacturing process [6]. The analysis of collected data allows the manufacturers to more accurately predetermine prices of manufacturing and estimate the time and material consumption [7]. Taking everything mentioned previously into account it is possible to state that an adaptive system that can collect data from existing equipment greatly benefits most manufacturing companies. This creates a stepping stone for smaller companies to apprehend smart technologies and data collection under a fraction of the cost of a new machine. A data collection system would provide the opportunity to understand where production is lacking in efficiency and allows management to take better weighted choices in the future while planning the production process. A use of such device not only reduces manufacturing process waste, but it would also reduce equipment waste since older machines could now be used in a smart factory.

Aim: to create a solution for monitoring and recording the state of sewing machines.
Tasks:

1. to compare different types of sensors for machine state sensing;
2. to select optimal placement positions of these sensors;
3. to evaluate and compare collected data from sensors;
4. to provide the design of the final solution;
5. to estimate the cost of the provided solution for data collecting.

Hypothesis: the system can collect sewing machine data that can be used for further analysis to optimise performance and efficiency.

1. Importance of Data Collection and Monitoring for Efficient Manufacturing

In the current manufacturing setting, automation is crucial for the successful production of quality goods at an affordable price range. The automotive industry is one of the first industries that introduced automated manufacturing and highly emphasised its importance for the reduction of labour costs [8]. The automation of manufacturing processes is directly proportional to the labour required to produce the goods, which leads to the conclusion that higher automation level manufacturing plants require less physical labour to produce the same amount of goods. Although it may appear promising, automation is usually quite difficult and expensive to achieve in an industrial setting due to the amount of equipment that must be changed or upgraded. A key factor in the automation process is data collection and data monitoring, which can be achieved through sensor implementation and data analysis.

1.1. Importance of Real-Time Management

In the current socio-economic background, the importance of efficient production is unavoidable. After the economic chaos in 2008, economic laws have been changed in European Union to accommodate a more stable pay rise that is more tied to the labour quality and efficiency of actual work. According to a technological trend analysis [9] the number of patented solutions for smart factories and data collection is vastly growing. Looking at Fig.1. it is possible to say that the number of smart factories associated patents has exponentially increased since 2015. This brings attention to a trend existing in the manufacturing field to collect and process manufacturing data to be analysed using software. According to the same source, the number of patents including the word "data" is the most prominent, placing in the first position by frequency and it is followed by "system", "device", and "network". Assuming from the use of these words in the patents registry regarding smart factories it is possible to deduce that the business owners in the industry invest large amounts of time and labour to produce technology for smart factory solutions, especially data collection and monitoring.

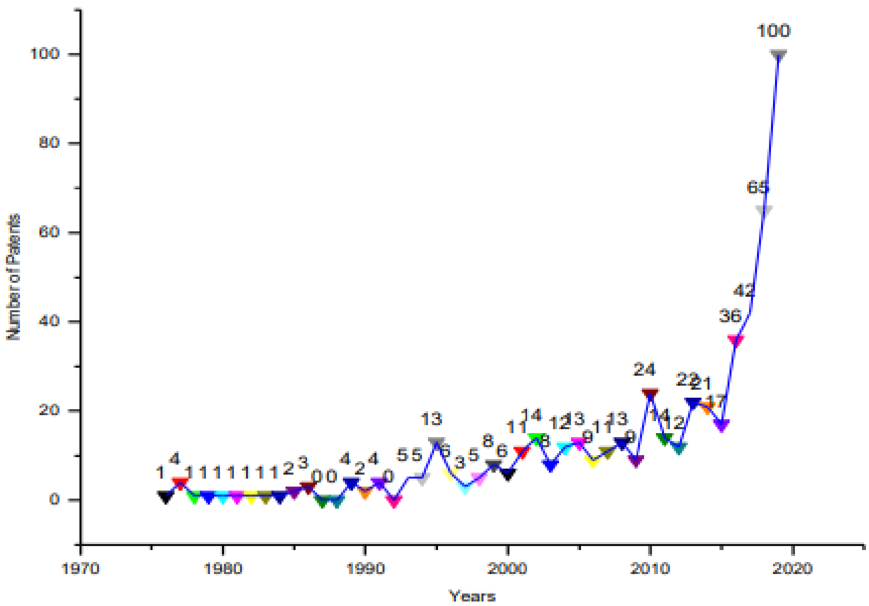

Fig. 1. Number of Patents Registered During the Years [9]

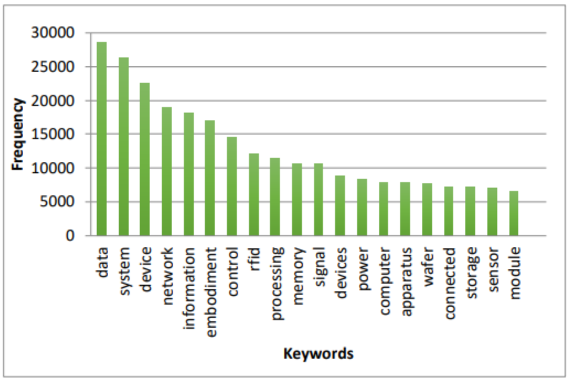

Fig. 2. Top Keywords in Smart Factory Associated Patents [9]

The previously mentioned graph depicting the number of patents registered throughout the years gives the impression that the manufacturing industry is bringing more effort into automation of data collection and analysis, but it is hard to identify that current manufacturing facilities have fully implemented automated data collection. A case study presented in [10] mentions the challenges that the management usually faces while trying to implement data collection and modernisation in becoming smart factories. The study has collected answers from 4,600 respondents and analysed the main reasons that the management team identified as challenges in automating data collection. One of the questions regarding the plans was "What actions will be taken in preparation for the changes in the next 10 years?". The recipients replied with three most common key points: clear use of scientific solutions from vendors, piloting of new technology, and increased investment in new technologies. These answers indicate that there is an ongoing discussion in the management layer about the future of automated data collection.

Table 1. Actions Taken in Preparation for the Changes in the Upcoming 10 Years [10]

Actions taken	**%**
Partnering with vendors to better understand applications and benefits	54%
Began piloting new technologies	51%
Increased investment/budget for innovative technologies	47%
Recruiting for different skillsets/incentives to align with future needs	45%
Changing organisational structure/incentives to create an innovation culture	41%
Reskilling and training workers for emerging technologies	37%

When asked about the major challenges that the manufacturers face in achieving performance at a larger scale, the majority answered "Deployment and integration of digital platforms and technologies" as shown in Table 2. This verifies that a root cause problem exists and gives the needed perception in which direction the technological solution must be implemented. Following this statement, the integration of technologies can be made easier by finding new ways and methods the data can be collected from the devices. A non-invasive method of data collection is always better to ensure the original reliability of manufacturing equipment and devices.

Table 2. Major Challenges Faced by Manufacturers in Achieving Performance at Scale [10]

Major challenges	**%**
Deployment and integration of digital platforms and technologies	45%
Data readiness and cybersecurity	40%
Hybrid, soft, and digital capabilities	37%
Leveraging data to continuously improve operations	37%
Vision, leadership, and transformation	35%
Being efficient by design	32%

1.2. Manufacturing Data Collection Methods

The manufacturing industry has always revolved around the improvement of processes to reduce final costs. This circles around the idea that by upgrading manufacturing processes, unnecessary expenditures would be saved. To achieve the goal, manufacturers imply different manual data collection methods like, the manual collection methods revolve around human interaction, meaning the accuracy highly depends on the labourer and their opinion on what is deemed unorderly or what is counted as appropriate in each situation. In existing solutions, regarding smart factories, the data collection is ideally automated to avoid biased opinions. Unfortunately, it difficult to do so in some situations due to the nature of the work itself. Such manufacturing fields as sewing are still highly dependent on human labour, therefore, hard to automate process status collection.

The original type of data collection method was based on human effort. Workers, operators or inspectors usually carried paper forms to be filled like the one shown in Fig. 3. or defect check sheet as seen in Fig.4. As mentioned previously this includes higher probabilities of human error in the final equation of evaluation. The other side of this issue is the required work hours to systematically transfer the first-hand data that is written in the check sheet for further statistics and analysis. In newer methods, tablets or RFID tags with scanners are used to make entries straight into the digital space [11]. This makes it easier to form databases from computerised input instead of handwritten but still requires a worker's physical action to interpret the current situation in the production station.

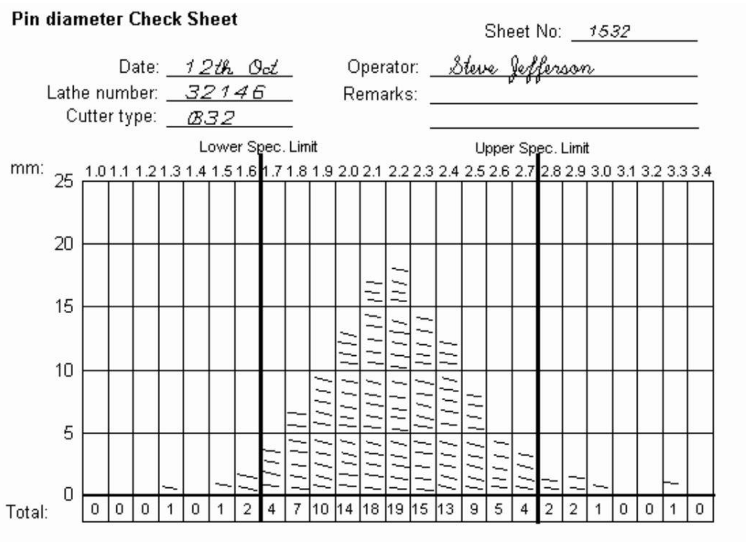

Fig. 3. Pin Diameter Check Sheet [12]

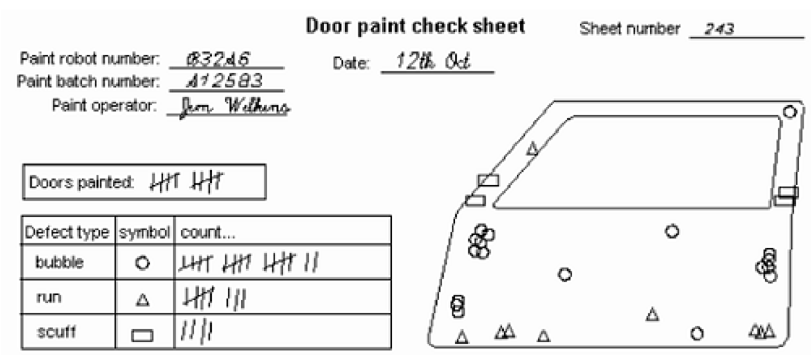

Fig. 4. Door Paint Check Sheet [12]

A smart factory depends on real-time data collection to reduce operational time, and errors, also improve productivity by adjusting management choices depending on the collected data. The main foundation for the integration of smart factory principles is the availability to collect the needed parameters, data, and status of the machines and equipment. Different industrial fields require individual adaptations of monitoring systems, even though the basic idea of data collection is similar in its essence for each case, the details of how it is realised differ. An overview of existing solutions in other industries gives the perspective of what checkpoints in realisation are critical for successful integration.

An interesting adaptation has been made for environmental vibration monitoring in an industrial manufacturing setting. The main concept is based on an Internet of Things approach where multiple wireless sensor nodes are collecting data to later be collected and analysed by the main system [13]. Looking at Fig. 5. the data collection point schematic can be described as a singular node being made up of an accelerometer ADXL001-70, amplifier PGA113, ADS8344 analogue to digital converter and a FPGA controlling the processing unit. The main foundation of this node is the field programmable gate array controller due to the integrated analogue-to-digital converter, integrated data buffer, and data compression within the microprocessor. All of this helps to reduce the required power consumption, which works very efficiently with the selected ZigBee protocol.

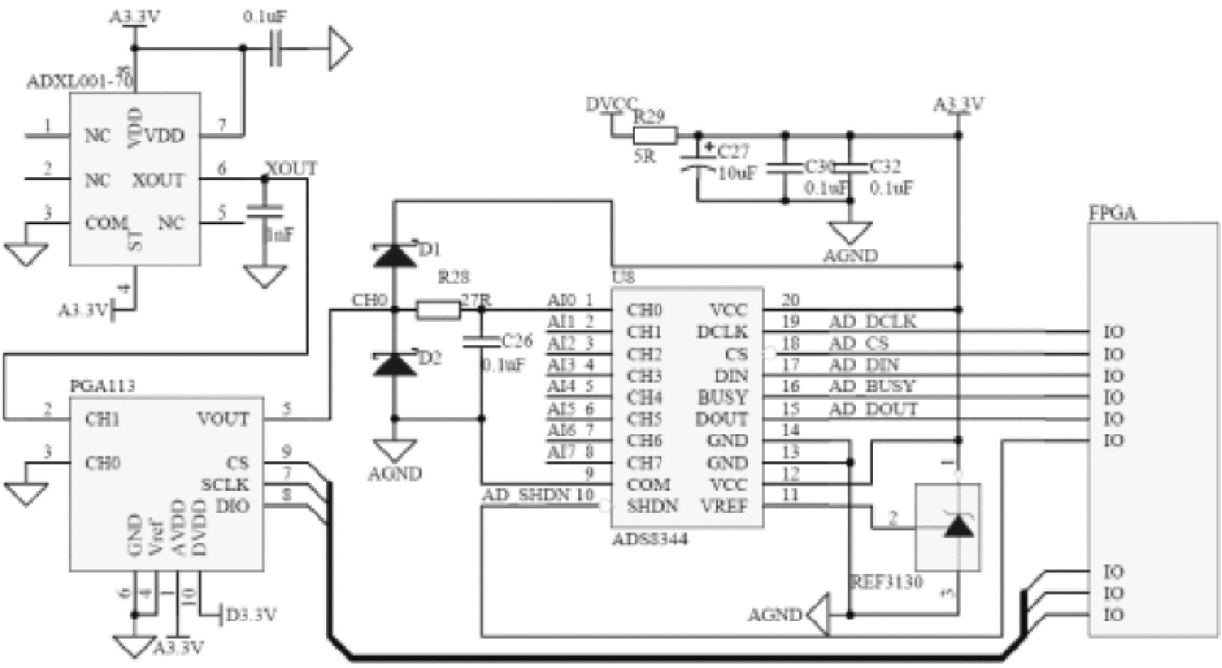

Fig. 5. Data Collection Point Schematic [13]

The collected signal is then transmitted via ZigBee wireless protocol to a sink node collection point where it is later transmitted using RS-232 protocol as shown in Fig. 6. The data then is stored in an embedded server where it can be accessed via the local pc or via the internet from a remote pc. Viewing other scientific sources, a similar topological layout has been used [14], [15]. The monitoring system is laid out in a tree topology meaning that if one sink node malfunctions, the branch of sensors following it fails to transmit data. As mentioned in the scientific sources, mesh topology is more complex to setup, but it provides more reassured data collection and higher reliability. Due to the complexity of setting up and maintaining such networks mesh topology is usually used only in critical infrastructure. Since infrastructure is not a critical part in the article talking about vibration monitoring system, the ZigBee protocol was configured in a tree or cluster topology to transmit the data to a sink node. ZigBee is an IEEE Standard 802.15.04 protocol suited for wireless networks, it provides low power consumption, and low to medium communication range. The maximum data transmission speed of the ZigBee protocol is 250 kb/s [16], this makes it a logical choice for local data collection. In the scientific paper, the system has been tested by creating a simple network made up of four terminal nodes, and a sink node. In the experiment, the metal frame has been affected by simulated sampling frequency of 10 kHz and the MEMS sensors were placed according to their respective sensing axis on the framework. By comparing the sampling frequency and the collected data, the maximum error has been calculated to be 2.0576%, which is quite low. In evaluation of the test procedure, the distance of data transmission is not described, therefore the error, due to data package loss is not involved nor calculated. The testing procedure of the system has been described only by the tested sensors' ability to correctly sense the vibrational range of the framework.

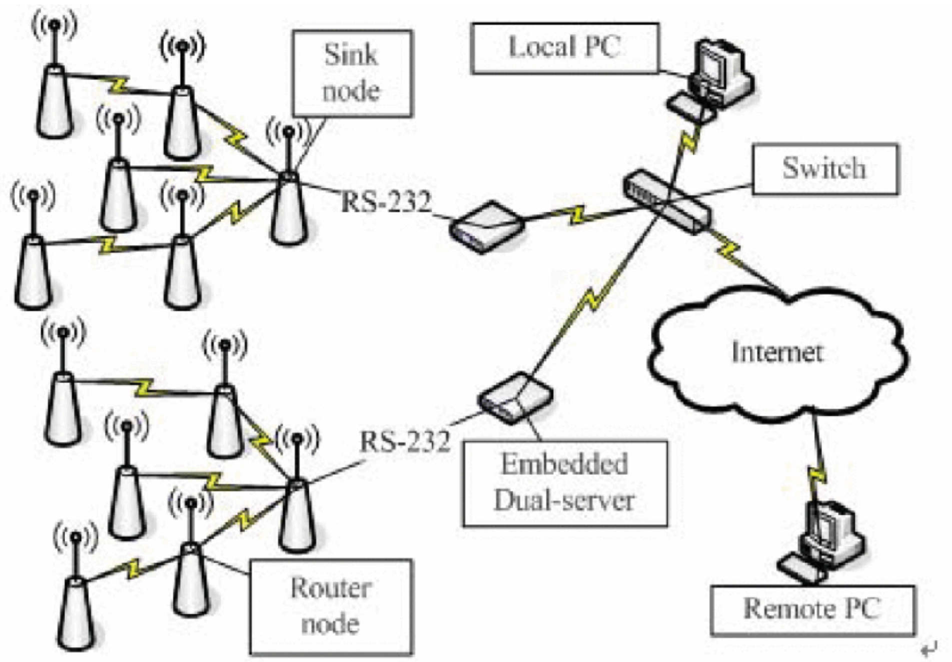

Fig. 6. Monitoring System Layout [13]

The success of implementation for data collection greatly depends on the selection and integration of a correct sensor. A system created for pico hydropower plant monitoring uses four different types of sensors: voltage, current, infrared sensor, and water flow [17]. The information is collected similarly to the vibration monitoring system described previously. The primary raw data collected by the three sensors is read by an Arduino microcontroller and then transferred to an ESP32 node MCU. The MCU collects the information from the waterflow sensor, and then, with the use of the TCP/IP protocol, transfers the data to a web server, as shown in the block diagram in Fig. 7.

