Design of a String Making Machine with Active Tension Control

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Abstract

This report presents the results of the first term of a capstone project carried out in collaboration with the string manufacturing company Primstrings. The aim was to develop a string making machine with a method to measure the tension of the strings during manufacturing and to apply a control loop for continuous automatic adjustment.

The project began with research into different force measuring methods, the current state of the art (SOTA) and alternative methods from neighboring disciplines. Next, a concept generation phase was conducted in which several tension-sensing solutions were explored and evaluated using a weighted decision matrix (WDM). From this, the selected solution was to use an S-shaped load cell attached to a linear rail connected to the spindle. The concept was then validated using two prototypes, one testing the accuracy of the load cell and the other analyzing the impact of noise on the measurement.

Throughout the spring term, the team has finished the concept generation phase and created an overview of the mechanical and electrical systems, as well as generating a list of core component for beginning implementation. The fall term will focus on finishing the final machine and testing it for accuracy and reliability. The results of this project will contribute to the next generation of string manufacturing machines at Primstrings.

Keywords: string making, load cell, tension sensing, tension control, actuator, mechatronics, concept development

Acknowledgements

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Acronyms

Abbreviation	Definition
FBG	Fiber Bratt Grading
HMI	Human-Machine Interface
IoT	Internet of Things
IPC	Industrial PC
KTH	Kungliga Tekniska högskolan
LSV	Laser Surface Velocimeter
MEMS	Microelectromechanical Systems
MR	Magnetorestrictive
PAC	Programmable Automation Controller
PID	Proportional–Integral–Derivative
PLC	Programmable Logic Controller
RPM	Revolutions per minute
SAW	Surface Acoustic Wave
SOTA	State of the Art
WBS	Work Breakdown Structure
WDM	Weighted Decision Matrix

Chapter 1

Introduction

This chapter serves as an introduction to the project. It provides an overview of the background, the project description, its purpose, and scope. Additionally, it outlines the team structure and identifies the criteria necessary for the project to be deemed successful. There is also a section detailing the requirements, explaining how they have been defined and categorized.

1.1 Background

This project is being developed as a part of the KTH Mechatronics capstone course, MF2121. The stakeholder of the project is the company Primstrings (Fröjel Strings AB).

The company Primstrings was formed in 1943 during the second world war, when the company's founder, Gunnar Fröjel, had great difficulty finding strings for his instruments [1]. Instead, he began making his own strings and selling them to his colleagues. In time, the company industrialized and is now run by the third generation of the Fröjel family. The company today manufactures a wide variety of strings for the violin, viola, cello and nyckelharpa at their manufacturing facility in Stockholm, Täby.

1.2 Project Description

When creating strings, everything from the tension on the core of the string to the winding of the outer layers to the grinding of the flat outer wire are important for the quality of the final product. Primstrings uses machines that have been developed entirely in-house. Due to the nature of the stringmaking business, this is also the case for most competitors. The secrets of their respective machines are a significant competition factor and are heavily guarded [2].

Today, Primstrings have both manually operated machines, and automatic machines for string making. However, for the next generation of machines, they wish to have more control over all parameters during the process. A significant factor in this is the tension on the core wire. Therefore, this project sets out to develop a stringmaking machine that can sense and control the tension on the core wire throughout the string making process.

1.3 Purpose and Goal

The purpose of this project is to create a string making machine that can sense and control the tension in the core wire during the entire string making process. This force should be able to be kept constant during the process. The method for measuring and controlling the tension should be transferable to the next generation of Primstrings manufacturing machines.

1.4 Scope and Delimitations

The scope of this project is to develop a prototype of a string making machine with active tension control. This encompasses the creation of hardware and software to accomplish this purpose. The tension measurement and control system should also be documented so that the knowledge gained can be transferred to the stakeholder. The prototype will not be a fully automatic machine, and will require human input to, for example, place and remove strings from the machine. The machine should be safe for human use.

Given the limited time of the project, the focus will be on constructing the prototype and integrating the mechatronic components of the system to demonstrate the functionality of the active tension control system. To demonstrate that this functionality works while winding the outer layers of the string, the machine will add a single outer layer. However, no further layers will be added and no grinding or other processes will be performed on the string. Furthermore, the quality of the finished strings and the success rate of creating finished strings is not within the scope of the project.

1.5 Team Structure and Management

The team in this project consists of eight (8) members from five (5) different nations and with different backgrounds. Most of the team had some form of mechanical or electrical engineering as a bachelor's program. When the project began, the group had team building lectures and exercises. Based on the information from these occasions, a code of conduct was drawn up. For the group, this meant a form of contract. The document contained three core values that the group agreed on and that everyone signed to follow during the project. This provided a stable foundation and a tool to be able to refer to during the project.

When the group became familiar with the project and its requirements specifications, an initial project plan was drawn up. The plan consisted of 6 main phases with a specified time period when these steps would take place. This structure served as a foundation for the project timeline and guided the early activities.

When the group had formed a picture of the project and its implementation, a look was taken at the team divisions and roles. First, a project manager was chosen. The main role of the project manager was to keep track of the project as a whole, to ensure that it progresses, to ensure that deadlines are met and to call meetings. To help him, a Co-Manager was chosen who is mainly responsible for communication with stakeholders and external parties. Together, these two made up the project management team.

At the beginning of the project, it was possible to simply divide tasks to each person, but later in the project it was found that it was beneficial to apply subgroups. As a result, two more teams were created: Mechanical and CAD Team and Electronics and Software Team. The purpose of creating these teams was to get a structure for the project, and for everyone to feel that they have responsibility. That everyone has a clear role is important for a project to succeed. At the same time, the group has also taken into account the learning objectives that should be achieved. Therefore, there is still flexibility in this structure. All members will all have the opportunity to learn and contribute to the Mechatronics core four: mechanics, electronics, software and control. During the course of the project, the group will therefore be able to implement subgroups based on current tasks. This gives people from the different teams the opportunity to integrate and work with tasks that belong to different categories. In other words, the focus will be on current tasks rather than what might be considered to belong to the role. But having a main manager who is in control throughout the entire project creates security and means that task-based subteams can always turn to someone.

According to this approach, an agile working method should be implemented throughout the project. This also includes weekly meetings where a review of the tasks that have been worked on is carried out and planning for the coming week what is to be done. Through this continuity for the project, it can be easier to note if certain tasks take longer than planned and if it's needed to add resources to them.

During the spring, the weekly meetings have been held every Monday. Clear meeting agendas have been created by the project manager and sent out to the group the day before. This has ensured that the discussions and concentration in the meetings have been maintained well. During the meetings, the project manager has served as the chairman and the secretary role has been rotating. By this, the meetings have progressed clearly, which has allowed the project to progress. This approach will therefore continue during the fall. Other meetings that have taken place during the spring have been meetings with stakeholders and supervisors. The meetings with stakeholders have consisted of a visit to the factory and signing of confidentiality agreements, a meeting to update on the progress of the project, and finally a meeting before the summer to order critical components. In addition, the group has had two individual meetings with supervisors where progress and feedback on the group's ideas have been presented.

The group has used various project management tools for the project. A list of what has been used and for what purpose can be found below:

- Task Management and Calendar: Monday.com.
- Storage of Files: Google Drive and Microsoft OneDrive.
- Communication Platforms: WhatsApp and Zoom.

Primstrings has previously used Monday.com as their task management tool, which made it a logical choice to use. This allowed to list both tasks within the group and also assign tasks to Primstrings, and have everything collected in one place. This also gave them the opportunity to follow the progress the group is making. Internally, the group has established an environment in Google Drive where the group saves documents being worked on. Document sharing with Primstrings is done via a OneDrive folder that they shared with the group. A WhatsApp group was created for quick communication between group members, including calling meetings and minor updates. To communicate with stakeholders and supervisors, Zoom has been used as a virtual meeting tool, as well as email for various questions and planning. In addition to these, Fusion has been chosen to be used as a CAD environment. For software management and code storage, GitHub will be used during the fall.

Finally, the team has also decided on a name and slogan. The name was developed based on suggestions from other project groups and was chosen during a meeting. StringMasters was the name that the group agreed on. The motivation was that the group members are Master's students and are carrying out a project that is about string manufacturing. The slogan was chosen to be “Attention to Tension”, also a suggestion from other groups. It was considered appropriate because of the main problem the group intends to solve.

Figure 1.1: Team logo.