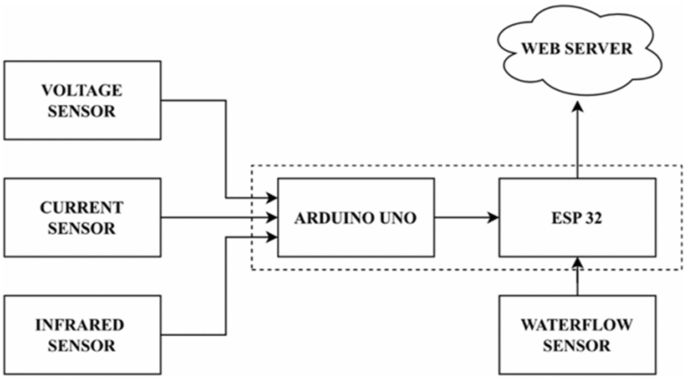

Fig. 7. Block Diagram of Pico Hydropower Plant Monitoring System [17]

Unfortunately, the system is overcomplicated and enables a variety of possible problems with all the different unnecessary sensors. In Fig. 8. the electrical schematic is shown, and it does not include the infrared sensor connection to the Arduino for rpm monitoring, presumably, due to difficult conditions during realisation of the project, the sensor has not been integrated. Instead, the rpms have been monitored using a hand-held tachometer, thus proving the importance of appropriate sensor selection and positioning. Looking at the real-life model of the pico hydropower plant shown in Fig. 9. it was possible to identify that there is an axle protruding from the device, therefore a rotational encoder was possible to be implement on its end to measure and count the rotations and rotational speed of the turbine.

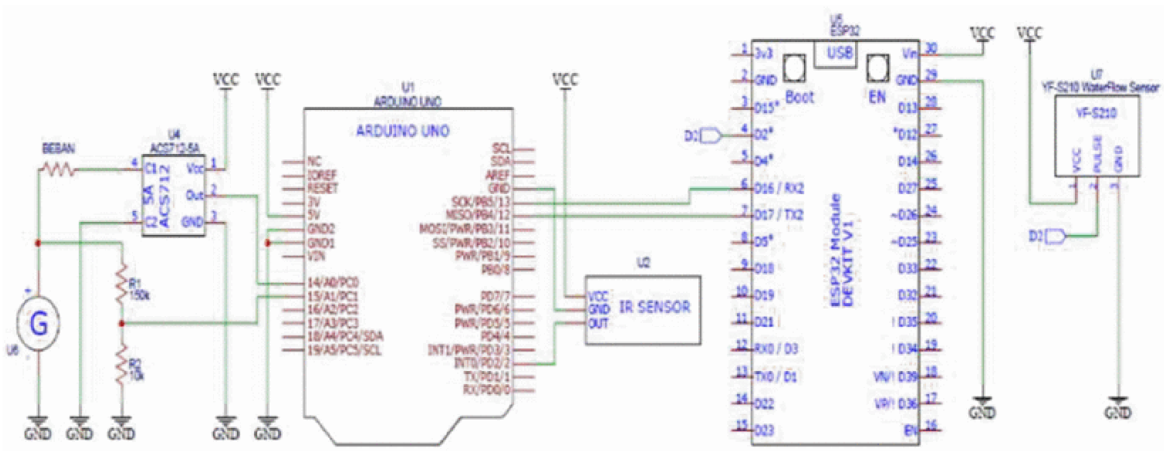

Fig. 8. Electrical Schematic of a Pico Hydropower Plant Data Collection System [17]

Fig. 9. Real-Life Model of the Pico Hydropower Plant [17]

A better example has been implemented in a solution for deep geological drilling monitoring. Geological drilling requires extensive knowledge on the process to be successful, thus meaning the learning curve is not very steep and requires more time for the operator to learn the ongoing process. The presented solution monitors key parameters such as rate of penetration, torque, weight on the drill-bit of the drill, and rotational speed. The collected data has been analysed using MATLAB software and the decisions were based on this information. This kind of a monitoring system has been implemented in Sandia National Laboratory, and according to the scientific source, the program was able to predict multiple statuses of the system: loss of cooling water circulation, the drill being stuck, and drill-sting washout [18]. Looking at the presented system architecture in Fig. 10., it is possible to see that industrial equipment has been used to collect the data from the monitoring site.

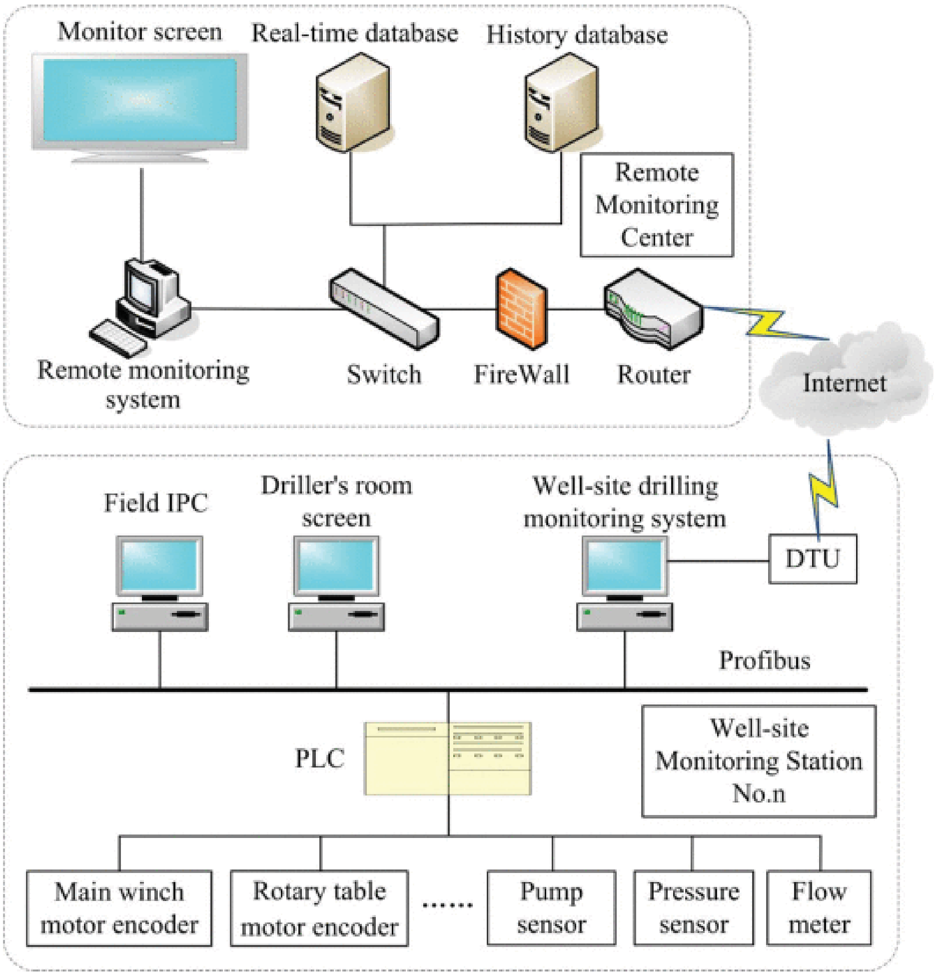

Fig. 10. Architecture of a Drilling Monitoring System [18]

The system architecture follows a similar topological layout, where one drilling site is represent as an individual sink node, from which the data is collected. In this case, the data is collected via transport utility point, which depends on 4G protocol or GPRS protocol. Deducting from the research data in Table 3., it was possible to conclude that data fusion from multiple sensors and data types provides a more accurate system status representation, compared to one independent evaluation of data from separate sensors. Meaning that a thought through combination of sensors can be used to describe the state of complex machinery that is made up of many sub-assemblies. Concluding the previously mentioned facts, research on correlation between multiple types of sensor data, shows promising results in determining the operational status more accurately for complex systems.

Table 3. All Data Types Collected by The Whole Local Monitoring System [18]

Data type	Content
Logging data	Natural gamma-ray, spontaneous potential, density, acoustic.
Log data	Drilling fluid density and temperature, electrical conductivity, total pool volume.
Drilling data	Weight on bit, rotation speed, flow rate, winch motor voltage and current.
Seismic data	P and S wave velocity of formation, amplitude, coherence cube, pore pressure gradient, fracture pressure gradient, collapse pressure gradient.
Trajectory data	Well depth, vertical depth, point angle, azimuth, inclination.

1.3. Chapter Summary

Summarising the reviewed data collection and monitoring solutions, all systems follow a similar approach of localizing a key parameter to be monitored. From the examples, it is possible to see that a singular key parameter gives the most information about the status of the system. The vibration monitoring system mentioned in [13] has chosen a vibrational parameter to be monitored, because more than one state can be defined from this parameter. The vibrational range describes the working state of the system, and it also describes, what load the system is experiencing, and how the physical condition of the machine is affected. Comparing the selection of parameters with the example from source [17], quantity of different sensors does not always guarantee more accurate representation of actual situation. In source [17] there are multiple implemented sensors to monitor the parameters of the system, but majority of the collected information is possible to be collected with just one sensor. The use of one high reliability current sensor provides the whole needed information of the system, example given: if the parameters and characteristics of a generator are known, the rotational speed of the generator is possible to be determined from the amount of generated current, a similar solution applies to eliminate the voltage sensor. By reducing the number of unnecessary sensors, the system costs of integration and manufacturing are reduced. For such cases as described in article [18], the use of multiple sensors is unavoidable, due to the complexity of the system. Complex systems typically have multiple mechanical sub-assemblies that require different types of monitoring to predict the actual state of the system. Due to their combined operating principle, where multiple sub-assemblies are running at the same time, it is hard to predict what is the state of the whole system without the additional monitored data. Considering all these different factors, it is possible to conclude that the critical part of a successful status monitoring system is identifying the key parameter, or parameters that give the most information for the least number of sensors.

2. Status Monitoring Solutions in The Sewing Industry

Textile industry has always been a critical part of society, it not only creates garments to wear but also manufactures furnishing, bedding, packaging, and other various components in everyday life. The nature of textile is malleable and flexible, therefore easy to work with for human workers but challenging to automate using robots and manipulators. The same also applies while trying to manufacture complex garments that require multi-dimensional comprehension of the stitch path. Considering the previous statement, existing data collection methods in the sewing industry greatly depend on the human input, making it troublesome to keep up with the working tempo, and hinder the ingrained workflow of workers. As the whole manufacturing industry is undergoing constant technological advancements, the sewing industry is also going through a remarkable transformation. The idea of sewing station status collection in the sewing industry comes from the need to improve the efficiency of the overall process. It is common in automation engineering and mechatronics engineering, to automate processes in existing systems with the use of sensors, to monitor the needed parameters. The newest solutions generated by these engineering fields, create systems to define and interpret sewing machine status. As previously mentioned, one of the most important processes in creating a successful system, is finding the best parameter, that describes the operation of the system. Therefore, an analysis of said system has to be done, to find the key parameters that best describe the state of the machine.

2.1. Structure of Sewing Machines

Sewing machines are intricate in their making and design, therefore an amateur understanding of how the machine operates is required to fully comprehend the solutions described in further scientific sources. The fundamental point of sewing automation lies in the main tool used to create a seam; the needle is the main instrument manipulated by a human hand to create a running seam. It is used to puncture the material and pull the thread through the material, to later be pushed back through the same material again, thus creating this sort of a wave pattern through the sown material called a running stitch as shown in Fig. 12. The problem that engineers have faced was that the needle had to be fully passed through the material to pull through the thread and then pass it back up the other side. This motion is generally hard to replicate with a mechanical solution due to the high manoeuvrability machinery required.

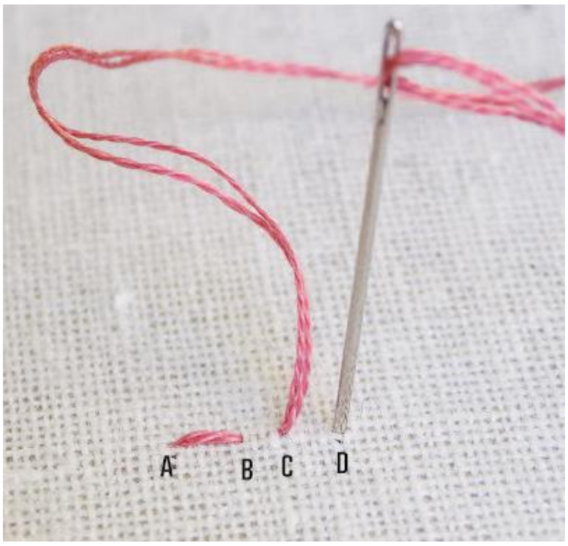

Fig. 11. Running Stitch [19]

The only solution found was to reinvent the needle and the sewing process itself to solve the issue of the thread following the needle while passing through the material. The needle hole has been moved to the front of the needle, meaning that the thread is pushed through the material without requiring the whole needle to pass through the material. This left one end of the needle always extruding from the sown material, meaning a manipulator could hold the needle and animate it [20]. A developed sewing machine needle and a handheld needle is shown in Fig. 12.

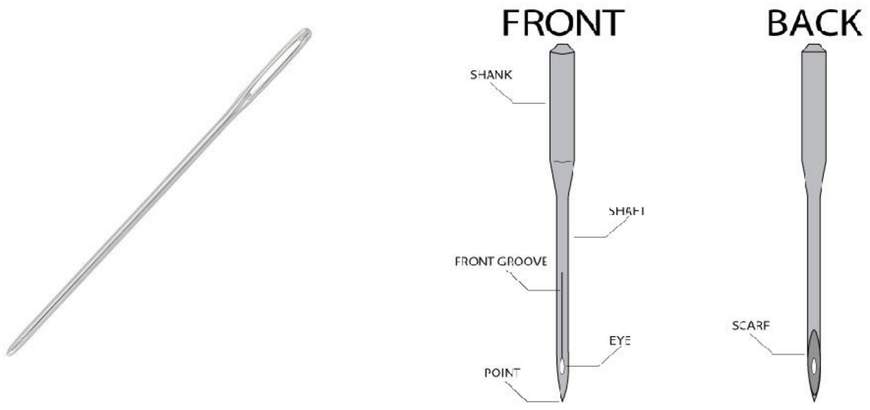

Fig. 12. Handheld Needle and Sewing Machine Needle

This solution presented the engineers with a different problem, by pulling the thread out together with the upward motion of the needle, therefore a locking solution for the thread was required. For this issue a lockstitch mechanism has been developed as shown in Fig. 13. The lockstitch is the name of the stitch itself, due to its nature of intertwining the two threads together. The difference between the old chain stitch and the lockstitch is that if one section of the seam is damaged the whole seam does not fall apart, therefore making it more reliable. The lockstitch mechanism is an ingenious design, because of the solution of putting the bobbin spool inside of the rotating hook. The process of sewing with a lockstitch mechanism is shown in Fig. 13. It starts with the needle penetrating the sown material, the action is marked as 1 in Fig. 13. Once the needle reaches the deepest point it starts to retract upwards leaving a small hoop of thread for the hook to catch as marked by number 2 in the same figure. The hook then catches the looped thread and wraps it around the bobbin thread like shown in steps 3 and 4. As the needle is approaching the high point of the motion, the slack pickup mechanism creates a small amount of tension which collects the excess upper thread from the seam, thus locking the two threads together [21]. The process is continued and repeated by the next puncture of the needle as shown in steps 4 and 5.