1.6 Stakeholders

The primary stakeholders of the project are Primstrings (Fröjel Strings AB), represented by Niclas Fröjel and Jessica Fröjel. Although the company is quite small in employee count, mainly 4 people, it is still a global player selling strings worldwide. The industry is niche and there are only around 10 string manufacturers in the world for these string instruments. They want to be the market leader and manufacture the world's best strings and therefore quality is of the highest priority.

The secondary stakeholders are the group's supervisors from KTH, represented by Mikael Hellgren and Daniel Frede. Through them, the group receives guidance and supervision through coaching sessions during the course of the project.

1.7 Requirements

The project requirements have been defined according to the requirements provided by the primary stakeholders. These are the frameworks for all the technical requirements developed. For clarity and effective project planning, the requirements are categorized into two main groups: Stakeholder Requirements and Technical Requirements, each with their own subcategories. In addition to project-specific requirements, the course also has learning objectives.

1.7.1 Stakeholder Requirements

Stakeholder requirements reflect the expectations and needs directly expressed by the project stakeholder. These are divided into Must-Have Requirements, which define the core deliverables necessary for the project's success, and Nice-to-Have Requirements, which represent additional desirable features that would enhance the system but are not essential for project completion.

1.7.1.1 Must-Have Requirements

The following requirements are critical to the successful delivery and functionality of the system:

- Controlled core wire tension.
- Adjustable winding tension.
- Adjustable feeding of material onto the core.
- Codebase developed using CODESYS.
- Industrial computer equipped with an HMI (Human-Machine Interface) screen.
- Safety system that halts the machine in case of string breakage.

- Emergency stop functionality for the entire system.
- System must be either purchased by or transferable to Primstrings.
- Continued usability and maintainability by Primstrings after project completion.

1.7.1.2 Nice-to-Have Requirements

These features are not essential for the core operation but would improve usability, safety, or performance:

- Servo motors operating below 60 Volts.
- Servo motors with integrated drivers.
- Vibration damping for core string oscillations.
- Recipe function to store and recall settings for different string types.
- Physical buttons for frequently repeated operations.
- Enhanced HMI interface for configuration and real-time monitoring.
- Compliance with the European “Machinery Directive” (Maskindirektivet) and CE marking requirements.

1.7.2 Technical Requirements

The technical requirements for the project were developed based on the stakeholder requirements. The purpose of having clear technical requirements is that every requirement can be measured via a test case. All technical requirements can be linked to the stakeholder requirements, and they were made to further specify the needs of the final product. The requirements will likely be refined and developed during the design phase in early fall, then a complete traceability matrix will also be developed to trace the links between the requirements. However, these already create a basis for the group for what to look for when choosing components and will also serve as a framework when documenting the machine's technical specifications. The technical requirements can be found in Appendix A.

1.8 Reader's Guide

The report is divided into seven main chapters as follows:

- Introduction
- SOTA
- Concept Development
- Concept Evaluation and Selection
- Discussion
- Conclusion

The SOTA chapter deals with string making machines and discusses research that has been done on tension and force control for industrial machines.

In the two following chapters, Concept Development and Concept Evaluation and Selection, the different concepts that the group has developed are presented. A concept evaluation is presented to explain how the group reasoned and came to the final choice of the concept.

In the final chapters, discussion and conclusion, risk analyses, purchasing of parts, the project plan for the autumn and an overview of activities and division of labor are presented.

Chapter 2

State of the Art (SOTA)

The SOTA research that has been done for this project gives an overview of the state-of-the-art technologies in the field of string making. A deep dive into the technology of tension measurement and force actuation in industrial machines has also been conducted.

2.1 String Making Machines

The violin string winding machine is a specialized piece of equipment used to wind the core of the string to achieve the correct tension and pitch. This machine is specifically designed to wind the strings evenly and precisely, ensuring that the final product is of the highest quality. The winding machine is typically equipped with adjustable tension and winding speed controls, as well as specialized winding heads that can be changed to accommodate different types of string cores and metal wires. Additionally, the machine may be equipped with a measuring device to ensure the precise winding length, which is crucial for accurate tuning and performance [3].

In Primstrings factory, the creation of a cello string was shown, where its core could be wound with up to five layers of wrapping, with each layer taking 30 seconds. Most of this is done by machine, but there is still a need for constant manual intervention, such as changing wires, threading, and operating the machine. Despite the old machines having some degree of automation, they still require a significant amount of skilled human input, while the newly built fully automated machine prototype is considered by the stakeholders to lack flexibility.

One of the most important aspects of the string-making process is determining the desired string tension. The companies strive to keep string tension as low as possible, but still high enough to meet the necessary requirements. The core of the string must also be able to withstand the required string tension. The company Thomastik-Infeld points out that when the string tension is defined as 5.50 kg, the core itself must support at least 5.5 kg of tension [4].

Some companies claim that their production lines include advanced twisting machines that produce uniform twisting effects and precise tension control [5]. In equipment descriptions of HY Stefano, they mention that tension testing devices can measure the exact tension of each string and provide precise quality control results, although the specifics of how this is achieved have not been disclosed. Another machine called WVI 200 Speed (Steel) from C.M.S. Ltd claims its tension regulation works as follows [6] :

- For the wrap wire: by a magnetic tensioner.
- For the steel core wire: by a digital manometer (from 0 to 4 bar).

Due to the secretive nature of the string making business, very little information can be disclosed regarding the current machines used by the stakeholders or their competitors. Therefore, the rest of the SOTA will instead be dedicated to the state-of-the-art of the individual parts of string making machines and processes.

2.2 Force Control and Tension Sensing in Industrial Machines

This chapter discusses force control and tension sensing in industrial machines. It discusses how tension is measured, and how tension is controlled from both a mechanical and software perspective.

2.2.1 Tension Sensing in Industrial Machines

Sensing tension, forces and torques in industrial machines is often very important both for functionality, and for a consistent and reliable result. Thus, there are multiple state-of-the-art methods used for accomplishing this. There are also multiple state-of-the-art measuring methods that are used in laboratories, but not in industries due to the special demands industrial applications place on the sensing methods.

Today, strain gauge-based load cells is the most widely used force measurement method, accounting for approximately 50 percent of the force sensor market in 2023 [7]. Load cells work by utilizing a strain gauge which is glued to the load cell. This is then connected to a Wheatstone bridge. When a load is applied to the load cell, this causes an elongation or contraction in the strain gauge. This then creates a voltage difference in the Wheatstone bridge which is measurable and can be correlated to the force applied [8].

However, there are a variety of other types of force or tension sensors also used in industry today. These include pressure-sensitive films, piezoelectric force sensors, and fiber-optical sensors such as FBG (Fiber Bratt Grading) sensors [9][10]. In some cases, such as with continuous production of sheet materials, LSVs (Laser surface velocimeters) can be used [11]. Some of the most recent advances in load measuring are MEMSs (Microelectromechanical systems), which have enabled the creation of miniaturized load cells [10]. Furthermore, alternatives such as SAW (Surface Acoustic Wave) sensors and MR (Magnetorestrictive) sensors exist that utilize changes in the acoustic or mangetic properties of a material while under load to determine the load [10].

Some of the most recent advances in tension sensing technology have also been in the integration of IoT (Internet of Things) and wireless features as well as implementation into the industry 4.0 framework [10]. This can also be augmented with digital filtering and distributed computing [12][13].

2.2.2 Tension Control in Industrial Machines

Tension control in industrial machines can occur in a variety of ways, depending on the process. For continuous processes, for example making rolls of flexible materials such as plastic, the tension is usually controlled by varying the speed and torque of rollers that the plastic is fed through [14]. However, in cases where the material is not moving continuously, other solutions must be used to control the tension.

In such cases, the most common way is for the material to be pulled apart by the machine in a controlled manner. To do this, motorization is needed. This can be achieved in multiple ways, one of the most common is with a linear actuator. A linear actuator is essentially a motorized linear rail, where a block on the linear rail can be moved back and forth with low friction using motors. This can be achieved using either a belt drive, or a lead screw. However, there are also pneumatic and hydraulic alternatives.

In the case of using an electric motor, belt drives and lead screw implementations have different advantages and disadvantages. Belt drives can generally have longer strokes and move faster, however they have lower accuracy and repeatability, and can have position drift during operation [15]. Lead screw implementations on the other hand generally have higher accuracy and less position drift, and can have self locking properties. However, they have limited speed, and their accuracy depends on the lead screw used [15].

To control the linear actuators, a motor is necessary. The state of the art in industrial precision motion control is the servo motor. However, referring to servo motors as a single type of motor is misleading. The term "servo" refers to the control architecture that enables precise regulation of motion [16], rather than to the motor type itself. A servo motor integrates an electric motor such as a DC-motor, stepper motor, BLDC-motor or AC-motor with a feedback element such as an encoder or a resolver, and a closed loop control system. Using this architecture, servo motors can be actuated with high precision and control of position, speed and torque.

2.2.3 Motor and Actuator Control in Industrial Machines

Modern industrial control systems are increasingly integrating different levels of distributed control within their architectures. These systems spread control logic across multiple interconnected components, such as programmable logic controllers (PLCs), input and output (I/O) units, motor drivers, and embedded nodes. This approach enhances modularity, flexibility, and scalability in various manufacturing contexts.[17] [18].

In particular, with motor control, specifically concerning servo motors, these are typically paired with drivers that feature built-in control loops. Depending on the application, these control loops can manage torque, velocity, position, or a combination of these parameters.

In industrial machines, there are three common types of main controllers: PLCs, PACs, and IPCs. While each of these controllers has its own origins and historically had distinct boundaries, the distinction between them has become less clear in recent years. Modern PLCs now offer many features that were once characteristic of PACs, and many IPCs run Microsoft Windows but still have the appearance and functionality of PLCs [19] [20].

To facilitate communication between these distributed components and the main controllers, many communication protocols and structures can be applied. In terms of wired communication (which is the most commonly used type in machines), there has been a historical trend moving towards industrial Ethernet. This migration is largely attributed to the existence of standards which supplement the Standard Ethernet with real-time properties, such as EtherCAT [21]. This results in a network that is cost-effective, easy to integrate, and meets all technical requirements [22] [23].

2.3 Eigenmodes in Spinning Strings

Eigenmodes, also known as natural modes or vibration modes, refer to the characteristic patterns in which a system tends to oscillate when disturbed. Each eigenmode corresponds to a specific natural frequency at which the system resonates. For a tensioned string, these modes determine how the string vibrates and ultimately how it sounds, particularly in musical instruments. In industrial contexts, especially in spinning, rotating, or winding strings, the study of eigenmodes becomes critical for understanding system stability, noise, and mechanical wear.

According to *Principles of Musical Acoustics* [24], the analysis of eigenmodes typically begins with a mathematical model of the string, described by the wave equation:

$$\frac{\partial^2 u(x,t)}{\partial t^2} = \frac{T}{\mu}\frac{\partial^2 u(x,t)}{\partial x^2}$$

where $u(x,t)$ is the transverse displacement of the string at position x and time t, T is the tension, and μ is the linear mass density of the string. Solving this equation under appropriate boundary conditions (e.g., fixed ends) yields a set of eigenfrequencies f_n and mode shapes, which is also known as Mersenne's laws:

$$f_n = \frac{n}{2L}\sqrt{\frac{T}{\mu}}, \quad n = 1, 2, 3, ...$$

Eigenmodes are closely related to acoustic performance. Since the quality of winding affects the uniformity of linear mass density, it can alter the natural frequencies and vibration patterns, thereby significantly influencing the tonal characteristics of the finished string.

2.4 Winding Techniques in String Manufacturing

The primary objectives of winding technology center on improving the performance and longevity of the string. First, maintaining stable tension throughout the tightening process is crucial, as it helps prevent both slackening and overtightening. Equally important is achieving accurate and consistent pitch, which relies on the uniformity of the winding across the entire string. Finally, enhancing durability is essential, the winding layer must remain secure and intact over time, while the outer layer should form a dense, protective barrier around the core to guard against oxidation and environmental damage [25].

The winding process begins with the pre-treatment of the string core, where surface oil and impurities are removed and the core is polished. To prevent relaxation during later use, the core is pre-stretched under controlled temperature and humidity conditions [26]. Following this, the winding equipment is calibrated according to product specifications, and appropriate tension parameters are set to ensure consistent operation [5].

During the helical winding phase, precise control of both the winding angle and speed is essential to maintain uniform winding density. Real-time laser monitoring systems are employed throughout this stage to track the position and alignment of the winding layer, enabling high-precision adjustments. After winding, end finishing procedures are conducted, and low-temperature thermal curing may be applied to enhance the structural stability of the wound string [25].

Once the winding is complete, a preliminary acoustic and visual inspection is carried out. This includes mechanical vibration testing, such as standing wave checks, as well as image-based inspection for detecting surface defects and inconsistencies in the winding. Sampling quality tests are then performed to verify key performance indicators. These include mechanical tension testing, frequency response analysis, damping and decay measurements, fatigue resistance testing, and final assessments of playability. The process concludes with final calibration and packaging. Finished strings are sorted, labeled according to their specifications, and prepared for distribution [4].

Chapter 3

Concept Development

This chapter outlines the process of concept development carried out during the project. It describes how the group explored and generated different ideas to find effective solutions to the problem, using methods such as brainstorming, research, and inspiration from related technologies.

3.1 System Overview

Before beginning concept development, a system overview was created. This system overview includes all the relevant features and functions of the machine, and can be seen in Figure 3.1. As this system overview shows, the string making machine has six crucial functions. These are user input, tension measurement, feedback and monitoring, tension control, core wire spinning and winding material feeding. For the concept generation phase, emphasis was placed on the tension measurement and tension control, as these were the novel parts of the project.

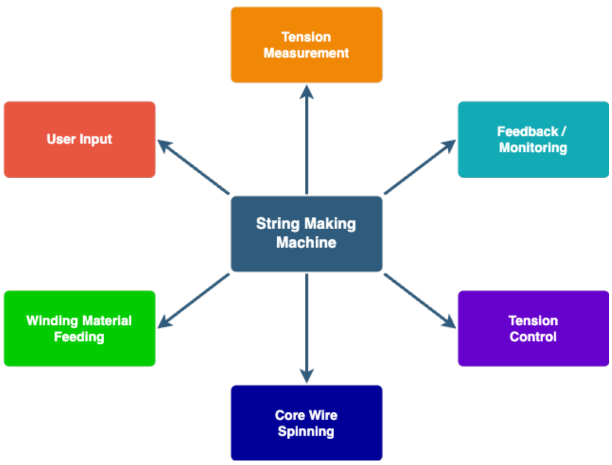

Figure 3.1: Concept diagram.

3.2 Concept Generation

After defining the project requirements, ideas for how the machine could work were explored. The goal was to identify as many practical and creative solutions as possible, ensuring that no promising approach was overlooked.

The team held brainstorming sessions to quickly generate a wide range of concepts without judging them too early. These ideas were informed by research into existing methods and manufacturing techniques from other fields that deal with wire tension measuring. All sorts of options were explored, ranging from eddy current systems to analyzing the sound properties of stretched materials. After the brainstorming sessions the group had a sessions discussing the advantages and drawbacks of each approach. All of these can be found in Appendix B.

This process resulted in several strong design concepts that met the technical requirements. Due to constraints in the length of the report only the three most promising concepts, which can be seen in Figure 3.2, will be described.

3.2.1 Load Cell Behind Spindle

An S-shaped load cell is placed between the spindle, which is supported by a low friction linear rail, and its mount. When the string is tensioned the resulting force pulls on the load cell, allowing it to measure the tension directly.

3.2.2 Tension Measuring Wheel

The string is threaded over a small wheel which is connected to a load cell perpendicular to the string. Tension causes the string to put pressure on the wheel, which is then registered by the load cell. Multiple wheels along the length can be used to improve measurement and dampen vibrations.

3.2.3 Dual Linear Actuator System

Similarly to the S-shaped load cell concept this concept uses linear rails and load cells. The difference is that this concept uses two linear actuators, one for rough movements and one for precise movements. The precise actuator has a built-in load cell to measure and control tension with finer control.

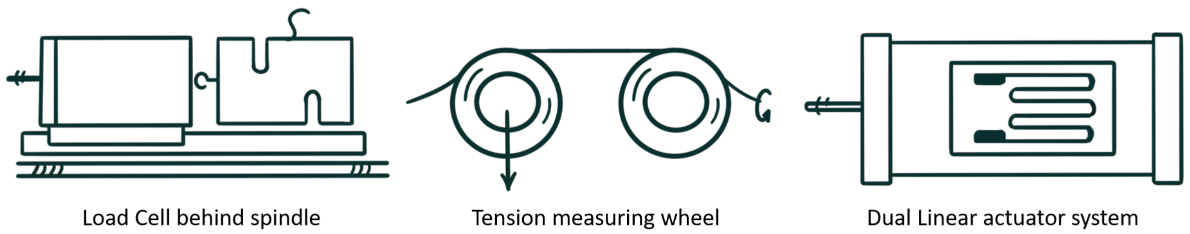

Figure 3.2: Illustrations of the three main design concepts described above: (1) Load cell behind spindle, (2) Tension measuring wheel, and (3) Dual linear actuator system.