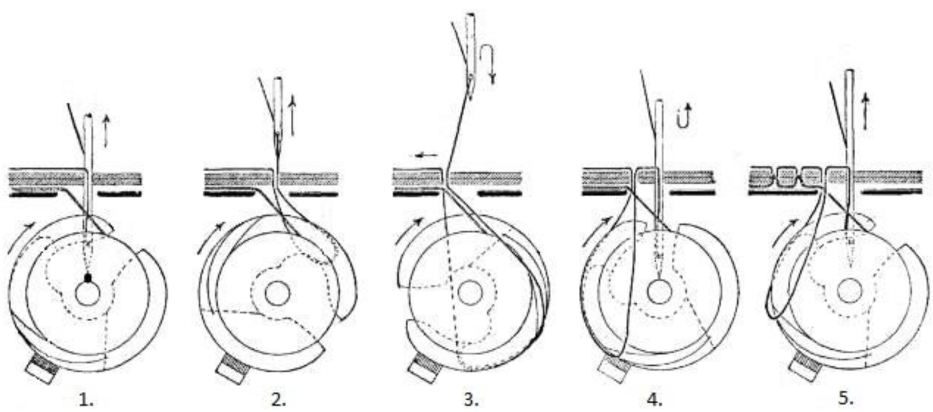

Fig. 13. Bobbin Mechanism [22]

To prevent the stitch from repeating in the same place, a feed-dog mechanism is implemented. The feed-dog mechanism is made up of a small metal foot, with minute protrusions representing the teeth of a cog, a driving mechanism, and a presser foot, which presses down the material to interact with the said teeth, as shown in Fig. 14. The feed-dog mechanism in many sewing machines is adjustable, meaning that the travel of the teeth can be adjusted according to the required stitch length. This allows for the operator to adjust the density of the seam, according to the requirements of the manufacture plan. In some machines the direction of operation of the feed-dog mechanism can be changed, this is useful for operators while sewing larger scale products. In most modern machines an ending stitch is performed automatically, meaning the sewing machine operator presses the foot pedal in reverse at the end of seam and the machine automatically makes a few stitches backtracking in reverse direction to lock the thread in place.

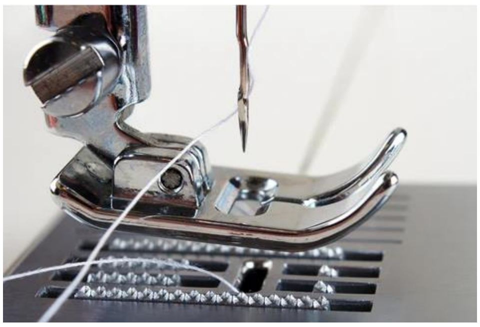

Fig. 14. Feed-Dog Mechanism

To further analyse the structure of the driving mechanism, a PFAFF 951 industrial sewing machine has been taken as an analysis subject, and it is shown in Fig. 15. The typical industrial sewing machine is driven by a three phase AC synchronous motor. When the machine is powered on, the AC motor runs constantly, and the movement of the sewing machine is controlled by engaging and disengaging the clutch. The clutch in PFAFF 951 is controlled electronically with a small servo motor. The sewing machine controller reads the position of the foot pedal and engages or disengages the clutch accordingly.

Fig. 15. PFAFF 951 Sewing Machine Setup

The motion to is transmitted via a belt drive to the upper sewing machine mechanism. The sewing machine itself can be divided into three main sections as seen in Fig. 16: the sewing head is marked as 1, transmission tunnel is marked as 2, and feed dog step and direction adjuster marked as 3. The sewing head includes the feed-dog mechanism, thread tension mechanism, and needle movement mechanism. The transmission tunnel includes the shuttle bobbin respooling assembly, and inside there is the main shaft, that moves all of the motion creating camshafts. The feed-dog step mechanism includes the reverse paddle and the step adjusting knob. The step adjusting knob directly manipulates the angle of the feed-dog camshaft thus extending or reducing the travel distance of the teeth themself.

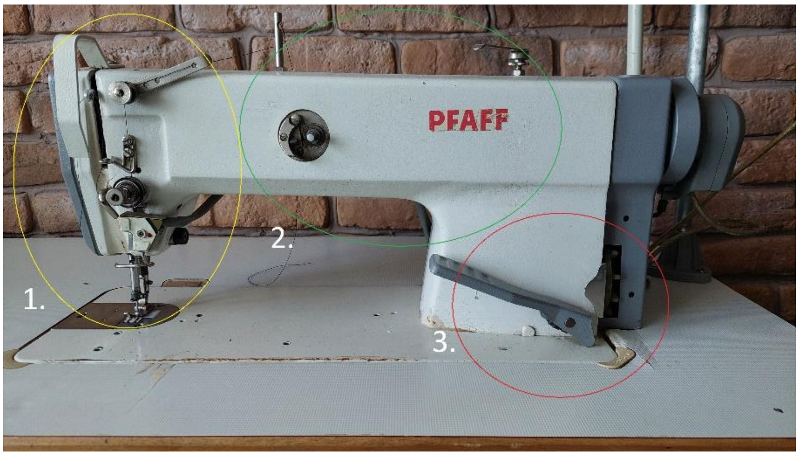

Fig. 16. PFAFF 951 Sewing Machine Sections

In Fig. 17. the camshaft mechanism of the sewing head is shown, the figure consists of three images, the first one depicts the assembly of the presser foot mechanism. The mechanism is held down with constant downward force from the leaf spring ‘c.’ in the second image. The lifting motion of the mechanism is actuated in two ways: manual, and automatic. The manual way of actuation is using the lever marked as ‘a.’ in the first image. The press-foot can also be lifted with the actuation of the solenoid shown in image 3. The solenoid is positioned under the sewing machine, and it transmits motion by pressing on the lever marked as ‘b.’ in image three. This transfers the motion to the press-foot mechanism and raises it from the feed-dog.

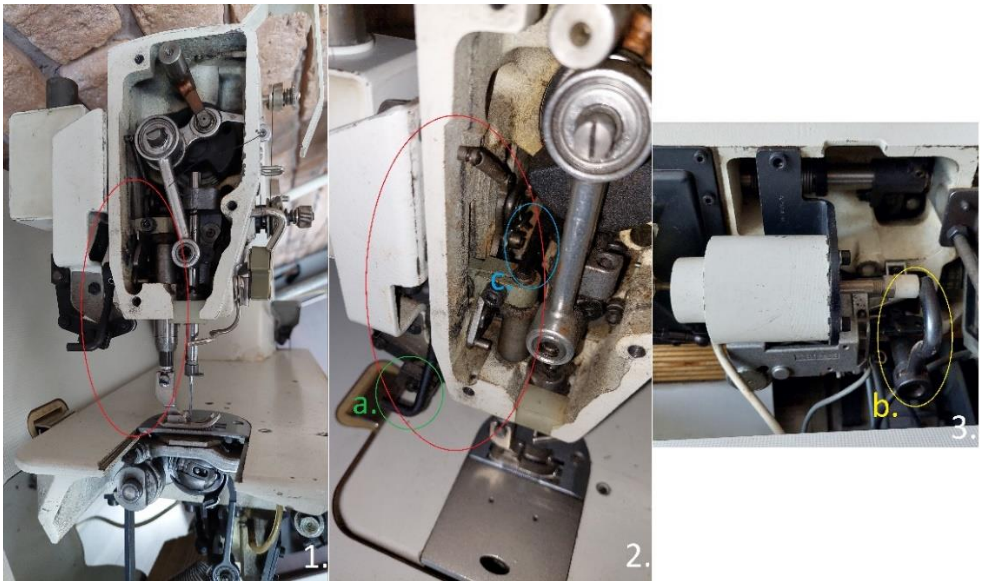

Fig. 17. Press-Foot Mechanism

The large number of synchronised actions engineered for the sewing machine can be shown by the camshaft mechanism of the needle actuation and slack pick-up Fig. 18. Image 1 depicts the kinematic schematic of the needle actuation. The white arrows depict the possible direction of rotation and the movement of the needle. The movement is actuated by the main camshaft of the sewing machine. At the same time the same camshaft actuates the action for slack pick-up in image 3. Image 2 represents the kinematic schematic of the needle angle change during one iteration of the process. The angle of the needle follows the movement of the material. This is needed to prevent force exertion on the needle from the pulled sown material. If this would be not implemented, pulling or snagging of the sown material occurs since the needle snags the moving material.

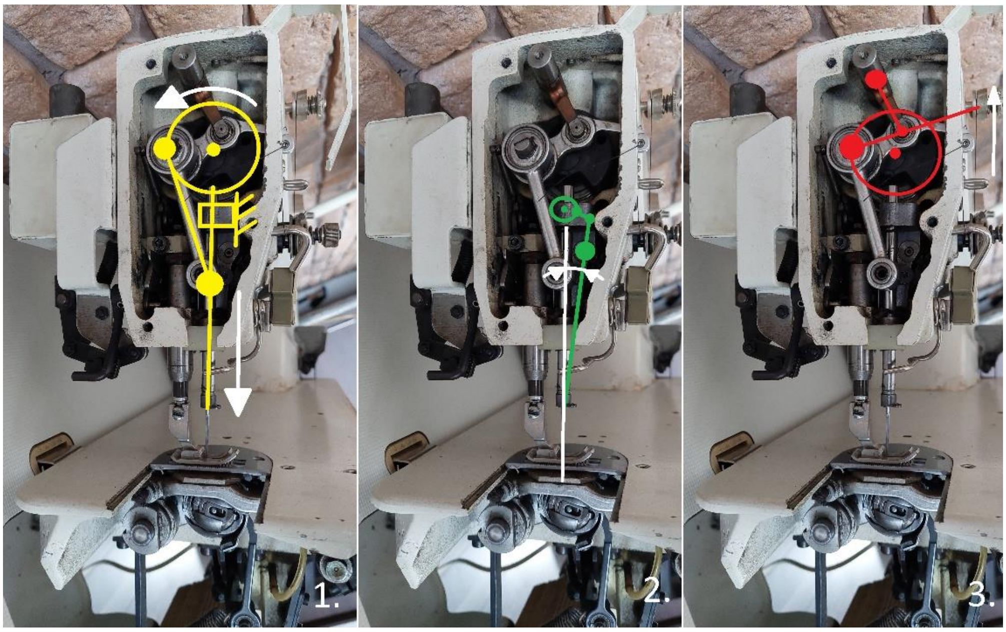

Fig. 18. Sewing Head Assembly

The transmission tunnel is shown in Fig. 19. It is very hard to access a full view of the camshafts since the whole frame of the sewing machine is cast-iron. The schematic in the figure represents existing shafts that work in synchronous with the main shaft marked 1. The shaft marked 2 actuates the angular rotation of the needle. It works in accordance with the reverse lever and step size selector. The shaft marked number 3 represents the actuation of the feed-dog pad. The shuttle bobbin filer is also driven from the main shaft by an angular gear assembly.

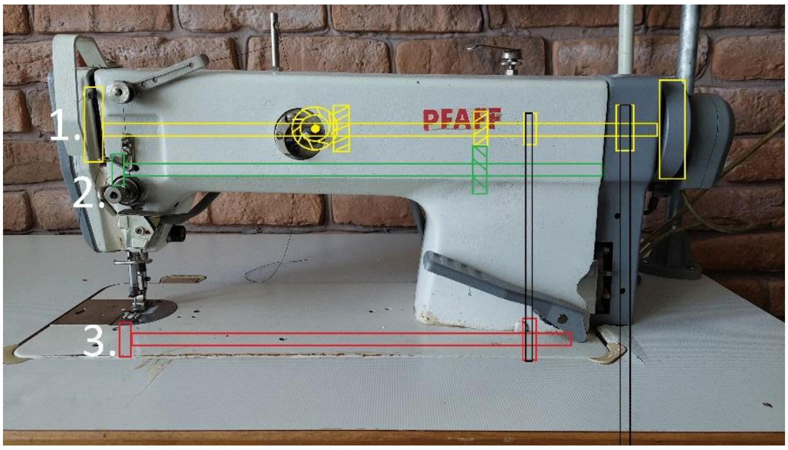

Fig. 19. Transmission Tunnel and Shuttle Bobbin Filler

2.2. Existing Solutions for Sewing Machine Monitoring Systems

After discussing the structure of an industrial sewing machine in the previous sub-section, it is now possible to understand the reasoning behind existing solutions implemented for status tracking. One of such solutions is presented in [23]. The root of this idea is based on the industry 4.0 revolution: internet of things, cyber-physical systems, and internet services. According to the source, a smart factory is a factory which is based on these technologies existing in production systems, and to do so the cyber-physical connectivity should be strengthened. The research presented in this paper revolves around the detection of the status of the lower thread positioned in the shuttle bobbin. To predict the status of the shuttle bobbin a photo-resistive sensor is used to calculate the rotations, and a combination of a pneumatic piston and a hall-effect distance sensor is used to detect the amount of the thread left on the bobbin. The number of rotations is recorded by the photo-resistive sensor and collected by the main controller to later be used in final calculations used to indicate the critical level of the shuttle bobbin thread. Fig. 20. shows the test stand made by the researchers to put their idea to practice.

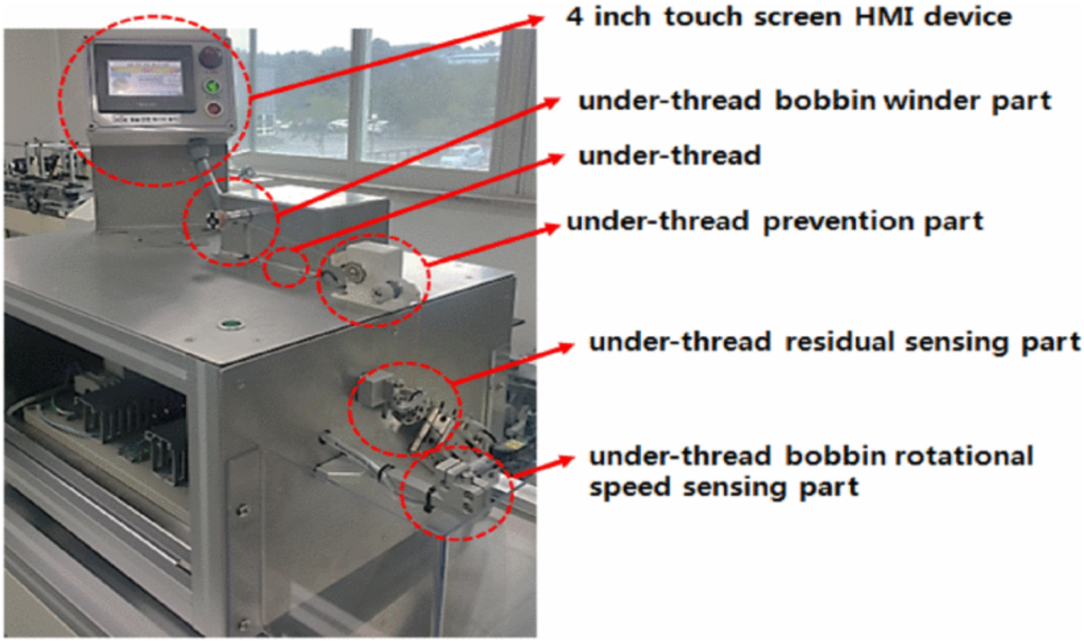

Fig. 20. Test Stand for the Thread-Tension Monitoring [23]

The found solution uses an Omron NPN type sensor E3Z-LL61 to check the rotation of the bobbin with four 45° angled white zones as shown in Fig. 21. and a FESTO SMAT-8M sensor for thread amount sensing. The FESTO SMAT-8M is an analogue sensor used for piston position sensing. In this case it is mounted on a SMC CXSM630 pneumatic piston. The piston has a protruding probe which touches the amount of the thread left on the bobbin. Deducting from the schematic and the presentation in the scientific source, the working principle of this system is to calculate the amount of the rotations and then calculate how much thread is left on the spool according to the wound radius. The results of such calculations only give approximate results of when the thread might run out, and this gives a false status of the machine to the data collection part of the system. The source mentions the use of an RFID tag to preset the machine for different parameters. The change of parameters would include only the change in the step length of the feed-dog since the selected sewing machine does not have any additional functions. This would improve the accuracy of the estimation, but the whole system is quite hard to implement on a larger scale since there are various types of the thread bobbin holding shuttle.

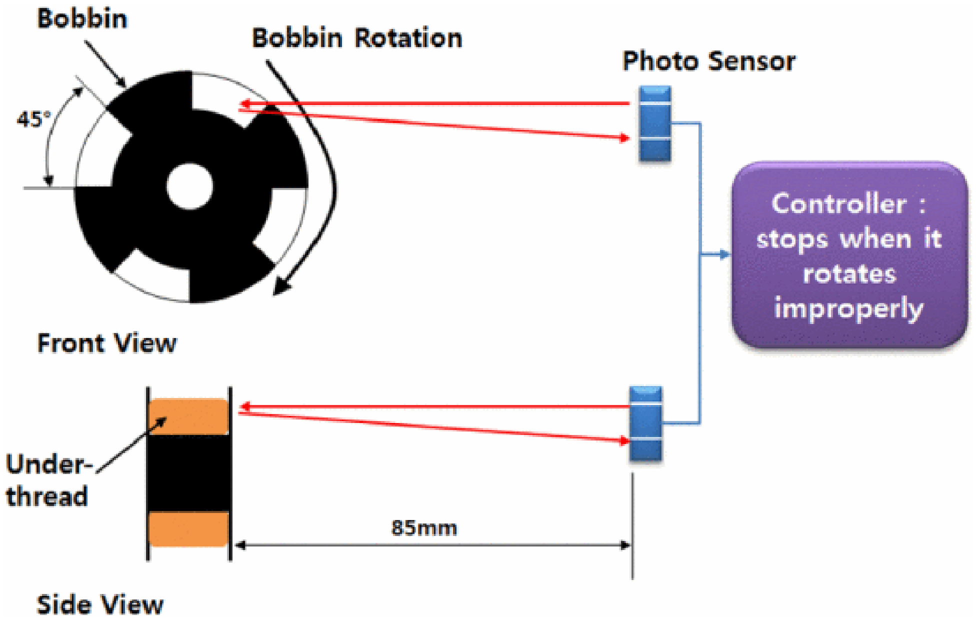

Fig. 21. Bobbin Rotation Speed Sensing Operation Mechanism [23]

According to a scientific source [24], there are three main parameters that are important to be measured in sewing process: material feeding, needle penetration and stitch formation/thread tension. The conducted research in scientific source [24] orbits around the idea of thread tension monitoring to collect the state of the sewing machine. To collect the status information of the sewing machine an optical rotary encoder is used as a time and position synchronizer and a thread tension sensor mechanism shown in Fig. 22. is used to monitor the thread tension. It is important to note that the author mentions that the thread tension sensor does not measure the actual tension on the thread, but it measures the pull force that is created by the sewing machines mechanism to collect slack from the thread. In Fig.22 three sections are shown: the first section on the left represents the mounting of the force sensor, the middle section represents the thread passage, and the last section represents how thread transmits the force unto the sensor.