Chapter 4

Concept Evaluation and Selection

This chapter highlights the methods how the group has come up with an agreement upon the final design concept. A section about prototyping the concept is also included.

4.1 Evaluation of Concepts

To systematically evaluate and compare the proposed tension measurement concepts, a weighted decision matrix (WDM) approach was adopted. Five key evaluation criteria were identified: implementation, cost, accuracy, reliability, and scalability. Each concept was assessed against these criteria, with scores assigned based on technical feasibility, anticipated performance, and ease of integration into the overall system architecture. The individual scores were then averaged to yield a composite score, providing a quantitative basis for comparison and decision-making. The resulting matrix is presented in Appendix C.

4.2 Selected Concept

The selected concept is referred to as the **'load cell behind the spindle'** concept. This solution was selected for its ease of implementation and proven success in industry. Load cells are used for most load-sensing functionalities in industrial machines, and thus, interfacing them with industrial controllers is also commonplace and supported by many I/O units. Furthermore, it can be mechanically integrated relatively easily into the machine. It is also not so sensitive to high-frequency vibrations, which was confirmed in a small scale test, see Chapter 4.4. One possible reason for this could be that the load cell is very stiff. Lastly, it is also possible to use the load cell solution, even if dampers or similar features are added to the machine that disrupt vibrations, eigenmodes and frequencies in the string.

The winning concept is shown in Figure 4.1.

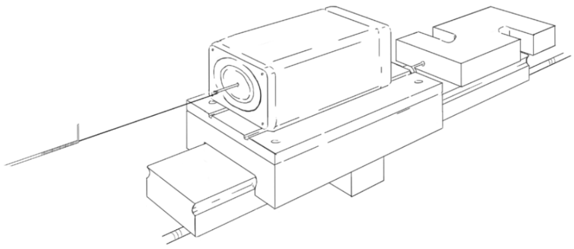

Figure 4.1: Sketch of the selected concept.

4.3 Parts and Systems Selection

A lot of time was spent on researching the critical components needed to build the machine. The main components considered essential for the machine were the following:

- Servo motors and drivers
- Linear rails
- Spindles
- Load cell
- Industrial PC
- Power Supply
- I/O units

4.3.1 Servo Motors and Spindles

When researching options for servo motors and spindles, the group looked into alternative solutions on how to achieve the requirement of 15 000 rpm. The two primary options considered were whether there were planetary gears that could be directly mounted on the servo motor axis or if there were spindles with integrated motors, i.e. electrical spindles. For the planetary gear idea, the group didn't find any viable options since this type of gear is usually not used to gear up to such high velocities. However, for the electrical spindles, there were some options found, but they didn't have precision encoders, and therefore could not be synchronized. As exact synchronization of not just the spindle velocity, but also the acceleration, is crucial for the functionality of the machine, the outcome from this research was to continue with the solution Primstrings currently uses: a servo motor connected to a spindle through belt-driven gears to raise the output speed on the spindle.

4.3.2 Programming and Communication

After conducting research on alternatives to CODESYS and considering the recommendation from the stakeholder, it was decided to move forward with CODESYS as the development environment for the software. The same goes for the communication protocol. Since Primstrings currently uses EtherCAT and since it was found to be commonly used with no major drawbacks compared to alternatives, the group chose to continue with that.

4.4 Prototyping and Early Testing

To better understand advantages and disadvantages two tests were produced that would help evaluate the concept.

4.4.1 Static Test

To verify the accuracy of the load cell, a static test was conducted by hanging known weights from it. After some initial calibration, the load cell provided accurate readings, even beyond the calibrated weight range. However, some signal drift over time was observed, where the output slowly changed after stabilizing before stabilizing again. This could affect long-term precision.

4.4.2 Dynamic Test

For the dynamic test, a prototype was built with a motor spinning a string. The string was intentionally made unbalanced to simulate exaggerated vibration and radial force conditions. The prototype observed less than 1% inaccuracy due to noise from the exaggerated vibrations. In addition, it was found that measurement accuracy actually improved at higher rotation speeds, which would further improve accuracy at the operating speeds of the final machine. More detailed data and process can be found in Appendix D and the test rig can be seen below in Figure 4.2.

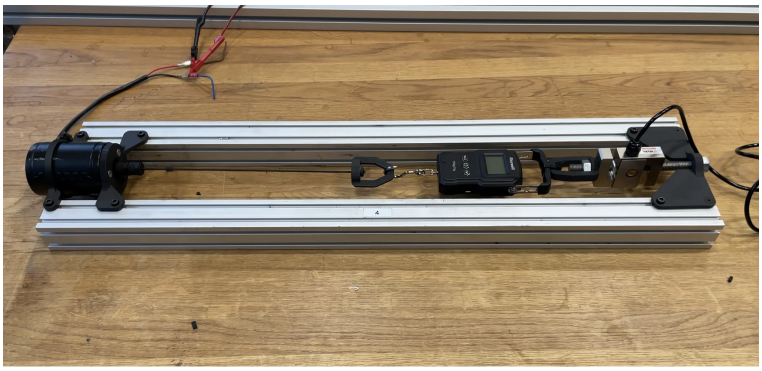

Figure 4.2: Dynamic test rig setup.

4.4.3 Future Prototyping

The final part to test before finalizing the design is tension control using a PID-controller. This will help ensure consistent string tension under varying loads and dynamics, and validate the effectiveness of the chosen tension measurement method.

Chapter 5

Discussion

The discussion part explains how the project will move forward. First a risk analysis the group have made is presented. This is followed by a presentation about the approach for purchasing the required parts. Finally, a description about the project planning including a time plan for the future work and arrangement.

5.1 Risk Analysis and Safety Precautions

In an engineering project, it is important to identify the risks that may be involved in the project. According to Tukes, a risk is described as follows: Risk refers to the probability of a nuisance as a result of exposure to a hazard [27]. The group has carried out risk analyses in order to be able to review measures to prevent the risks from arising or to minimize the result of a risk. This helps the project to progress more smoothly. In addition, it provides an overview of safety aspects that may need to be taken and when. Safety is the be-all and end-all of the project.

5.1.1 Risk Identification

The identification of risks was first divided into three (3) different risk analyses. First, an analysis was made of the project as a whole, which risks could prevent the project from being successful and completed according to schedule. Then, an analysis was made of the physical hazards that may be relevant for the construction of a string making machine. The last analysis was a mandatory risk analysis that belonged to the building where the group will work. The risks in this largely consisted of the risks in the physical risk analysis, but with a slightly different structure since there was a ready-made template for the analysis principle for the building.

For the project-specific risk analysis, inspiration was taken for the structuring according to an article from PMI (Project Management Institute) [28]. A table was created in Google Sheets where risks were categorized into four main categories: Technical, Organizational, Project management and External. This was followed up with columns with risk description, consequence, probability of occurrence, severity and proposed measures to prevent or minimize the risk. For simplicity, three levels of probability and severity were chosen: Low, Medium and High. The risk analyses for the project in general as well as the potential physical risks involving the machine can be found in Appendix E.

5.1.2 Risk Mitigation

Some notable risks that can be identified from the analysis for the project as a whole include if the concept turns out to be trickier to implement than expected, which could lead to delays. To prevent this, the group will carry out tests early and test subsystems separately before integration. The group also has a plan B, an alternative concept that the group can switch to if it turns out to be too complex.

Another risk that was identified at organizational levels was coordination failure, which could lead to the group missing deadlines or having problems with system integration. Measures taken to address this include role divisions and continuous meetings.

To highlight one last point, problems with components can be mentioned. Delays in orders or critical components that break can cause the project to be stopped and delayed. To avoid this, the group should place orders on time and use certified components. Another factor to consider is to look for local suppliers and see if the component is ready in stock at the supplier. In addition, the purchase of specific components should be reviewed to see if it may be worth manufacturing them yourself in some cases.

Regarding the analysis of the physical risks, it was found, among other things, that if a string comes loose when the machine is spinning at full speed or if a limb gets caught in a moving part of the machine this can cause serious harm, and these are considered serious risks. To prevent this, the group will wear safety glasses when working with the machine and have a safety zone where the machine is located. In addition, there must be an emergency stop available next to the machine.

5.2 Budget and Purchasing

A specific budget was not provided by our stakeholders, however, they emphasized the use of high quality industrial components from reputable sources as the most important factor when deciding on components. The components we use will also be used in the future for their machines. To aid in finding suitable components, we researched options from companies such as Beckhoff, Faulhaber, Beijer Electronics, and others. From the data gathered, together with information from our stakeholders, it was possible to estimate an approximate reasonable cost for each component. This information is shown in Table 5.1.

Table 5.1: Component List with Quantities and Approximate Costs.

Component	**Quantity**	**Approx. Unit Cost (SEK)**
Servo Motor	4	10,000
Linear Rail Tension	1	15,000
Linear Rail Winding	1	15,000
Spindle	2	30,000
Load Cell	1	5,000
Industrial PC	1	20,000
Distributed I/O	1	2,000
Power Supply	1	3,000

Using this list as a base, multiple options were gathered and presented to the company. The proposed component list is found in Table 5.2. For some components, two alternatives in different price ranges were presented. In the case of the distributed I/O unit and power supply, no specific model was specified. This was because those units were widely available, and sourcing them from the same source as the industrial PC would reduce the work necessary to integrate them, while having low or no effect on the cost.

Table 5.2: Component List for Stakeholders with Specifications, Unit Pricing, and Lead Times.

Component Type	Component Name	Description	Qty	Supplier	Part Number	Unit Price (SEK)	Lead Time
Servo Motor alt.1	AMI8122 | Compact integrated servo drives	Servo motor with integrated EtherCAT driver 48V	4	Beckhoff	AMI8122-3000-1J20 / Standard	11,550 + cable costs	30 days
Servo Motor alt.2	MD60-040-DMAK-EA-000 400W 3000rpm EtherCAT	Servo motor with integrated EtherCAT driver 48V	4	Sigbi	MD60-040-DMAK-EA-000	5,940 + cable costs	30 days
Linear rail tension	LEFSH32NXB-600	Linear rail with ball screw	1	SMC Pneumatics	LEFSH32NXB-600N	11,686	25 days
Linear rail winding	LEFB32NXS-1100	Linear rail with belt	1	SMC Pneumatics	LEFB32NXS-1100	14,100	25 days
Spindle	MBC-50 Axial	Spindle with EXS20 collet chuck	2	Meyrat	174-06-00	30,000	35 days
Load Cell	Lastcell 25 kg. OIML C2	Stainless steel load cell, OIML C2	1	Vetek	TS 25kg	4,910	35 days
Industrial PC alt.1	Beckhoff Panel PC	IPC/PLC with integrated HMI	1	Beckhoff	Multiple options	Price upon request	30 days
Industrial PC alt.2	X2 Control 10	IPC/PLC with integrated HMI	1	Beijer Electronics	X2 Control 10	15,758	30 days
Distributed I/O	Analog I/O unit EtherCAT	I/O unit for interfacing load cell with IPC	1	Purchase from Industrial PC supplier			
Power Supply	DC Power supply 24/48V	Power supply for motors and other electronic components	1	Purchase from Industrial PC supplier			

As none of the lead times of the components were substantial, our stakeholders agreed to work with us for the remaining part of the term to fully define all parts needed. Ordering will then take place during summer. This should ensure that most, if not all, parts are available at the start of next term when work begins again.

5.3 Project Planning and Management

Project management is an important part of making a project successful. In this project, the following parts have been created as a framework for the project: A document with a project plan divided into phases, a sub-plan for the spring semester, a work breakdown structure, a Gantt chart and a responsibility matrix. These points tie together a good basis for how the project will be implemented.

5.4 Future Work and Fall Semester Planning

When the group meets again in the fall and work resumes, the first thing on the agenda will be to finalize the complete design for the machine in CAD. In addition to ensuring that the functions interact with each other, the focus will also be on ensuring that the machine is as user-friendly and ergonomic as possible. The design phase is then followed by the development phase, which runs until the end of October. This is followed by a month of integration, testing, verification and validation. The machine is scheduled to be ready by the end of November, which means that documentation, presentation and completion are then all that remains.

5.4.1 Time Plan and Planned Activities

To take a closer look at the different steps in the project, the development phase can be divided into six different parts: tension measurement, tension control, string attaching and spinning, string winding, finishing and release, and monitoring/interface. These parts in turn contain all four (4) building blocks in mechatronics. The six categories all have several subcategories that create a clear structure of what needs to be done for each part. According to these, task-based subgroups can be applied. In addition, these also provide an indication of how the group will be able to test subsystem by subsystem and integrate parts step by step. A schedule in the form of a Gantt where this is visualized more clearly can be found in Appendix F, as well as a work breakdown structure that describes the six focus areas for the machine's manufacturing process in Appendix G.

The hope is that the critical parts will be ordered before the summer and that they will have arrived when the group resumes the project in the fall semester. The group has tried to work towards this by submitting a document to Primstrings listing the critical components with the necessary information to be able to order them. This would make it easier not to have to worry about ordering and waiting for critical parts during the fall, as this could halt the progress of the project.

Of all the project phases, the test phase is the trickiest to schedule. It is difficult to estimate how long it might take since you don't know in advance what problems might be encountered, especially when integrating all subsystems. However, it feels safe that the group will continue with the same structure and meeting schedule as in the spring semester. Having a clearly structured meeting once a week where things are reviewed with the entire group means that the work can be adapted to succeed with the project.

5.4.2 Work Arrangement

The role distribution and team structure that the group developed in the spring will be continued in the fall. The group has agreed that if there are too many people responsible for one thing, it means that no one feels truly responsible, which means that productivity is not at the level that is sought. As long as everyone is aware and agrees that they accept this, it constitutes a stable foundation. A team structure view and a responsibility matrix for the roles and the team is visualized in Appendix H and I.

As described in the introductory chapter, we still want to emphasize the collaboration beyond the subteam boundaries. You are not locked into one position. We want all people to collaborate with each other and be able to adapt work pairs and groups depending on the tasks we have immediately in front of us. We think it can be good with variety as well, as it makes new inputs/aspects a problem. If only one and the same person works on it, it can easily happen that you become narrow-minded. At the same time, this collaboration also ensures that the learning objectives are met and that we all learn various things.

While the project is being worked on, documentation will be done in parallel. Documentation is important for remembering what, how and why we did something. Documenting this also ensures that the content of the final report will be very descriptive. Each person will need to work with different logbooks and documents where results and progress are compiled and can be recounted during the weekly meetings.

Meetings with stakeholders and supervisors will also be held at regular intervals. One to two times per month with both parties will be necessary. No exact schedule for this has been drawn up, but the next meetings are planned one by one after each meeting and can be adjusted according to when updates are to be presented or if any major problems are encountered that need to be discussed.

Chapter 6

Conclusion

In this report, the background, state-of-the-art technology, and design process for the project is presented. The spring semester's work has mainly focused on theory study, concept development, and planning.

The chosen concept and project structure form the basis for the fall semester. During that term, design, implementation, integration, and testing will take place. A risk assessment has been performed to identify uncertainties. Based on this analysis, the risks have been reduced as much as possible. A plan for how the project will progress has been developed in order to be able to move forward effectively.

The continuation of this project will consist of verifying the functionality of the proposed solution. This will involve handling open challenges. Finally, a demonstration of a working prototype in line with the expectations of the stakeholders will be presented.

References

[1] *Primstrings - Svensktillverkade strängar sedan 1943*. www.primstrings.com. URL: https://www.primstrings.com/i/om-prim.html?language=sv_SE (visited on 04/18/2025).

[2] 23 April 2013. *Inside the top-secret world of string manufacturing*. The Strad. URL: https://www.thestrad.com/inside-the-top-secret-world-of-string-manufacturing/3034.article (visited on 04/18/2025).

[3] HY Violin strings. *HY Stefano strings & HY Frei strings*. URL: https://www.violinstringsmaker.com/stefano-violin-strings (visited on 05/19/2025).

[4] *Construction of a string | Thomastik-Infeld Vienna*. URL: https://www.thomastik-infeld.com/en/stringtelligence/string-technology/how-is-a-string-made (visited on 05/19/2025).