Fig. 22. Thread Tension Sensor Setup [24]

The custom designed sensor in the paper is described as a cantilever beam with semiconductor strain gauge at the base. It is connected as a complete Wheatstone bridge, meaning that the sensor is placed between two voltage dividers in parallel. The “bridge” is the difference between two voltage dividers. This solution is usually used when electrical resistance is not known. It works by comparing the unknown resistance to a known resistance thus giving small error range usually down to milli-Ohms.

The mentioned sensor assembly was used to collect the following data shown in Fig. 23. The graph in figure is defined by the thread force upon the sensor and the angle is defined by the optical angle encoder. The graph is divided into three sections; each section represents a different action made by the machine. The first section is from 190° to 270°, it defines the thread being guided around the bobbin by the hook. At 270° the lever responsible for slack retention is in its lowest position. The second section is from 270° to 295° the needle is returns to the top position and the thread slack lever starts the upward movement to retract slack. The third section is between 295° and 380° the thread tension lever pulls up the slack, the highest forces are observed in this range. Table 4. summarises the results of the graph.

Table 4. Events Corresponding to Rotational Angle

Phase	Approx. angles	Event
1	190º-270º	Needle thread is being guided around the bobbin by the hook. At approximately 260 degrees, take-up lever is in its lowest position.
2	270º-295º	Needle is approaching highest position; thread take-up lever initiates its upward movement.
3	295º-380º	Thread take-up lever pulls thread up. In this phase, the highest thread tensions are observed.

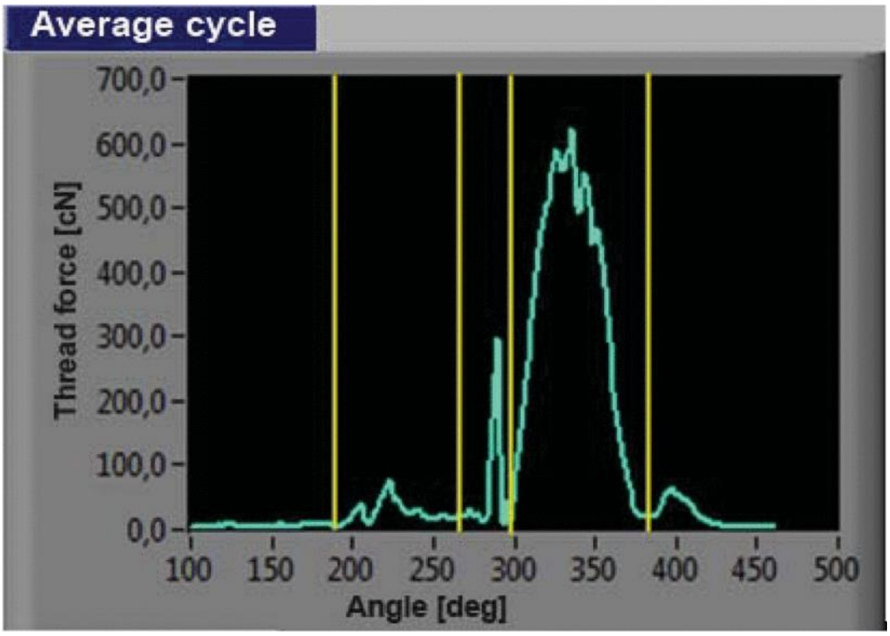

Fig. 23. Thread Force for One Stitch Cycle [24]

After analysing the information presented previously it is possible to say that the sensor placement for the initial purpose was very successful. The sensor system allowed to successfully indicate the real time activity of the machine. The retrieved graph can be interpreted clearly depending on the action of the machine and according to the presented conclusions in the source there is significant difference between material types and thickness. The only downside which could bring doubt for this solution is the repeatability factor, meaning what would be deviation in the segment peaks of the Fig. 23 graph between ongoing, repeating stitches. Another question arises, how impaired the system becomes and how accurate it is, once different thread diameters and materials are used, since some threads have lower friction coefficients and other have higher coefficients.

Thread tension monitoring in describing the state of the machine has received quite a bit of attention, looking at existing research papers. Another paper [25] describes a similar approach to monitoring a sewing machine status. The focus of this paper is to find a way to monitor and control the thread tension to reduce error occurrence in production. In a nutshell it follows a similar approach of using a tensile load cell to monitor the thread tension as shown in Fig. 24. The experiment presented in the paper describes the comparison of three values regarding needle thread tension. The theoretical tension has been calculated according to a mathematical model presented in the paper and is used as a base parameter to compare practically retrieved values from the load cell. Since the paper is written while taking in mind woven fabrics the unwinding tension was also recorded as shown in Table 5.

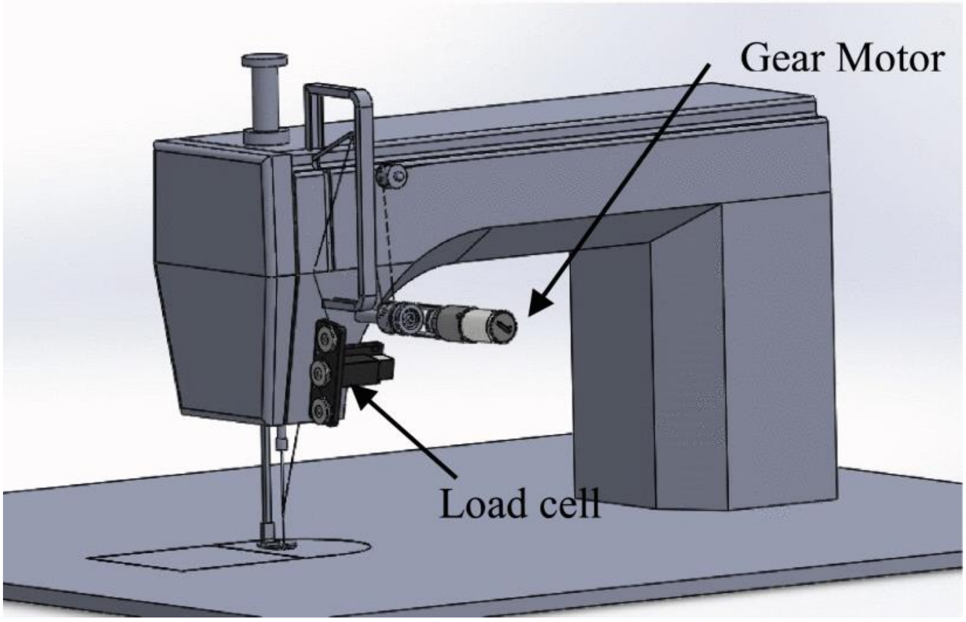

Fig. 24. Thread Tension Monitoring and Adjustment System [25]

Table 5. Comparison of Theoretical and Practical Data [25]

Unwinding tension (cN)	Theoretical average needle yarn tension (cN)	Experimental average needle yarn tension (cN)
0.43	9.357	7.73
0.55	12.033	11.86
0.65	13.895	14.3
0.66	16.081	16.53
1.29	20.967	22.68
1.33	21.278	21.53

As it is possible to see from the Table 5, the theoretical and practical values are not that different meaning that the use of a load cell as a thread sensor could be possible to implement. Looking at Fig. 25. a pattern can be seen repeating in the graph meaning that number of stitches made can be deducted. A deeper analysis of such solution could provide insight into possibility of differentiating errors affecting the status of the sewing station.

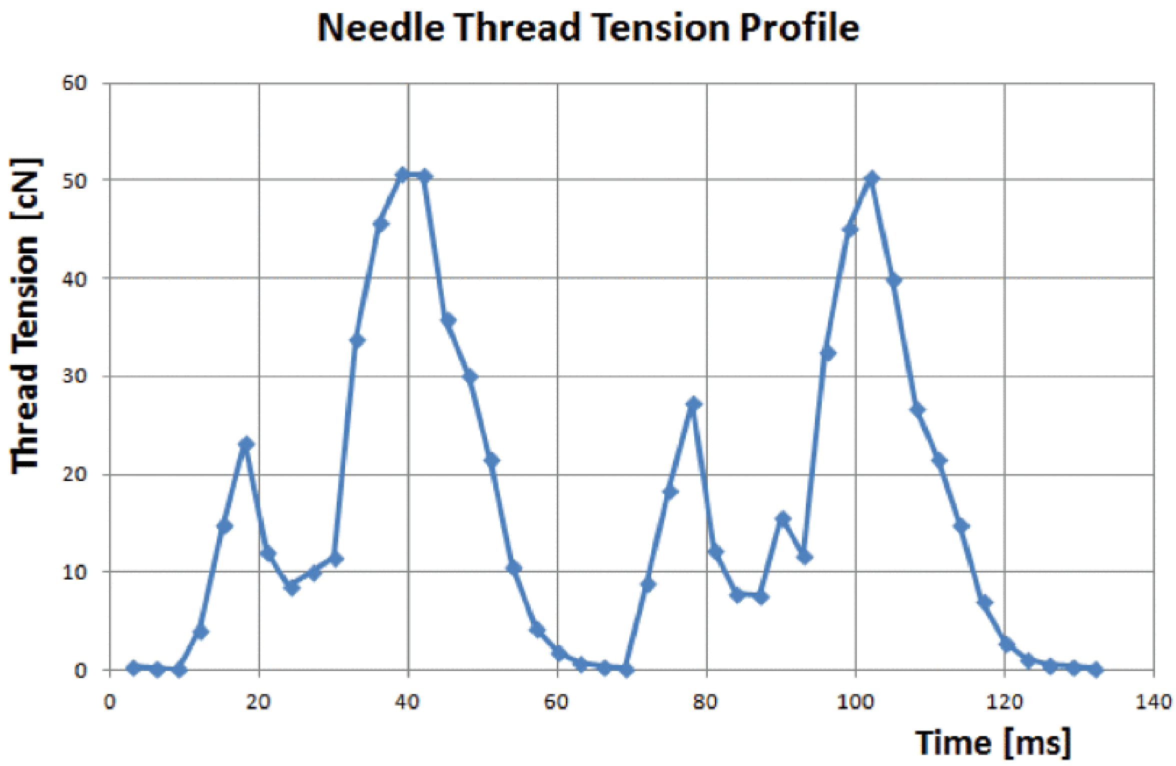

Fig. 25. Needle Thread Tension Profile in Correspondence to Time

2.3. Chapter Summary

The understanding of the sewing machine working principle and structure is critical while analysing existing solutions for sewing machine state interpretation. The seam creation process has been described in minute detail to better interpret the complexity and intricacy of found solutions. The sewing machine itself is a system that mainly works in synchronous regime between its various camshaft assemblies, thus presenting the idea that most of the components are mechanically timed and intertwined. Continuing in this path of thought, it is possible to deduct that by knowing one important parameter such as thread tension, it is possible to describe the position of machine or what part of cycle it currently is in. By collecting the information creating median based models it is possible to differentiate between error state of the machine and the productive state. Bringing a conclusion that the success of determining the state of the machine greatly depends on the selected sensor and the monitored parameter.

3. Developing a Solution for Sewing Machine State Monitoring and Recording

Sewing machine state monitoring and recording is a process that requires intricate solutions and planning. This section describes the process of analysing and comparing different sensors, their positioning and reasoning behind those solutions.

3.1. Sensor Selection and Justification

The current selection range of sensors is quite large and must be narrowed down by selecting the properties that must be measured, the surrounding environment of the measured system, and the economic price range viable for the manufacturer [26]. Looking back at the second section, it is possible to see that not a lot of attention has been brought to the selection of specific sensors. Majority of the systems mentioned in the first section also have not provided any justification to the sensor selection. According to a scientific article on sensor selection, it is generally a problem of optimization with multiple objectives and constraints [27]. The source describes that there are two methods of selection; model based, or data based.

An issue occurs when selecting a sensor for a new system that does not have any pre-recorded data. The source recommends comparing the newly created system with already existing systems and to analyse the recorded data of those systems. The article also outlines the most important online monitoring (OLM) parameters as shown in Table 6. Based on the previously mentioned article the sensor type and position will be decided according to already existing solutions and their retrieved data.

Table 6. Sensor Selection Qualities for Online Monitoring [27]

OLM Capabilities	**Description**
1. Fault Detection and Discrimination (FDD)	A property of OLM systems for detecting and identifying various types of faults in the target system.
2. Risk Reduction (RRD)	A property of OLM systems for reducing system risk by forecasting component failures during system operations.
3. Sensor Failure Tolerance (SFT)	The tolerance to sensor failures during the operation of OLM systems.
4. Observability (OBV)	A property of OLM systems for observing system signals and states.
5. Functionality (FNC)	A property denoting whether the functions of a sensor satisfy the requirement of the OLM system
6. Integrability (INT)	A property representing the difficulty of installing a sensor into the monitored system.
7. Cost (CST)	The expenses for adding a sensor to the OLM system

To successfully record data, it is mandatory to select key elements of the system to be monitored with the sensors. Looking at previously analysed examples, the common parameter to be monitored is thread tension and bobbin thread amount. Although these parameters can help identify errors in the manufactured product, they can not accurately describe the state of the manufacture process. To accurately depict the state of the work process and the sewing machine, parameters to be monitored had to be selected. the main driving shaft and a sensor to determine what the thread or the needle is doing., for this purpose, the reviewed sources use rotary encoders. They create a position-based reference system for description of secondary collected parameters, such as thread tension. Thread tension is an analogue parameter that has been monitored using a load cell or a custom sensor to differentiate the position of the needle according to the exceeded force by the thread in reviewed examples.

According to [28] the current of a motor differentiates depending on the external load applied to it. This happens because as the motor is exposed to an external load and the rpms of the motor decrease. Following this process, the windings do not get as many interactions with opposing magnetic forces from the rotor, therefore creating less counter electro-magnetic forces in the windings which in general reduces the overall impedance of the motor windings. According to the Ohms law, if the resistance, or in this case overall impedance, decreases, the current rises.

By monitoring this change of the external load of an electric motor using a current sensor it could be possible to determine when the sewing machine operator releases the clutch and starts to sew. Keeping in mind previous solutions, the current sensor could be used in cooperation with a rotational encoder to determine different actions of the operator. In doing so the status of the sewing station can be determined. After searching the most used sensors for preliminary development in reviewed and other existing scientific sources, the found sensors have been inserted into Table 7. The selection of monitored parameters has been guided by the aim of accurately identifying sewing states, their reactiveness to changing state of the machine, and the feasibility to integrate the retrieved operators' actions with the use sensor data and classification of the retrieved data. The main objective that was considered during the selection process was the relevance to describe different machine operating parameters with a real-time representative axis.

According to previous sewing machine structure analysis, the main driving element of the sewing machine is an AC motor. Therefore, electrical current sensors have been selected to experimentally analyse the correlation between the state of the machine and the actual current draw. There are various types of current sensors that can be divided into invasive and non-invasive types. The retrieved data on correlation of current draw of the AC motor, depending on sewing machine action, can be successfully implemented in further AI based classification models.

Angular rotation of the main driving shaft is also monitored to represent the state of the whole machine, since it actuates the following sub-assemblies of the machine, such as the bobbin spool winder, reverse stitch, and automatic end stitch. A sensor that can monitor angular rotation of the main driving shaft also correlates with the real-time axis giving an approximate state of the sewing machine station. The collected information can also be classified into different actions in future research projects including AI based classification models.

Table 7. Found Applicable Sensors

Name	Type
AS5600	Hall-effect absolute rotary encoder
LPD3806	Incremental optical rotary encoder
E3Z-LL61	NPN type photo sensor
TA12-200	Current transformer
ACS723	Hall-effect type current sensor
SCT 013	AC current transformer
INA219	Shunt type current sensor
KSPB-2-120-E3	Tensometric beam
S256	Semiconductor strain gauge
NA27	Load cell

The found sensors are of a lower budget range but allow a wider range of testing. The first in Table 7 is AS5600 absolute rotary encoder, it is based on hall effect sensor. It has been selected due to its versatility and ruggedness. It is simple to integrate but requires additional mounting for implementation with error range of +-1º. A different type of encoder is LPD3806, it is an optical encoder mountable on the driving shaft and measures the rotation in increments compared to AS5600 which measures absolute angle of the shaft. An optical encoder is larger in its size and could prove difficult to be implemented. To measure the load on the AC synchronous motor, a current transformer TA12-200, current sensor ACS723, SCT013 AC current transformer, and INA219 shunt type current sensors are selected.

These current measuring sensors could be used to monitor the current load on the synchronous motor while the clutch engages and disengages, also to see if there is any possible way to determine the position in seam creation. The key factor for success of using current sensors to detect load differences from the current is the accuracy range. Since the load on the motor is not that large in general. For measuring of the tension on the thread two sensors have been found according to previously reviewed sources. KSPB-2-120-E3 tensometric beam and S256 which is a semiconductor strain gauge. Both sensors will require additional designs and circuitry to implement them which will make it harder to use. They also have a higher price range and problematic availability because they are not that common. As an alternative a NA27 load cell combined with HX711 operational amplifier can be used to track tension of the thread. From the found sensors, three were selected for further implementation in the work due to their properties mentioned in Table 8 according to source [27].

Table 8. Sensor Comparison According to Description

Name	Type	Integrability	Functionality	Observability	Cost
AS5600	Hall-effect absolute rotary encoder	Requires minimal additional fixtures to mount	Provides a reference for synchronisation of monitored data	12-bit resolution, providing 4096 values per rotation, with error range +-1°	10.70 Eu
TA12-200	Current transformer	Does not require additional fixtures to mount	Provides ability to describe ongoing system process	Measuring range 0-5 A, with 50mA error range	11.50 Eu
ACS723	Current sensor	Requires soldering to implement	Provides ability to describe ongoing system process	Measuring range 0-5 A, with-30mA error range.	16.80 Eu

The three sensors were selected considering existing research on sewing machine state tracking and current methods that focus on thread tension tracking, using load cells or bobbin spool runout, using optical sensors. The selected sensors broaden the research range, thus giving valuable insight into the topic, and if successful the solution would be easier to implement into existing industrial sewing machines.

3.2. Sensor Placement, Setup, and Verification

Sensor placement is an important factor in the success ratio of the project; therefore, the three sensors are planned to be implemented according to the key status defining parameters that were mentioned previously. The parameters have been determined to be angular rotation of the driving shaft and AC motor current consumption. The implementation of the sensors required creation of additional brackets for mounting them. Since the AC current sensors are measuring the same value and they are being compared later in the work, they share the same housing, meaning that if only one of the sensors would be used the final size of the integrated device would be a lot smaller. The Fig. 26. shows the view where both current sensors, marked as 1., and the AS5600 rotational magnetic encoder, marked as 2., will be integrated into the sewing machine assembly.

Fig. 26. Sensor Mounting Positions

For the first position, in which the current sensors are mounted, one general housing box has been created, and its model is shown in Fig. 27. For the second position marking AS5600, the bracket used for verification and testing is shown in Fig. 28.

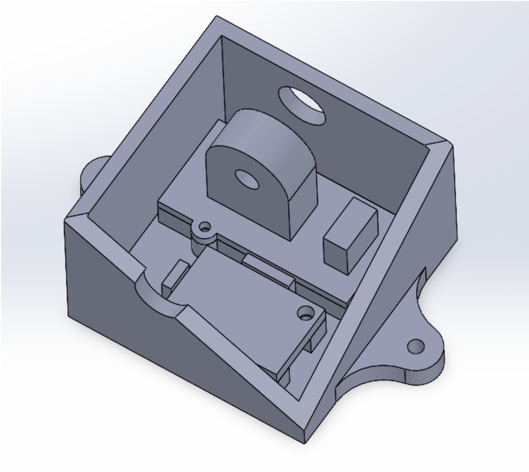

Fig. 27. Case for TA12-200 and ACS723 Sensors

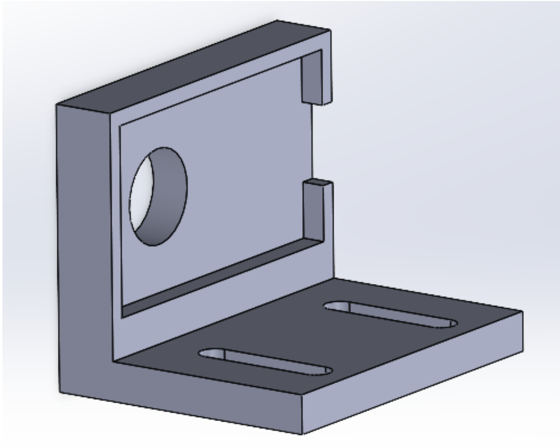

Fig. 28. Holder for AS5600 Rotary Encoder Sensor

Verification of sensor data allows to determine the sensor implementation success and accuracy of the recorded data. Even though the sensor manufacturer specifies the error range to be quite low, often other factors such as, system noise affect the final accuracy of the sensor. To investigate the actual accuracy of the applied sensors, a higher precision device will be used for the current sensors and an angular scale will be used to determine the accuracy of starting point repeatability of the magnetic rotary encoder. The device used to check the current consumption of the AC motor is FLUKE 325 clamp meter. It has a determined accuracy range of 40 A ± (2% + 5), which means that at 2% error range the number shown after the 5th digit of the reading scale is unreliable because the meter cannot determine the actual measured value anymore from existing noise. For the magnetic rotary encoder an angular scale has been used to determine if the sensor reading is actually similar to the physical value of the rotating scale. The manufacturer of the selected angular scale is Hogert and according to their instrument datasheet, the actual error range of the scale is up to 2°, meaning that the actual scale may differ from the perfection division of a circle by 2°. This gives an average estimate of angular representation of the actual angle of the shaft compared to the recorded angle of the sensor, the used devices used for the verification of the sensors are shown in Fig. 29. and Fig. 30.

Fig. 29. FLUKE 325 Clamp Meter [29]

Fig. 30. Hogert Angular Scale [30]

To accommodate the Hogert angular scale, a mounting bracket has had to be made. The bracket assembly consists of two parts: the shaft mounting bracket, and the diametric magnet holding bracket as shown in Fig. 31., and Fig. 32. To make the position of the sensor adjustable, calibrated aluminium profiles have been used together with the 3D printed bracket shown in Fig. 33., making the X, Y, and Z position adjustment possible. The distance between the diametric magnet and the AS5600 sensor has been set to approximately 3mm as specified by the manufacturer. The assembled sensor testing bench for the AS5600 magnetic rotary encoder is shown in Fig. 34.

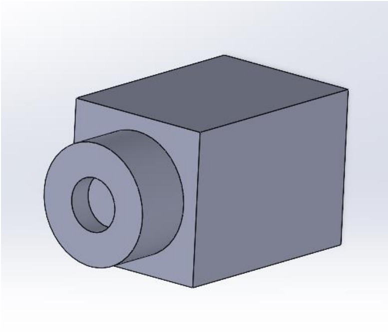

Fig. 31. Diametric Magnet Holding Bracket

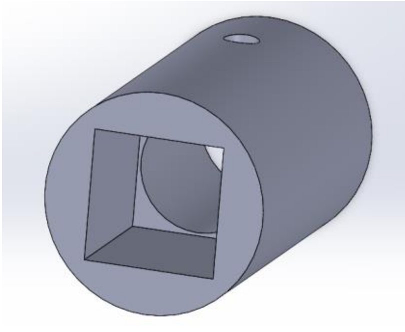

Fig. 32. Angular Scale Mounting Bracket for the Main Shaft

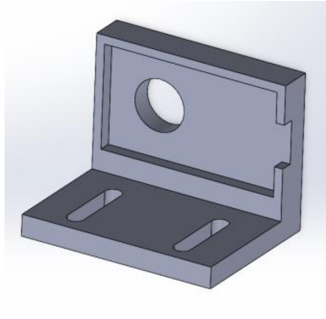

Fig. 33. AS5600 Holding Bracket

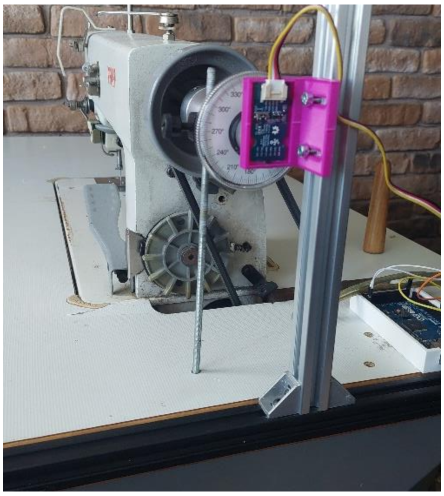

Fig. 34. Assembled Testing Bench for the AS5600 Magnetic Rotary Encoder

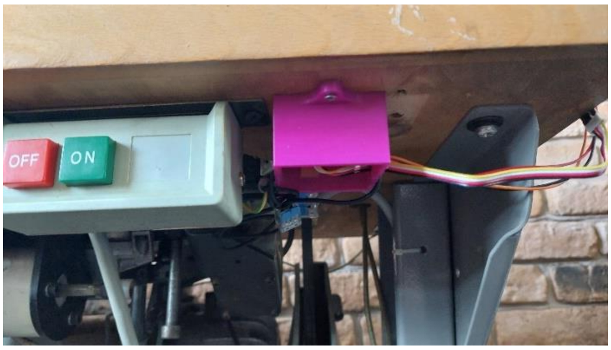

Fig. 35. Implemented Holding Bracket for the TA12-200 Current Transformer and ACS723 Hall Effect Current Sensor

For the implementation of the AC motor current sensors TA12-200, and ACS723 the bracket shown in Fig. 35. has been 3D printed and implemented. To collect the information from the sensors an Arduino mega2560 microcontroller has been used. The sensors have been connected to the microcontroller according to the datasheet requirements as shown in Fig. 36. The TA-12-200 uses only the analogue read A1 pin and the ground pin to allow the Arduino mega2560 to read the differentiating voltage across the burden resistor. The burden resistor is used to dissipate the generated current in the secondary coil, because Arduino mega2560 is only able to measure the voltage difference and not the current itself. According to the datasheet provided by the manufacturer the sensor does not require any additional power supply. The ACS723 is a Hall-effect based sensor which measures the magnetic field generated by the passing current. The design of the selected sensor requires for the sensor to intercept into the measured wire which has been done as shown in the schematic in Fig. 36. by soldering the wire leads to the +Ip and -Ip pins. The ACS723 sensor requires 5V of supply voltage and transmits the voltage difference through Vout pin which is connected to the A2 pin on the Arduino mega2560. The BW_SEL pin allows to select the inner low pass filter parameter between 20kHz and 80kHz. Since the measured AC current only has 50Hz frequency, according to the Lithuanian and European power grid parameters, the pin is left disconnected from ground pin, setting its low pass filter parameter to 20kHz. The AS5600 magnetic rotary encoder can be connected in two modes: I^{2}C or PWM. The I^{2}C mode outputs the raw data of the uncalculated data and the PWM mode outputs the high, low parameter read by the sensor.

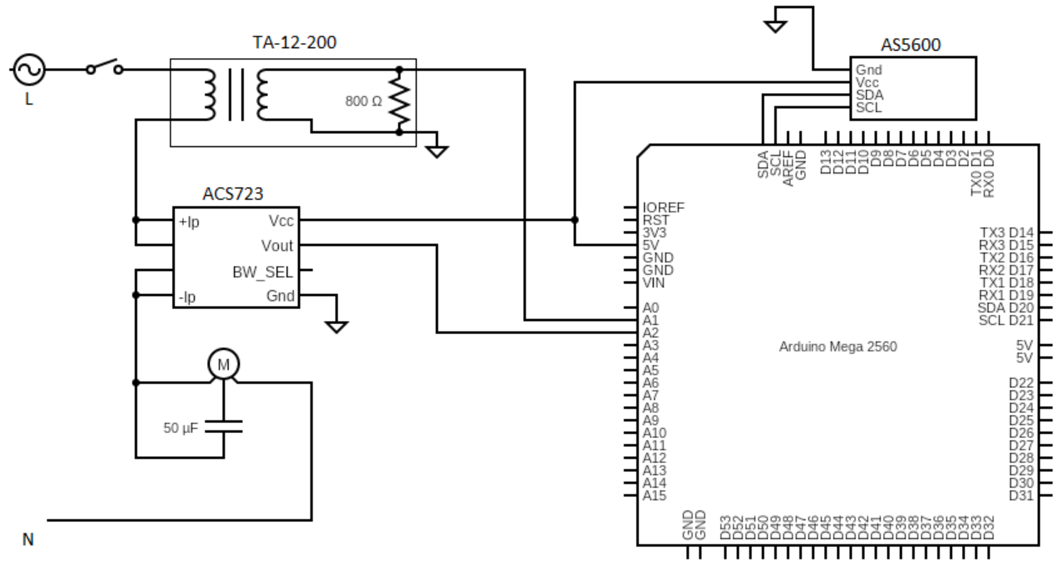

Fig. 36. Electrical Connection Diagram of the Tested Sensors

The prepared testing bench has been programmed using Arduino IDE interface which is based on C++ programming language. The code has been written considering the sensor manufacturer specifications regarding sensor parameters, the program code has been written for the magnetic angle encoder based on I^{2}C communication protocol. It is a simple 2-wire serial bus communication protocol based between a master device and a slave device. The communication is happening through two pins: SDA, and SCL. SCL is the serial clock which describes the communication data transfer rate, it is required for the synchronization of the slave and the master devices. The SDA pin is the data transfer pin, and since it is a bidirectional bus, the data can be sent and received through the same pin. The protocol itself is based on a half-duplex principle, so the devices must take turns to send and receive information from each other. The I^{2}C protocol requires an address to successfully establish communication with the needed device, for this sensor, the address provided by the manufacturer has been, 0x36 in hex code or 00110110 in binary. The Arduino uses 7bit addresses for the I^{2}C protocol according to the American standard code for information interchange, therefore the address of the sensor is written in 7 bits. In Fig. 37 the written code for AS5600 is shown, the first four lines describe what libraries have been used and how the variable holding the address of the device is named. In lines 5-9 the initial setup settings have been described. The serial communication rate or baud rate is set to be 9600 and the serial communication is initialised. For the looped program cycle in lines 10-31 the slave-master communication is described. In lines 14 the described function initialises the internal buffer, new slave device address is stored in it, and the master device is set to write mode. In lines 15-16 the register from which the data will be retrieved has been described, and line 16 describes that the communication is still not over. The line 17 send the address again and verifies that it will read data now from the two bytes. The following if function statement confirms the retrieval of the two bytes and if it is positive in the lines 20-21 reads the high byte and the low byte. The high byte and the low byte describe the most and the least significant bytes, together they make the raw data value. To be able to read the actual value that is being sent it is necessary to check how many bits describe the sent value, since the device is 12-bit resolution, the amount of bits that describe the sent value are 12 According to the AS5600 sensor datasheet specifications, the high byte carries 4 bits of value and the first four bits of the whole byte are unnecessary or noise, therefore in line 22 a bit operation is done by comparing the high byte with 0x0F byte using "AND" function. The modified byte is then shifted to the left side by 8 positions meaning that the first four bits in the 12 bits that were received is only of the high byte, and finally to connect the high byte and the low byte an "OR" operation is used. The value that has been described by the 12 bits is now converted to degrees by using proportional value from the maximum value of 4096 divided by 360 degrees and multiplied by the retrieved raw angle. To print out the retrieved values in the serial monitor, the lines 25-28 have been used.

```
1  #include <Wire.h>
2
3  #define AS5600_Adress 0x36
4
5  void setup() {
6    Serial.begin(9600);
7    Wire.begin();
8  }
9
10 void loop() {
11
12   // AS5600 measurement
13
14   Wire.beginTransmission(AS5600_Adress);
15   Wire.write(0x0E);
16   Wire.endTransmission(false);
17   Wire.requestFrom(AS5600_Adress, 2);
18
19   if (Wire.available() == 2) {
20     int highByte = Wire.read();
21     int lowByte = Wire.read();
22     int rawAngle = ((highByte & 0x0F) << 8) | lowByte;
23     float degrees = (rawAngle * 360.0) / 4096.0;
24
25     Serial.print(" Raw Angle: ");
26     Serial.print(rawAngle);
27     Serial.print("AS5600 Degrees: ");
28     Serial.print(degrees);
29   }
30
31 }
32
```