[5] TAKU. *High-Precision Guitar / Bass / Violin String Winding Machine*. URL: https://www.takustringmachines.com/manufacturer/string-winding-machine-wmb/ (visited on 05/19/2025).

[6] C.M.S. *WVI 200 Speed (Steel) – Cms Machines*. URL: https://www.cmsmachines.net/product/wvi-200-speed-steel/ (visited on 05/19/2025).

[7] Verified Market Reports. *Force Sensors & Load Cells Market Size, Competitive Overview & Forecast 2033*. Verified Market Reports. URL: https://www.verifiedmarketreports.com/product/force-sensors-and-load-cells-market/ (visited on 04/20/2025).

[8] *How a Strain Gauge Load Cell Works? What is a Load Cell? | FUTEK*. URL: https://www.futek.com/how-a-load-cell-works (visited on 04/21/2025).

[9] Jacob Fraden. "Force and Strain". In: *Handbook of Modern Sensors*. Springer, Cham, 2016, pp. 413–428. ISBN: 978-3-319-19303-8. DOI: 10.1007/978-3-319-19303-8_10. URL: https://link.springer.com/chapter/10.1007/978-3-319-19303-8_10 (visited on 04/23/2025).

[10] Yazan Hamed et al. "Strain Sensing Technology to Enable Next-Generation Industry and Smart Machines for the Factories of the Future: A Review". In: *IEEE Sensors Journal* 23.21 (Nov. 2023), pp. 25618–25649. ISSN: 1558-1748. DOI: 10.1109/JSEN.2023.3313013. URL: https://ieeexplore.ieee.org/document/10250192 (visited on 04/23/2025).

[11] *Tension control in production processes using laser sensors from Polytec - Polytec*. URL: https://www.polytec.com/us/velocimetry/areas-of-application/converting-plastics-textiles/tension-control? (visited on 04/24/2025).

[12] Mohamed M. Elgaud et al. "Digital Filtering Techniques for Performance Improvement of Golay Coded TDM-FBG Sensor". In: *Sensors* 21.13 (Jan. 2021), p. 4299. ISSN: 1424-8220. DOI: 10.3390/s21134299. URL: https://www.mdpi.com/1424-8220/21/13/4299 (visited on 04/23/2025).

[13] *[1009.4870] Hallway Monitoring: Distributed Data Processing with Wireless Sensor Networks*. URL: https://arxiv.org/abs/1009.4870 (visited on 04/23/2025).

[14] Jingyang Yan, Xian Du, and Jingyang Yan. “Web Tension and Speed Control in Roll-to-Roll Systems”. In: *Control Theory in Engineering*. IntechOpen, Jan. 24, 2020. ISBN: 978-1-83880-424-4. DOI: 10.5772/intechopen.88797. URL: https://www.intechopen.com/chapters/68827 (visited on 04/24/2025).

[15] *Belt Driven or Lead Screw Driven Linear Actuators? | PBC Linear*. URL: https://pbclinear.com/blog/2020/february/lead-screw-or-belt-drives (visited on 04/24/2025).

[16] Lei Feng. *Lecture Notes: MF2007 HT24 Dynamics and Motion Control (50536)*. URL: https://canvas.kth.se/courses/50235/pages/lecture-notes?module_item_id=970187 (visited on 04/24/2025).

[17] Bonnie S. Heck, Linda M. Wills, and George J. Vachtsevanos. “Software Technology for Implementing Reusable, Distributed Control Systems”. In: *Applications of Intelligent Control to Engineering Systems*. Springer, Dordrecht, 2009, pp. 267–293. ISBN: 978-90-481-3018-4. DOI: 10.1007/978-90-481-3018-4_11. URL: https://link-springer-com.focus.lib.kth.se/chapter/10.1007/978-90-481-3018-4_11 (visited on 05/14/2025).

[18] Peng Zhang. *Advanced industrial control technology*. 1st ed. Amsterdam ; Elsevier, 2010. 865 pp. ISBN: 978-1-282-77036-2.

[19] Jon Breen. *Know the differences among a PLC, PAC and IPC*. Control Engineering. May 1, 2020. URL: https://www.controleng.com/know-the-differences-among-a-plc-pac-and-ipc/ (visited on 05/14/2025).

[20] Jeff Payne. *Convergence of PACs, PLCs, IPCs*. Control Engineering. Nov. 17, 2015. URL: https://www.controleng.com/convergence-of-pacs-plcs-ipcs/ (visited on 05/14/2025).

[21] Richa Bansal and Anil Kumar Dubey. “Communication protocols used for industrial automation”. In: *Computational Intelligence in the Industry 4.0*. Num Pages: 22. CRC Press, 2024. ISBN: 978-1-00-347903-1.

[22] Carlos Rojas and Peter Morell. “Guidelines for Industrial Ethernet infrastructure implementation: A control engineer’s guide”. In: *2010 IEEE-IAS/PCA 52nd Cement Industry Technical Conference*. 2010 IEEE-IAS/PCA 52nd Cement Industry Technical Conference. ISSN: 1079-9931. Mar. 2010, pp. 1–18. DOI: 10.1109/CITCON.2010.5469772. URL: https://ieeexplore.ieee.org/abstract/document/5469772 (visited on 05/14/2025).

[23] Oliver Riedel, Armin Lechler, and Alexander W. Verl. “Control Architecture for Automation”. In: *Springer Handbook of Automation*. ISSN: 2522-8706. Springer, Cham, 2023, pp. 357–378. ISBN: 978-3-030-96729-1. DOI: 10.1007/978-3-030-96729-1_16. URL: https://link-springer-com.focus.lib.kth.se/chapter/10.1007/978-3-030-96729-1_16 (visited on 05/17/2025).

[24] William M. Hartmann. “Standing Waves”. In: *Principles of Musical Acoustics*. Ed. by William M. Hartmann. New York, NY: Springer, 2013, pp. 67–75. ISBN: 978-1-4614-6786-1. DOI: 10.1007/978-1-4614-6786-1_7. URL: https://doi.org/10.1007/978-1-4614-6786-1_7 (visited on 05/19/2025).

[25] Ali Khodayari Bavil and Seyed Esmail Razavi. “On the thermo-flow behavior in a rectangular channel with skewed circular ribs”. In: *Mechanics & Industry* 18.2 (2017). Number: 2 Publisher: EDP Sciences, p. 225. ISSN: 2257-7777, 2257-7750. DOI: 10.1051/meca/2016057. URL: https://www.mechanics-industry.org/articles/meca/abs/2017/02/mi160132/mi160132.html (visited on 05/19/2025).

[26] Jeffrey Landtroop and Donald Dykstra. “Guitar string manufacturing auto start winding process”. U.S. pat. 20010039722A1. Individual. Nov. 15, 2001. URL: https://patents.google.com/patent/US20010039722A1/en (visited on 05/19/2025).

[27] *Vad betyder fara och risk?* Säkerhets- och kemikalieverket (Tukes). URL: https://tukes.fi/hem-och-fritid/kemikalier-i-hemmet/vad-betyder-fara-och-risk- (visited on 05/14/2025).

[28] *Project risk analysis*. URL: https://www.pmi.org/learning/library/risk-analysis-decisions-uncertain-times-6686 (visited on 05/14/2025).

Appendix A

Technical Requirements

This section defines the measurable and concrete technical requirements derived from stakeholder needs. The requirements are grouped by system function.