Fig. 37. AS5600 Code

In Fig. 38. the code for TA12-200 current transformer has been written to measure the current consumption of the AC motor. The 1st line describes the variable for the analogue pin to which the sensor has been connected, and in lines 3-5 the initial setup is done by setting the baud rate. In lines 9-11 the raw sensor value has been retrieved and converted to measurable voltage, following the Ohm's law I=U/R the current has been calculated from the measured voltage. The retrieved current is then multiplied by 2000 since that is the transformation ratio of the current transformer, meaning that if the calculated current in the second winding is 0.001 A the value on the measured line would be 2 A. Since the calculated current was that of the sine wave peak value the effective value must be calculated to represent the true current consumption. This has been done in line 11 using the root mean square method. In lines 19-35 the function used to find the peak value has been described, and for it an inbuilt function millis has been used. It describes the time the device has started to run, so the function creates a time reference based on the internal clock of the microcontroller and saves it as the start_time variable. The following line 25 states that while the time difference between the current time and the start_time is less than hundred, the described loop will repeat. During this time increment in lines 24-32, the sensor value is read and compared to its previous reading which has been saved as sensor_Max value, in each repetition if the new reading is higher, the sensor_Max value is replaced with it. After the time increment is completed, the function returns the found maximum value of the sensor reading which would be the highest peak current found.

```
1  const int ta12_200_sensor_pin = A1;
2
3  void setup() {
4    Serial.begin(9600);
5  }
6
7  void loop() {
8      // TA12-200 measurement
9    int peak_adc_ta12_retrieved = get_peak_value_ta12_200();
10   float peak_current_TA12 = (float)peak_adc_ta12_retrieved/1024*5/800*2000;
11   float currentRMS_ta12200 = (float)peak_current_TA12/sqrt(2);
12
13   Serial.print("TA12200 RMS Current: ");
14   Serial.print(currentRMS_ta12200, 3);
15   Serial.println(" A");
16
17 }
18
19 int get_peak_value_ta12_200()
20 {
21     int sensor_Value;
22     int sensor_Max = 0;
23     uint32_t start_time = millis();
24     while((millis()-start_time) < 100)
25     {
26         sensor_Value = analogRead(ta12_200_sensor_pin);
27         if (sensor_Value > sensor_Max)
28         {
29             sensor_Max = sensor_Value;
30         }
31     }
32      return sensor_Max;
33 }
```

Fig. 38. Code for Current Transformer TA12-200

For the third sensor the code is shown in Fig. 39, the code for the ACS723 current sensor has been written differently than that of the TA12-200 current transformer since the sensor has a different working principle. The sensor output for the ACS723 is centred around 2.5V, the calculations are different for the results. In the mentioned figure, the first 5 lines describe the initial information and variables retrieved from the datasheet. The reference voltage for the sensor is 5 V since it is the same as the Arduino voltage and half of that voltage would represent the offset for our calculations. The offset in line 3 has been adjusted to 2.52V because the offset value may differ up to +- 0.02V according to the manufacturer's specifications. The sensitivity parameter describes how much the read voltage changes per ampere of the measured current, the value has been retrieved also from the sensor datasheet of the manufacturer which is 0.4 mV/A. The variable described in line 5 describes the number of samples that will be collected. The lines 7-9 describe the initial setup of the microcontroller, in this section only the communication rate is described. In the line 11-29 the main logic has been written. The line 13 describes the summed voltage from the stored samples that have been retrieved from the for cycle in lines 15-20. In these lines the raw value of the sensor pin has been read and transformed into voltage by making a proportion from the maximum resolution value and the reference voltage. To accommodate the realistic value that has been collected an offset is applied in line 18 then the result of the squared voltages is summed in line 19. Following the root mean square formula, the voltage sum is divided by the number of samples that have been retrieved, and the root value is obtained. The mean voltage value of the collected interval is then calculated into current by dividing the retrieved value by the sensitivity parameter. To present the calculated result in the serial monitor on the computer lines 25-27 have been written.

```
1  const int acs723_sensor_pin = A2;
2  const float vRef = 5;
3  const float offset = 2.53;
4  const float sensitivity = 0.4;
5  const int samples = 500;
6
7  void setup() {
8    Serial.begin(9600);
9  }
10
11 void loop() {
12   // ACS723 measurement
13   float voltageSum = 0;
14
15   for (int i = 0; i < samples; i++) {
16     int raw = analogRead(acs723_sensor_pin);
17     float voltage = (raw * vRef) / 1024.0;
18     float centeredVoltage = voltage - offset;
19     voltageSum += centeredVoltage * centeredVoltage;
20   }
21
22   float voltageRMS_acs723 = sqrt(voltageSum / samples);
23   float currentRMS_acs723 = voltageRMS_acs723 / sensitivity;
24
25   Serial.print("ACS723 RMS Current: ");
26   Serial.print(currentRMS_acs723, 3);
27   Serial.print(" A, ");
28
29 }
```

Fig. 39. Code for ACS723 Current Sensor

To verify the retrieved results from the rotational angle encoder an experiment has been performed by rotating the main shaft by hand and comparing the read value after a one full cycle with the value displayed by the angular scale. To verify the repeatability of this process, the experiment has been performed for 20 iterations by recording the measured value and the actual value of the scale and recording the results in Table 9. During the experiment it has been noticed that the deviation mostly occurs during loading of tension on the testing mechanism. It has been observed that this slight warping occurs on the connection joints of the stand, meaning that tighter tolerance fitting would decrease the warping, but it would be harder to manufacture them. The retrieved average error of the magnetic angular encoder has been calculated to be 0.466 ° comparing to the +-1 ° described in the datasheet. From the experiment results it is possible to determine that the data repeatability is valid enough to continue experimentation with the sensor while collecting information from the system.

Table 9. Magnetic Angular Encoder Result Verification

Recorded data by the sensor	Actual value measured by the angular scale
0.01º	0º
1.04º	0º
0.05º	0º
0.90 º	0º
0.83º	0º
0.23º	0º
0.02º	0º
0.09º	0º
0.46º	0º
0.72º	0º
0.59º	0º
0.01º	0º
1.12º	0º
1.04º	0º
0.86º	0º
0.65º	0º
0.08º	0º
0.36º	0º
0.19º	0º
0.07º	0º

The verification of the current sensors has been done in a similar manner by doing parallel measurements with the clamp meter and the programmed sensors. The first sensor to be tested has been the ACS723 hall effect current sensor and the experiment for it consisted of parallel measurement of the starting current draw and no-load operation current draw. The values that have been recorded by the clamp meter and the ACS723 current sensor have been placed in Table 10. The values that have been inserted for the ACS723 sensor have been calculated from time period averages for each section depending on the on-going action. The calculated average values for no-load current and the starting current have been represented in Fig. 40 and marked in orange and grey colours. By comparing the placed results retrieved from the mentioned devices in Table 10. it is possible to verify that there is some error involved in the recording the current value with the ACS723 sensor. Taking a deeper look in the ACS723 sensor datasheet [31] it is possible to find the offset voltage error to be up to +-20mV which means that the value read by the shut off current section is representing this error. Another difference is seen by comparing the starting current column values because the actual value recorded by the clamp meter is 16,03A and the sensor measured value is 5,66. This is since the current range is exceeding the maximum detectable current during start-up time. Once the value drops back to the normal operating range it is possible to see that the difference average between the clamp meter and the sensor falls to only 0,05A for the remaining duration. Once again, according to the manufacturer datasheet the total output error varies between +-3% of the recorded value, meaning that for the 1,25A being recorded the error can be up to 0.038A, or in this case the error has been found to be 0.070A. To avoid these errors, most likely caused by noise, meticulous programming would have to be implemented to filter out the encountered deviations.

Table 10. ACS723 Current Consumption Comparison with FLUKE 325 Clamp Meter

Device	Shut-off current, A	Starting current, A	No-load operation, A
Fluke 325 clamp meter	0,00	16,03	1,25
ACS723 sensor	0,02	5,66	1,32

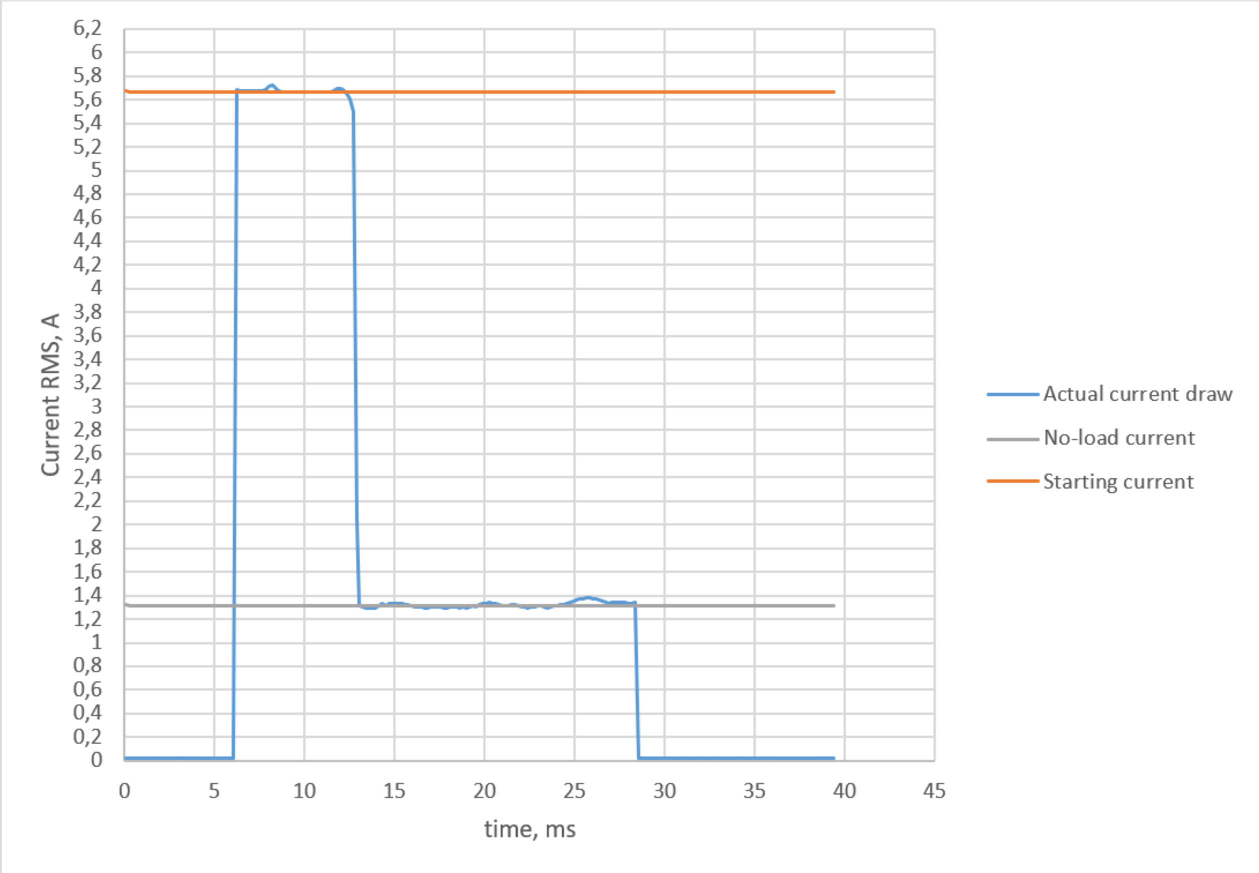

Fig. 40. ACS723 Current Sensor Configuration Graph

The same exact verification procedure for the TA12-200 current transformer has been applied to check and compare the values recorded with the sensor and with the clamp meter. The calculated averages for the starting current and the no-load current have been represented in Fig. 41. with green and orange lines. The average value for the starting current has been calculated to be 8.83 A and for the no-load current it has been calculated to be 1,46 A, these values are compared in Table 11. with the readings from the FLUKE 325 clamp meter. From Table 11. it is possible to see that there is no current difference between the clamp meter and the TA12-200 sensor while the device is shut off, since the sensors' working principle is that of a transformer, if there is no running current through the main measured wire, there is no generated current in the secondary wiring. For the starting current the same explanation fits as with the ACS723, the TA12-200 sensor is built to measure up accurately up to 5A according to the datasheet [32], [33]. Comparing the no-load currents between the clamp meter and the TA12-200 sensor a difference of 0.080 A has been found. According to manufacturer documentation, the accuracy error should be around +-1% while measuring in 5A range and in -40 to +25 C^{o} temperature range, meaning for 1.25A actual current the maximum error should reach to 0.013A. According to various engineering forum sources [34], [35], the error is higher because the Arduino mega is only capable of measuring the positive cycle of the AC current sine wave and the

TA12-200 is only presenting the positive cycle of the sine wave. In theory when the sine wave is in ideal form the negative and positive peaks are the same, but in reality, the sine wave is not perfect form, and the peak value may be higher than the actual RMS value of the current leading to this error.

Table 11. TA12-200 Current Consumption Comparison with FLUKE 325 Clamp Meter

Device	Shut-off current, A	Starting current, A	No-load operation, A
Fluke 325 clamp meter	0,00	16,05	1,25
TA12-200 sensor	0,00	8.83	1,33

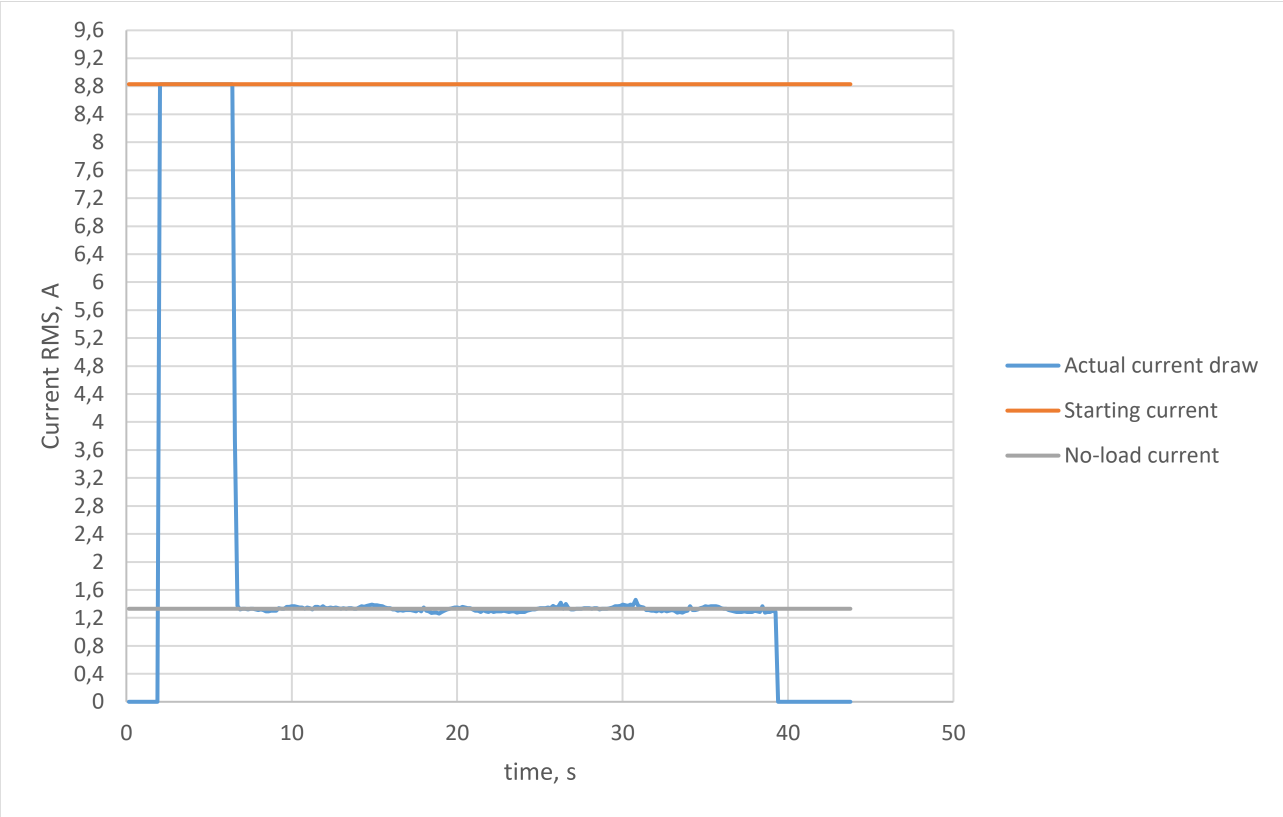

Fig. 41. TA12-200 Current Sensor Configuration Graph

Looking at the verified results, it is possible to say that all three sensors are fit to use in further experiments. The magnetic rotation encoder has been tested to be differentiating from the actual scale within the +-1^{o} range, which gives accurate estimation of the actual position of the driving shaft. Looking at both current sensor an average error of +0.075A occurs due to as determined previously system noise. To reduce the error range of the current sensors a filter could be implemented to reduce the existing noise in the retrieved data.

3.3. Creating the Data Monitoring and Recording System

Collection and comparison of sensor data gives insight into on-going processes of the sewing station, to collect this valuable information verified sensors have been used. Sensor data has been collected with a unified system including the previously written separate code snippets. The retrieved data has been compared on the same time axis to represent how data collected from different sensors depicts the same on-going processes. Multiple microcontrollers have been used to represent multiple sewing stations and how data would be collected from them.

To create a real-time based monitoring and recording system for data collection, the event time axis had to be synchronised with real-time clock. Since Arduino mega2560 does not have real-time synchronization capabilities, a micro-computer has been used to collect the information and store it with real-time data reference. Raspberry pi 3B+ microcomputer has been selected for this purpose due to its versatility and user-friendly interface. It provides a stable platform for data collection and storage that has internet access. To simulate multiple sewing stations connected to the same microcomputer, an additional Arduino Uno microcontroller has been used. The Arduino Uno has been configured to collect the rotational speed of the main shaft with AS5600 magnetic rotary encoder and send it to Raspberry, while the ACS723 and TA12-200 current sensors have been configured with Arduino Mega2560 to collect information about current consumption relative to on-going processes. The electrical block diagram shown in Fig.42. represents the setup used to collect the real-time data from the sewing station using two separate microcontrollers as explained previously.