A.1 Spindle and Drive Requirements

Table A.1: Spindle and Drive Requirements

ID	Requirement	Metric / Note
TR1	The spindle must reach a maximum speed of 15,000 rpm	Achieved via mechanical gearing
TR2	The system shall support violin winding at 12,000 rpm	Test case
TR3	The system shall support cello winding at 10,000 rpm	Test case
TR4	The spindle shall brake to 0 rpm within 0.5 seconds upon string break	Safety feature
TR5	The motor shall have a power output between 100–400 W depending on load	Depends on spindle inertia and gearing
TR6	The system shall support Ethernet bus communication, preferably EtherCAT	For modular I/O and real-time control

A.2 Length Adjustment Requirements

Table A.2: Length Adjustment Requirements

ID	Requirement	Metric / Note
TR7	The machine must support core lengths from 600 mm to 1100 mm	Adjustable for different string types
TR8	Core positioning shall be automated via servo motor for fast changeover	Reduces production time

A.3 Tensioning Requirements

Table A.3: Tensioning Requirements

ID	Requirement	Metric / Note
TR9	The core wire tension must be controllable between 4–20 kg with ±5% accuracy	Wire tension only

A.4 Winding Feed Requirements

Table A.4: Winding Feed Requirements

ID	Requirement	Metric / Note
TR10	A hysteresis brake with 0–10 V analog control shall be used for tension regulation	Controlled via analog output
TR11	The feeding mechanism for winding shall be adjustable	Required for different winding patterns

A.5 Software and Interface Requirements

Table A.5: Software and Interface Requirements

ID	Requirement	Metric / Note
TR12	Programming shall be done in Codesys	Reuse of existing codebase
TR13	A PLC or industrial PC with Codesys control and HMI capability shall be used	Central control system
TR14	The system shall use distributed I/O modules over an Ethernet bus	For modular design
TR15	A recipe system shall be available to store string type settings	Improves repeatability
TR16	Physical buttons shall be available for repetitive tasks; HMI for settings and monitoring	Ergonomic operation

A.6 Safety Requirements

Table A.6: Safety Requirements

ID	Requirement	Metric / Note
TR17	The machine shall include an emergency stop that halts all motion	Stop time ≤ 1 s
TR18	The system shall detect broken strings and stop spindle rotation within 0.5 s	Active safety mechanism
TR19	A risk analysis according to ISO 12100 shall be conducted	For CE compliance
it		

A.7 Hardware and Integration Requirements

Table A.7: Hardware and Integration Requirements

ID	Requirement	Metric / Note
TR21	Components shall be transferable to or usable by Primstrings post-project	Ensures project value
TR22	Servo motors should operate at 24V (under 60V preferred)	Low-voltage system
TR23	Servo motors with integrated amplifiers are preferred	Reduces system complexity
TR24	The machine shall include vibration dampeners to improve winding precision	Mechanical stability

Appendix B

Brainstorming Ideas

Ideas	Description	(+) Advantages	(-) Disadvantages	More Notes	Y/N
S-shaped load cell before the spindle/motor	An s-shaped load cell placed between the motor/spindle and motor/spindle mount. When the string is tensioned, this tension pulls on the load cell giving the tension	Relatively straightforward solution, load cells are standard components with standardized ways to read them. Often used for similar tasks for measuring tension in crane wires. Seems relatively cheap. Proven method, go-to in industry (according to chatGPT)	Might have noisy measurements, mounting needs thought to ensure correct measurements.	This would most likely need a mounting solution similar to what Henrik sketched? Maybe we could also look into other shapes of load cell to make a rigid connection possible (might help with robustness and vibrations) (examples pancake, inline, Through-Hole load cell)?	Yes
Thread the string over a small wheel connected to a load cell. Maybe multiple along the length. Movement = tension	Thread the string over a small wheel connected to a load cell. Maybe multiple along the length. Movement = tension	Load cells like this for strings exist. Can also be used for damping string vibration	String vibration (eigenmodes) might make readings noisy. Might cause wear and tear on wheels. Sensor will have to move out of the way when we want to spool on wire	If there are multiple dampeners how will this affect the reading, especially the moment they start or stop dampening	Yes
Dual Servo System with Linear Actuation	A linear servo motor with built-in load cell with its piston attached to the servo motor spinning the string	Keeps the amount of different components low. Should be easy to get it to run. Robust. Possible to have both fine and rough movements	Not sure the linear servo motor with built-in load cell is easy to find, might not give any advantage over just measuring with an external load cell	Maybe if we don't find one we could combine this solution in the way Henrik proposed?	Yes
Load cell inside the spindle. Expensive but exists	Load cell is inside the spindle, string pulls in spindle which pulls on load cell which gives tension reading	Very elegant and compact solution. Works out of the box hopefully	Finding such spindles seems to be difficult. Might be very expensive or custom built	Are there slip rings or how will the wires be connected? Could be nice, but maybe too advanced/expensive?	Yea..
Torque based measuring of the motors	Using the motor current / voltage to calculate the torque the motors are pulling the string apart with, and thus the tension	Uses parts we already will need. Overall very elegant solution if it works well	The company has already tried this and been unsuccessful. Unclear if it will be accurate enough. Not entirely sure but the belt driven actuator should have one of the lowest static friction	Still has to be calibrated and the friction might still be too high in other options. Not the main solution but we could implement it as a failsafe still	Yea..
Use springs to convert tension to distance	Springs placed between the motor/spindle and mount. Tension causes elongation, measurable by distance sensor. Knowing Hooke's law, this can be converted into tension	Easy and cheap solution. Springs are easy to source, distance/TOF sensors are common	Distance sensors might not be accurate enough. Very non-stiff solution, may cause harmonics or motor bounce	Most vibrations should be perpendicular to the string. On a linear rail, with proper damping, it might work	No

FSR (Force sensing resistor)	A round patch-like sensor measuring compression forces on the surface	Very cheap	Only measures compression. Questionable accuracy and reliability	We'd need to design such that tension becomes compression on the FSR	No
Rotating load cell, spinning with the string	Load cell placed between spindle/motor and string, measuring tension directly	Simple in theory	Load cells with slip rings measure torque only. Wireless versions exist but only for cranes/heavy loads. Adds rotating mass		No
Optics and laser interferometry	Using a camera to detect changes in surface patterns due to string stretch	Very high precision, used in labs	Sensitive to vibration. Requires ML-based analysis		No
Measure movement with magnets (Hall effect?)	Magnetic properties might change with tension. Or magnets on spindle measured with Hall effect sensor		Vague idea, needs study into how magnetism is affected by tension		No
Eddy currents	Eddy current sensor could monitor displacement or strain-induced deformation of a metal part under tension		No known implementation. Concept unclear		No
Ultrasonic pulse along string	Ultrasonic speed depends on string tension. Measure time for pulse to travel a known distance to infer tension		Needs transceivers, very sensitive to vibrations from eigenmodes		No
Measure frequency via eigenmodes (optics)	Detect eigenmode frequency using camera and infer tension	Non-obstructive, no contact needed	Damping ruins eigenmodes. Frequency also changes with added material		No

Appendix C

Decision Matrix for Design Concepts

Ideas	Description	Implementation	Cost	Accuracy	Reliability	Scalability	Total
Weight		0.3	0.2	0.2	0.15	0.15	1.00
S-shaped load cell before the spindle/motor	An s-shaped load cell placed between the motor/spindle and motor/spindle mount. When the string is tensioned, this tension pulls on the load cell giving the tension	4.5	4	4.5	4.5	4	4.33
Thread over wheel with load cell	Thread the string over a small wheel connected to a load cell. Maybe multiple along the length. Movement = tension	4	5	4	3	4	4.05
Dual Servo System with Linear Actuation	A linear servo motor with built-in load cell with its piston attached to the servo motor spinning the string	4	3	4	3.5	4	3.73
Load cell inside the spindle	Load cell is inside the spindle; string pulls in spindle which pulls on load cell giving tension reading	3.5	3	4.5	4	3.5	3.68
Torque-based motor measurement	Using motor current/voltage to calculate torque, and thus the tension	3.5	4	3	3.5	4	3.58
Springs to convert tension to distance	Springs elongate under tension, elongation measured by distance sensor, converted via Hooke's Law	4	4.5	3	3	3.5	3.68
FSR (Force sensing resistor)	A round band-aid-like patch to sense compression forces	3	3.5	3.5	3	3	3.20

Rotating load cell	Load cell between spindle/motor and string, measuring direct tension	4	4	3	2.5	3	3.43
Optics and laser interferometry	Camera detects surface movement on string to detect elongation	3	2.5	4	3	2	2.95
Magnets / Hall effect	Magnetic properties or position sensors detect tension changes	3	2.5	3	3	3	2.90
Eddy currents	Sensor detects deformation or displacement in metal components under tension	3	2.5	4	3	3	3.10
Ultrasonic time-of-flight	Sound velocity changes with tension; sensors measure travel time to compute it	3	3	4	2	3	3.05
Frequency analysis (optics)	Detect eigenmode frequency optically, compute tension from it	3.5	3	4	2	3	3.20

Appendix D

Spring Term Prototyping Logbook

D.1 Purpose of Prototyping Week

Validate early design choices. Test key components (load cell, mechanical rig, actuator). Evaluate signal quality and controller feasibility. Build knowledge for integration and full system test.

D.2 Daily Logbook

Monday, May 5 – Soldering & Setup

Observations:

- Soldering was finished successfully.