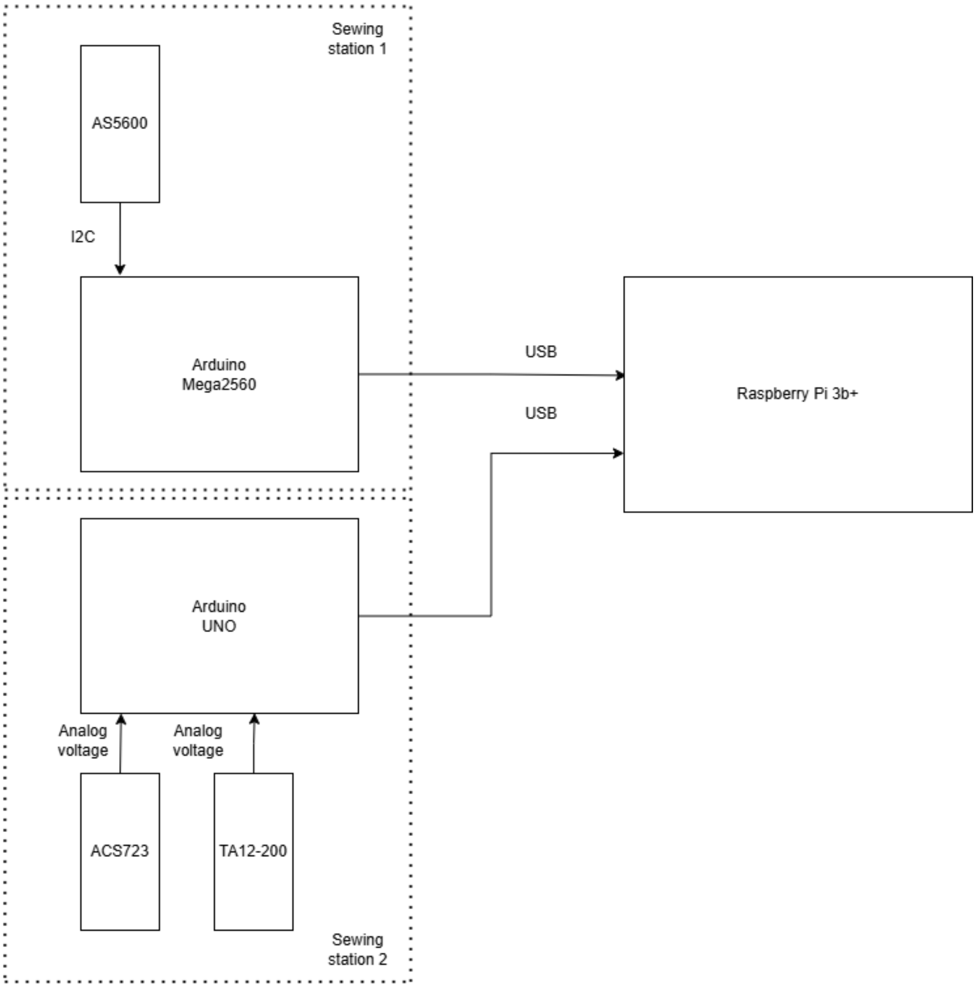

Fig. 42. Electrical Block Diagram of the Data Collection and Monitoring System

To prepare the Raspberry pi 3B+ for data collection and recording a program has been written, it is shown in Fig. 43. The lines 1-4 describe what type of modules have been used for the program: serial module imports the necessary means to communicate via serial ports with Arduino microcontrollers, threading module was used for data logging, time module has been used for time synchronization between the Arduinos and the raspberry since Arduino microcontrollers only support millis() format, datetime module has been used to save the retrieved data with current real date and time stamp. In lines 6-11 the ports, communication rate, and timeouts have been described. In lines 13-14 the serial communication is opened with the two stations, once that has been done the Arduinos reset and require time to fully boot, therefore line 15 gives a 2 second rest interval in raspberry program giving time for the Arduino to reset. In lines 17-21 current time in milliseconds has been called up to synchronize the microcontrollers. The synchronization message is sent to Arduino Mega and Uno and the same time is printed out in the serial window on the Raspberry pi. In lines 23-24 two text files have been created and prepared for data logging. The function in line 26 has three arguments: serial object which is the described serial port, object name which describes the name of the station in the log file, and the last argument is the variable which describe to which opened log file the data is saved. The following lines 27-38 is the while cycle that repeats itself until an error occurs, if an error occurs it breaks the cycle and stops the program. In line 29 waiting for data from microcontroller is described, in line 30-35 if data has been received, an entry is made. In lines 40 and 41 thread objects have been described, since both serial ports must be active at the same time. The threads are activated at the same time with lines 42-43.

```
1  import serial
2  import threading
3  import time
4  from datetime import datetime
5
6  Port_1 = '/dev/ttyACM0'
7  Port_2 = '/dev/ttyUSB0'
8  Baud_1 = 115200
9  Baud_2 = 1000000
10 Timeout_1 = 2
11 Timeout_2 = 1
12
13 Arduino_Mega = serial.Serial(Port_1, Baud_1, timeout=Timeout_1)
14 Arduino_Uno = serial.Serial(Port_2, Baud_2, timeout=Timeout_2)
15 time.sleep(2)
16
17 Millisecond_Time = int(time.time())
18 Synchronization_Message = f"SYNCHRONIZE:{Millisecond_Time}\n"
19 Arduino_Mega.write(Synchronization_Message.encode())
20 Arduino_Uno.write(Synchronization_Message.encode())
21 print(f"[SYNCHRONIZE] Synchronization time for stations: {Millisecond_Time}")
22
23 log_file_1 = open("ArduinoMegaStation1_log.txt", "a")
24 log_file_2 = open("ArduinoUnoStation2_log.txt", "a")
25
26 def Read_From_Station(Serial_Object, Object_Name, Logfile_Name):
27     while True:
28         try:
29             line = Serial_Object.readline().decode(errors='ignore').strip()
30             if line:
31                 Time_Stamp = datetime.now().strftime('%Y-%m-%d %H:%M:%S:%f')[:-3]
32                 Entry_Log = f"{Time_Stamp} [{Object_Name}] {line}"
33                 print(Entry_Log)
34                 Logfile_Name.write(Entry_Log + "\n")
35                 Logfile_Name.flush()
36         except Exception as e:
37             print(f"[{Object_Name} ERROR] {e}")
38             break
39
40 t1 = threading.Thread(target=Read_From_Station, args=(Arduino_Mega, "ArduinoMega", log_file_1))
41 t2 = threading.Thread(target=Read_From_Station, args=(Arduino_Uno, "ArduinoUno", log_file_2))
42 t1.start()
43 t2.start()
```

Fig. 43. Program Code Written for Raspberry Pi 3B+

For the microcontroller side, two codes for each Arduino have been written to synchronize time with the raspberry and send data, both programs rely on the same principle that has been shown in Fig. 44. The lines 36-42 describe the conditional if statement, meaning that if the microcontroller has received data the data will be read until the end of the line received and put into the input string variable. The following line 38 checks the read string variable for the excluded word. If the statement is true, synchronization command is started and the synchronized time is set to the input value, once the operation is complete synchronized bool variable is set to true to represent the state of the synchronization. The following if statement in lines 45-51 sends the sensor data every 500ms and does so repeatedly until the device has been shut off or conditions are not met. The same logic has been applied for the Arduino Uno with AS5600 sensor, the only difference has been that the data is sent every 50ms.

```
35    // Synchronization part
36    if (Serial.available()) {
37      String input = Serial.readStringUntil('\n');
38      if (input.startsWith("SYNCHRONIZE:")) {
39        Synchronization_Time = input.substring(13).toInt();
40        Synchronized = true;
41      }
42    }
43
44    // Send data every 0.5 second
45    if (Synchronized && millis() - Last_Sent >= 500) {
46      Serial.print(Current_RMS_ACS723);
47      Serial.print(" ");
48      Serial.println(Current_RMS_TA12);
49      Last_Sent = millis();
50    }
51  }
```

Fig. 44. Arduino Synchronization and Data Transmission

3.4. Comparing the Retrieved Sensor Data

To better understand what the collected data should represent an action plan for the testing of the system has been created. To simulate the sewing operation, the following actions have been decided to be performed as shown Table 12. The chosen actions seek to represent what an operator would perform while creating a product, therefore different paces have been performed by sewing a cotton cloth.

Table 12. Actions Plan for the Simulation of Operator Work

No.	Action	No.	Action
1.	Turning on the machine	8.	Short average paced seam
2.	Long average paced seam	9.	Automatic end seam
3.	Long average paced seam	10.	Long average paced seam
4.	Long average paced seam	11.	Short paced seam
5.	Short maximum speed seam	12.	Long paced seam
6.	Short average paced seam	13.	Turning off the machine
7.	Short average paced seam		

The first data file has been collected by the Arduino Mega2560, depicts the results collected with the ACS723 hall-effect current sensor and TA12-200 current transformer, the data has been moved to Microsoft Excel and transformed into a graph which has been presented in Fig. 45. The presented graph depicts two curves representing each sensor, as described in the legend, the graph depicts the current change, according to the performed operation on the sewing machine station. The figure has been divided into 13 different actions by a red line marker depicting current change during as according to the action plan.

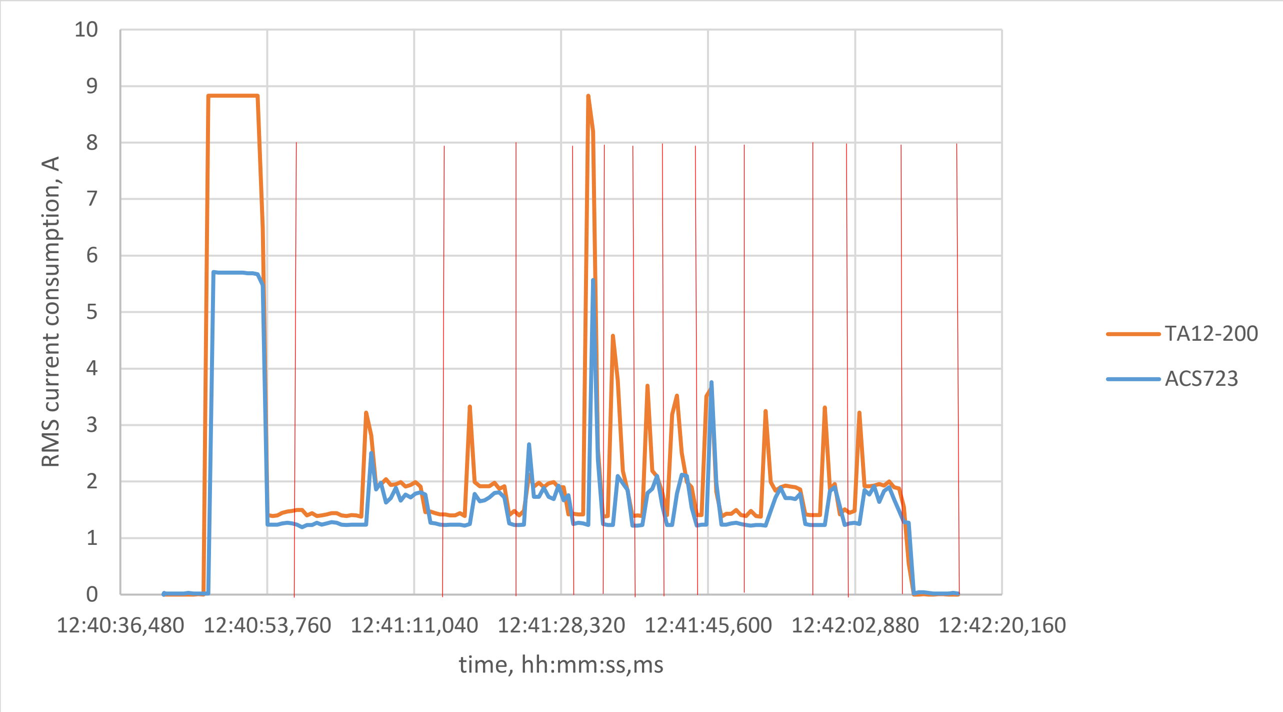

Fig. 45. Current Consumption Graph of ACS723 and TA12-200 Current Sensors

From the two curves in the graph, it is possible to see that TA12-200 sensor has a higher sensitivity to instant change compared to ACS723, to calculate this time difference an average value of the difference between the time stamps of the start of current change has been taken. The value calculated has been found to be 479ms, meaning that it is the average time delay between ACS723 and TA12-200. The cause of this delay arises due to the written program code and the working principle of the sensors themselves, since the set sample size for the ACS723 sensor is quite large it takes a while to collect this information, but it provides a more accurate representation of the RMS current value, because it actually find the mean of the current over time instead of using the peak value recorder. If the same principles would have been applied to both sensors there would not be any time difference.

$$\Delta T = \frac{\sum t2 - t1 + t4 - t3 \ldots + t24 - t23}{12} = \\ = \frac{\sum \begin{matrix} (12{:}40{:}47{,}410 - 12{:}40{:}46{,}831) + \\ (12{:}41{:}05{,}970 - 12{:}41{:}05{,}390) \\ \ldots \\ + (12{:}42{:}03{,}395 - 12{:}42{:}02{,}237) \end{matrix}}{12} = \\ = 479\ ms \tag{1}$$

Looking at the data retrieved by the other microcontroller, which has AS5600 rotational angle encoder connected to it, the data represents the rotational angle of the main driving shaft as shown in Fig. 46. From the data the rotational movement of the main driving shaft can be depicted and divided into 11 movements. The difference that has been noticed from the graph is that it is quite impossible to tell when the AC motor is started or stopped, meaning the data changes only if the operators engage or disengages the clutch which moves the main shaft. Comparing the actions that have been determined in the action table with the retrieved data it is possible to identify the 11 actions that involved the main driving shaft movement. Looking at the graph it has been determined that regions depicting the higher revolution speeds, e.g. maximum speed seam and automatic end-seam, have poorer resolution. This has been determined to be due to the recording rate of the microcontroller because the recording rate does not pick up all the fast changes in position giving us a graph section, marked red, which has a smaller number of points over time as shown in Fig. 47. compared to the blue graph section which depicts a short average paced seam. Looking at the short average paced actions, the graph depicts a larger number of points over a similar time meaning that the data resolution is affected.

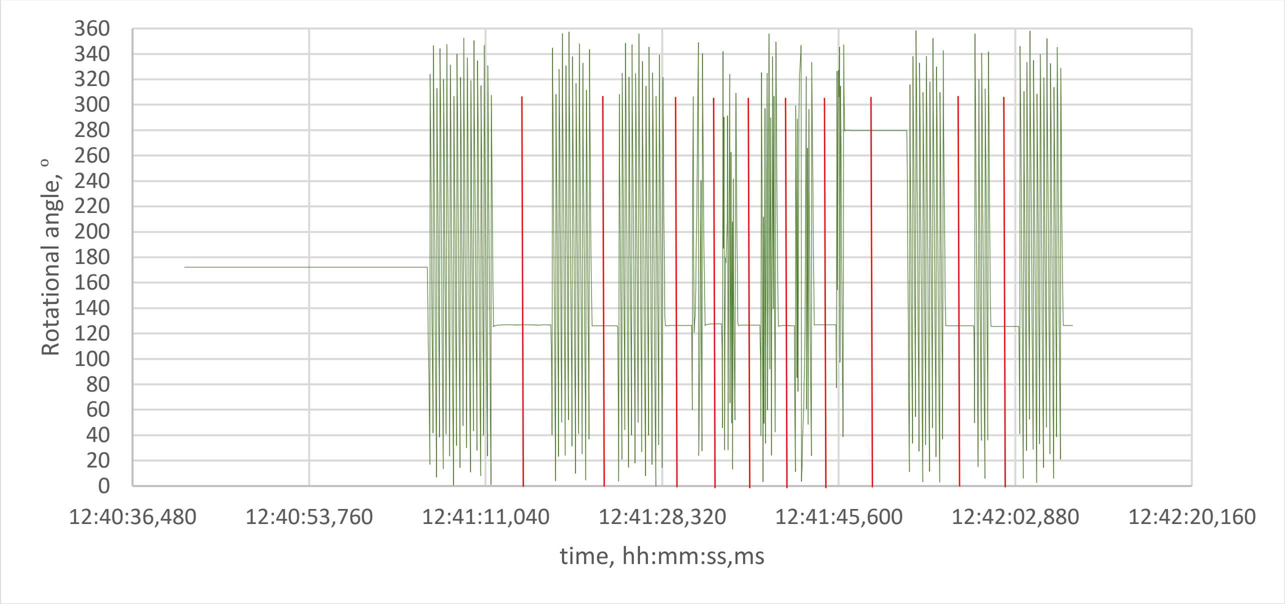

Fig. 46. Rotational Angle of the Main Driving Shaft Recorded by AS5600

Fig. 47. Maximum Speed Seam and Short Average Paced Seam

To compare all three sensors, their curves have been inserted into one graph represented by a unified real-time axis. From the combined graph data shown in Fig. 48, it has been determined that three sensors can identify seam creation, and only the two current sensors can identify the seam type confidently. The different types of seams have been identified by comparing the retrieved current parameters data. It has been found that the current sensors ACS753 and TA12-200 can identify different types of seams due to varying current consumption during the experiment, faster seams have put more load on the AC motor, meaning more current has been drawn resulting in higher peaks in the graph. The AS5600 could successfully depict the length of the seam but failed to successfully identify the seam speed. The higher the speed of the seam the less reliable the information becomes, because the refresh rate at which the microcontroller collects and sends information becomes too small, meaning that the curve has less values to depict it correctly. Another downside of using the AS5600 is that the turning on and off the sewing station could not be identified. The advantages and disadvantages described have been organized in Table 13.

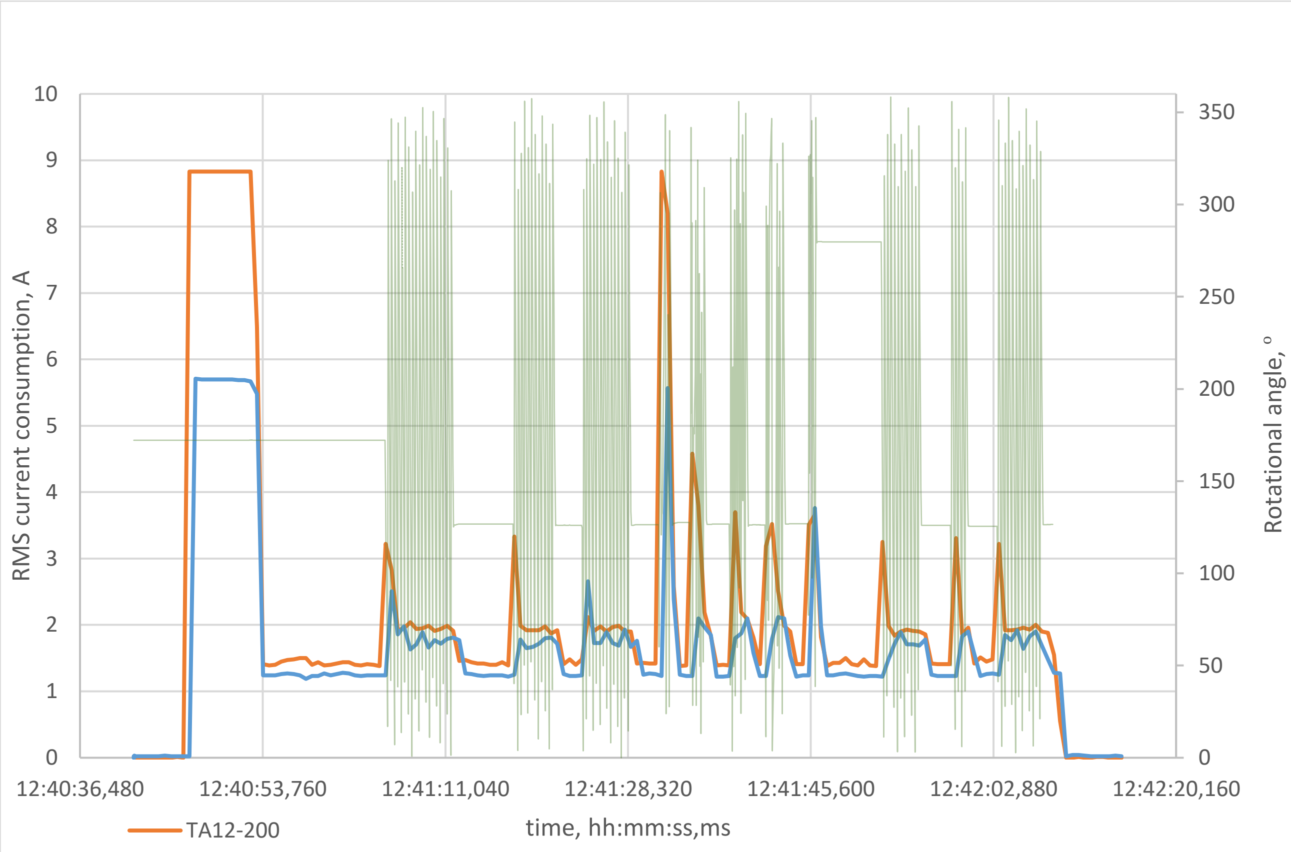

Fig. 48. Real-Time Combined Sensor Data

Table 13. Found Advantages and Disadvantages of the Used Sensors

Sensor:	**Advantages:**	**Disadvantages:**
TA12-200 current transformer	Can reliably depict seam length and speed	Higher RMS current deviation
ACS723 Hall-effect current sensor	Can reliably depict seam length and speed	Longer time deviation from the actual real event upon receiving data
AS5600 magnetic rotational encoder	Can reliably depict seam length	Cannot depict seam speed and machine turn on/off times

3.5. Design of the Final Solution

The final solution for system monitoring and data collection must be discrete and comfortable for the operator while still being effective in its purpose and easy to implement. Looking at the figures 45, 46, 48, and table 13. it is possible to conclude that current sensors are the optimal choice to represent the state of a sewing machine due to their responsiveness, reactiveness, and ability to represent exact moment of the operation beginning and ending. There were two types of current sensors that have been compared: intrusive and non-intrusive. Looking at the graphs 40,41, 45, and table 13. it is possible to determine, that TA12-200 sensor has similar accuracy, and better responsiveness than that off ACS723, meaning that it is a more viable option since it is non-intrusive and easier to install. In Fig. 49 the final solution of the full structure is depicted.

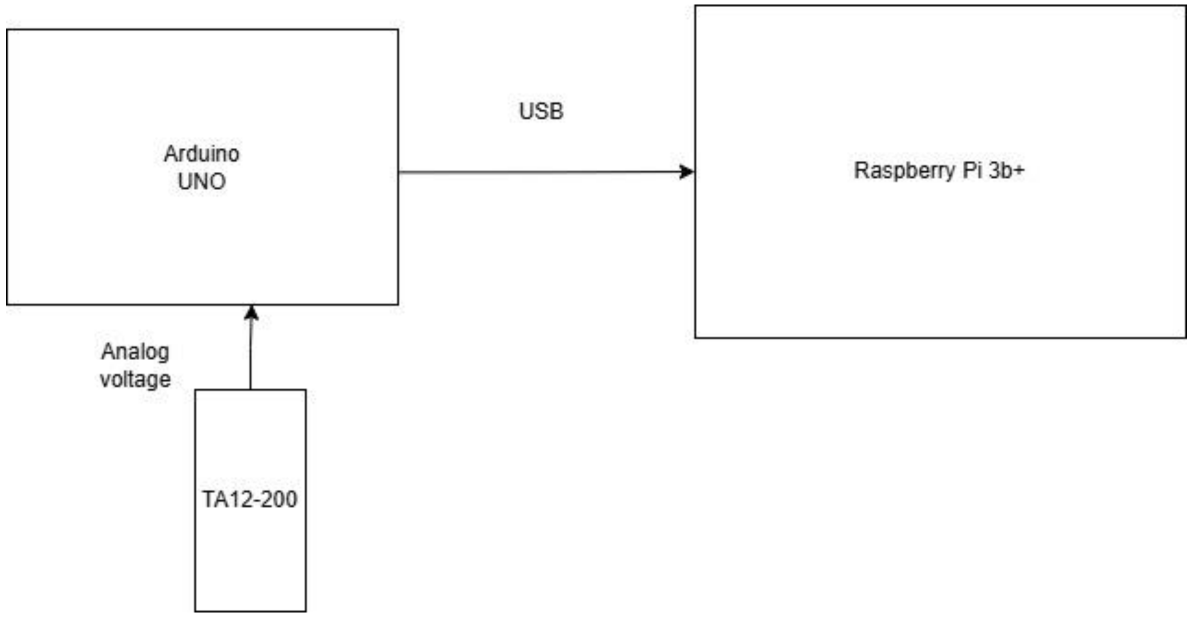

Fig. 49. Structure Diagram of the Final Solution

3.6. Chapter Summary

During this chapter a few key tasks have been fulfilled: the selection of optimal sensor placement has been decided, the data retrieved with the created system has been verified, a unified recording and monitoring system has been created to depict events that have happened in real-life time, the information retrieved with the system has been analysed and compared. To find the best suited sensors for this task, an in-depth analysis including existing comparison methods has been done. Once, the sensors have been decided, their placement for optimal data retrieval and ergonomic design for the user has been discussed. To show that the created system can monitor and recorded the information of more than one sewing machine station, the sensors were implemented using different microcontrollers to communicate with the main micro-computer. For final depiction that the system works as intended a comparison of the collected data has been performed according to the same real-time axis.

4. Economic Review of the Data Monitoring and Recording System

In this chapter the economic part of the project has been discussed considering all details of creating this project. The main point of this project has been to find a way to reduce production costs via collecting and recording the manufacturing information. In the first chapter of this work, it has been determined that collection of manufacturing data is a critical part of LEAN and 6σ methodology. These methodologies have been created to improve the efficiency of business processes including manufacturing, meaning that implementing the created recording and monitoring system allows more fluent data collection without the disruption of the workflow making these processes more efficient. The key point of this chapter is to determine the cost of this system and provide important information in decision making regarding inclusion of such system in a manufacturing plant.

4.1. Cost of the System Creation

To estimate the cost of the project creation, all the bought, created, and used parts have been written down in Table 14. The total expenditure does not include labour costs for developing and implementing the system into a real-life sewing plant. To accurately estimate the cost of part manufacturing, cost of the 3D printed parts has been calculated. In total three parts have been printed for the final implementation: AS5600 magnet mounting plate to the rotating shaft, AS5600 holding bracket, TA12-200 and ACS723 case. The cost of the printed parts has been calculated according to the printing parameters, time estimation, and material estimation from UltiMaker Cura 3D printing program as shown in Table 14.

Table 14. Material and time consumption for 3D printed parts

Part	Material PLA	Time
AS5600 magnet mounting plate	0.3 g	6 min
AS5600 holding bracket	5 g	41 min
TA12-200 and ACS723 case	23 g	3h 48min

To transform the information shown in Table 13 into actual cost, the power rating of the 3D printer and the price of the used filament had to be acquired. The used 3D printer has been Ender 3 V1, its power rating is 270 Watts, the average price of the filament has been found to be 16 Euros per 1 kg. In equations eq.2, eq.3, eq.4, eq.5 the price for each part has been calculated and added into table 15, the used electricity price per kWh has been 0,21 Eur.

$$\begin{aligned} Price\ of\ part &= Price\ of\ filament\ \ \times Used\ material\ weight \\ &\quad + Electricity\ price\ \ \times Time\ to\ print\ the\ part \end{aligned} \tag{2}$$

$$AS5600\ magnet\ mounting\ plate = \frac{0.3}{1000} \times 16 + \frac{6}{60} \times 0.21 = 0.026\ Eur \tag{3}$$

$$AS5600\ holding\ bracket = \frac{5}{1000} \times 16 + \frac{41}{60} \times 0.21 = 0.224\ Eur \tag{4}$$

$$TA12 - 200\ and\ ACS723\ case = \frac{23}{1000} \times 16 + \left(3 + \frac{48}{60}\right) \times 0.21 = 1.166\ Eur$$

(5)

Table 15. Cost of Parts List

Part	Name	Cost
Current transformer	TA12-200	11.50
Hall effect current sensor	ACS723	16.80
Magnetic rotational encoder	AS5600	10.70
Microcontroller	Arduino Mega2560 Rev3	53.10
Microcontroller	Arduino Uno	28.60
Micro-computer	Raspberry Pi 3B+	62.60
Connection cables	Shielded transmission cable CAT5	2.30
Additive manufacturing part	AS5600 magnet mounting plate	0.03
Additive manufacturing part	AS5600 holding bracket	0.22
Additive manufacturing part	TA12-200 and ACS723 case	1.17
	Total expenditure:	**187.02**

The cost of the final solution differs from the cost of the project since the final solution does not include all of the tested sensors. The final part list with the costs is represented in table 16

Table 16. Cost of the Final Solution

Part	Name	Cost
Current transformer	TA12-200	11.50
Microcontroller	Arduino Uno	28.60
Micro-computer	Raspberry Pi 3B+	62.60
Connection cables	Shielded transmission cable CAT5	2.30
Additive manufacturing part	TA12-200 and ACS723 case	1.17
	Total expenditure:	**106.17**

4.2. Cost Comparison with Existing Solutions

Business enterprise is a structure whose decisions are mostly influenced by financial statistics, meaning that comparison of available options is always mandatory. To financially estimate which is the most cost-effective solution for a business – either implementing the designed system or buying a new sewing station with integrated technology – a comparison has been made. To calculate the price of the found system implementation, a hypothetical situation has been created where a small company needs to upgrade 20 sewing machines to gain data collection capability for the production plant. To calculate the costs more accurately human work that is required to implement the new system must be considered. The average salary of an installation engineer of 2500 euros before tax, has been taken and calculated for the working hours required to install the system for 20 sewing machine stations. Since the system is not complex to install physically, the average time for one machine could take up to 1 hour, meaning that for 20 machines it would take a maximum amount of 20 hours. In rough estimate the implementation of created system would cost 250 Euros for all the machines to be fitted with the created system as calculated in equation 6. Meaning that the average cost for this project would be as calculated in equation 7.

$$P_{Implementation} = \frac{2500\ Eu\ salary}{25\ work\ days \times 8\ work\ hours} \times 20\ work\ hours = 250\ Euros$$

(6)

$$P_{Whole\ system} = Labour\ time + Hardware\ costs = \\ = 250\ Euros + 106.17\ Euros\ \times 20 = \ 2\ 373.4\ Euros$$

(7)

In Table 17. the price of existing sewing stations with data collection features have been written down. Looking at the Table 16. the average price of a sewing station capable of IoT data collection is 3 305.67 Eur, meaning that the average price for the hypothetical situation would be 66 113.4 Euros considering that the new sewing machines do not require specialists to be set up. The final cost comparison between the found solution can be seen in table 18. In the table it is possible to see the cost difference between the found solution and already existing solutions to be around 63 740 Eur. This cost is the average difference between upgrading existing equipment and implementing the found solution, meaning the found system could save quite a significant part of costs for the business.

Table 17. Existing Sewing Stations with Data Collection Features Cost

Manufacturer	**Model**	**Cost**
Brother	Nexio S-7300A [36]	2 128 Eur
PFAFF	PFAFF Performance Icon [37]	4 498.99 Eur
JUKI	DDL-9000C-FMS [38]	3 290 Eur

Table 18. The Found Price Differences for the Hypothetical Situation

Implemented system type	**Cost**
Implementation of created system	2 373.4 Eur
Implementation of existing industry solution	66 113.4 Eur
Cost difference:	63 740 Eur

4.3. Chapter Summary

In this chapter the price of the system has been estimated according to the used components in the final solution. A hypothetical situation has been analysed, and the cost of the created system has been compared to already existing solutions from such manufacturers as: Brother, PFAFF, and JUKI. It has been found that the average cost of a new IoT capable machine costs around 3 305.67 Eur. A rough estimate has been calculated for the hypothetical situation, where a small manufacturing plant owning 20 sewing machines needed to implement data collection and recording. The cost difference, between implementing the created system and changing the old equipment to new, has been found to be 63 740 Euros, meaning that the found solution would save a significant part of the costs.

Conclusions

1. During this work ten different sensors have been analysed and three have been selected and tested: TA12-200 current transformer, ASC723 hall-effect current sensor, and AS5600 magnetic rotary encoder. It was found that all three sensors are able to describe the state of the sewing machine, but current consumption monitoring sensors are able to describe more parameters of the system by giving a clear indication of when the system is turned on. Both current sensors have been compared on the aspect of integration, and it was found that TA12-200 current transformer offers a non-intrusive method to monitor the current consumption while offering a similar accuracy range of 50mA to the ACS723 30mA error range.
2. The positioning of the sensors has been selected according to the found key parameters, that describe the status of the system, and according to the functionality and comfortability of the sewing machine operator. Different mounting brackets have been manufactured depending on the sensor type and placement. The mounted sensors have been verified with a higher or equal accuracy equipment, and it has been found that the retrieved data is valid.
3. The selected sensors have been implemented into a real-time monitoring system which consists of a microcontroller, to collect the system data, and a microcomputer, to store the data with a real-time timestamp. By comparing the retrieved data with the performed sewing action plan, a clear correlation has been found. It was determined that the current sensors can indicate the starting and stopping of the sewing machine, seam length, stitch speed, and performing of an automatic end seam. On the other hand, the magnetic encoder was not able to describe the starting and stopping of the electric motor but was able to describe all other features performed on the sewing machine.
4. The final system design has been represented with a block diagram giving an overview of the system and a real-life picture of how the sewing machine looks before and after the implementation of the system. The final system design has been decided to include TA12-200 current sensor due to its ability to describe a wider range of states of the sewing machine and ease of implementation with sufficient accuracy. The final system consists of a microcontroller Arduino Uno, TA12-200 current transformer, and Raspberry pi 3B+ microcomputer.
5. Finally, the cost estimation has been performed, providing an exact estimate of the parts and how much it costs to create this product, 106.17 Eur. The created product price has been compared with the average existing solutions in the market price 3305.67 Eur and a difference of approximately 3 199.5 Eur has been found excluding the required labour to assemble the project. A hypothetical situation has been analysed where upgrading equipment costs have been compared with integration of new equipment costs, and it was found that for a small factory of 20 sewing machines, the created product would save 63 740 Eur, including the required labour to install the created system. The possible costs of whole system integration have been calculated according to current labour costs of installation engineers at approximately 2 373.4 Eur.

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