Wednesday, May 7 – Static Testing

Observations:

- Load cell was calibrated using a wrench (420g).
- Tested with wrench and 5kg backpack (verified with kitchen scale).
- Observed low variance (10–20g for wrench, 50g for backpack).
- Some drifting before values stabilized.

Thursday, May 8 – Disturbance & Vibration Testing

Observations:

- Test rig built.
- Horizontal force validated with baggage scale.
- Load cell readings consistent with baggage scale.
- Low speed (<500 RPM): some vibration noise.
- High speed (2000–3000 RPM): minimal noise (typically within 10g of average).
- Setup was not optimal mechanically but still yielded good results.

Figure D.1: Graph showing load cell signal during vibration testing.

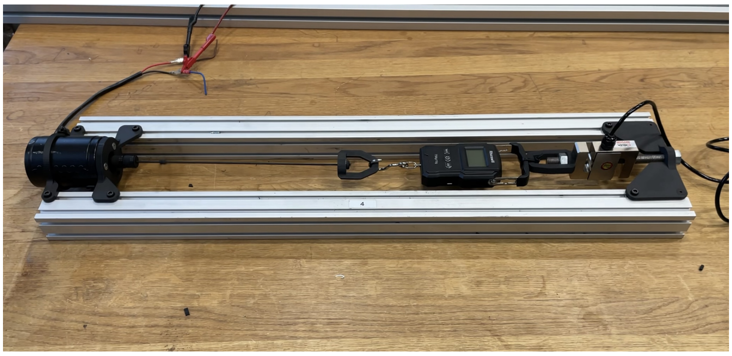

Figure D.2: Test rig used for disturbance and vibration testing.

D.3 Summary of Results

Test	**Result**	**Conclusion**
Soldering & Setup	Finished	Soldering completed successfully
Static Testing	Deviations of 50g for 5kg backpack	Calibration is important; load cell reasonably accurate
Vibration Testing	Noise: 5–20g	Load cell unaffected by vibrations; stiffness seems to help

D.4 Reflection & Project Value

The load cell handles vibrations well and rejects low-amplitude, high-frequency noise, especially at higher RPMs. This supports continued use in the project. Calibration will be important and needs to be addressed in the final design.

D.5 Next Steps

Begin building full-scale machine and determine how to integrate load cell, likely via analog I/O unit.

Appendix E

Risk Analysis

This appendix includes two detailed risk assessments:

- **Appendix E.1** – Project-wide risks categorized using PMI standards.
- **Appendix E.2** – Physical risks related to machine use and testing.

Appendix E.1 – Project Risk Analysis

Risk Category	Risk Description	Consequence	Probability	Severity	Action / Prevention
External	Delay in delivery of components	Project is delayed, tests cannot be completed on time	Medium	Medium	Order well in advance, have backup components
Organisational	Illness of key person in the group	Lack of competence, delays	Medium	Medium	Documentation, knowledge transfer, rotate responsibilities
Project management	Poor communication in the group	Misunderstandings, inefficient work	Medium	Medium	Weekly meetings, clear division of labor
Technical	Technical difficulties with the design	Does not meet requirements, additional work	High	Medium	Early prototype, regular validation
Technical	Control system/software problems	Does not work as intended	High	Low	Code review, test cases, backup plan
Project management	Lost or corrupt project data	Time is lost, risk of rework	Low	High	Regular backups
Technical	Concept much harder to realize than expected	Increased workload, risk of failure, delays	Medium	High	Early testing, divide problem, plan B
Organisational	Long-term absence in team	Increased workload, lost competence	Medium	Medium	Share knowledge, document decisions
External	Missing stakeholder deadline	Loss of trust, missed demo/test opportunity	Low	High	Frequent communication, timeline buffer
Organisational	Conflicts in team	Bad team morale, inefficient work	Medium	Medium	Team values, open discussions
Technical	Integration issues late in project	System doesn't work, delays	Medium	High	Early integration, clear interfaces, regular tests
Organisational	Trouble booking machine/shop time	Delay in fabrication or testing	Medium	Medium	Book early, have alternative methods
External	Missing KTH deadlines / feedback delays	Project milestones slip, reporting issues	Low	Medium	Communicate early, weekly follow-ups
Organisational	Insufficient resources	Delays, reduced performance	Medium	Medium	Resource planning, request funding
Organisational	Coordination failure	Missed deadlines, poor integration	Medium	High	Clear roles, common communication tools
Organisational	Technical misunderstanding	Design errors, incompatible solutions	Medium	Medium	Involve team in reviews, align understanding
Organisational	Documentation errors	Rework, misunderstandings	Low	Medium	Coaching sessions, version control
Technical	Late delivery of critical components	Delays, missed test windows	Medium	High	Order early, monitor suppliers
Technical	Broken or faulty sensor	Incorrect readings or function	Medium	Medium	Validate sensors, choose reliable parts
Technical	Software/hardware integration issue	Control fails	Medium	High	Early integration tests
Technical	No test plan or validation procedure	Can't verify system before deadline	Low	High	Clear test plan, distribute tests
Technical	Broken control board, ICP/PLC	Testing halted, system down	Low	High	Backup boards, static-safe handling
Technical	Model/simulation mismatch vs. real	Control fails, invalid assumptions	Low	High	Compare model with real data early
Technical	Control system not responding	No testing possible	High	Medium	Backup firmware, troubleshooting checklist
Technical	Use of un-certified components	Overheating, failure	Medium	High	Verify marking, test in operating conditions
Project management	Tasks take longer than expected	Delays in schedule, not following project plan	High	Medium	Conservative planning, start early
Project management	Scope creep	Wasted effort, missed deadlines	Medium	Medium	Define clear boundaries, review weekly
Project management	Lack of documentation	Confusion, traceability lost	Medium	Medium	Assign responsibility, track progress
Project management	Group falling behind	Missed goals	Medium	Medium	Weekly checks, scope adjust
Organisational	Wrong/missing parts due to miscommunication	Extra cost, lost time	Medium	High	BOM responsibility, cross-checks

Appendix E.1 – Project Risk Analysis

Organisational	Team overloaded	Burnout, missed deadlines	Medium	Medium	Scope control, team sync
Organisational	Competing course load	Progress slows	Medium	Medium	Coordinate early with team
External	Long delivery of mechanical parts	Delayed assembly and testing	Medium	High	Order early, local suppliers, consider making them ourselves
External	Stakeholder changes requirements mid-project	Redesign needed, delays	Low	High	Version-controlled specs, regular contact
External	Global component shortage	Part unavailable, redesign	Medium	High	Use in-stock parts, flexible design
External	Stakeholder specs not met	Rework, failed validation	Medium	High	Clarify specs early, regular feedback
External	No access to tools or labs	Testing blocked	Low	High	Book early, create backup plan

Appendix E.2 – Physical Safety Risk Analysis

Risk Category	Risk Description	Consequence	Probability	Severity	Action / Prevention
Physical	Damage during testing	Equipment failure, project delays	Medium	High	Structured test protocols, limit power during initial runs
Physical	Mechanical failure	Injury or prototype damage	Medium	High	Simulate loads, verify design before high-speed testing
Physical	Sudden acceleration of system (uncontrolled)	Unavailable to stop the system safely and quick, string deattaches from spindle	Low	High	Secure test setup, consider using soft start-up, restrict access during spin-up, use safety goggles when testing
Physical	Getting limb stuck in moving parts	Crush or cut injuries	Low	High	Use mechanical guards when necessary, label danger zones, no loose clothing, use cut-protection gloves when necessary
Physical	Loose cables / objects around machine	Tripping or entanglement	Medium	Medium	Tidy work area, secure cables and tools
Physical	String detaching during test	Whiplash injury, flying debris	Medium	High	Containment shield, wear goggles, keep safety distance
Physical	AC voltage in exposed areas	Electric shock	Low	High	Use insulation, covers, proper markings

Appendix F

Gantt Chart

Activity \ Month				August	September					October				November				December	
Week	Beginning Week	End Week	Duration in Weeks	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Design	35	38	4	■	■	■	■												
Development	38	43	6				■	■	■	■	■	■							
Testing & Feedback	41	43	3							■	■	■							
Integration	44	45	2										■	■					
System Test & Verification	46	47	2												■	■			
Documentation & Presentation	48	49	2														■	■	
Final Delivery	49	50	2															■	■

Figure F.1: Gantt chart showing the project plan for the fall term.

Appendix G

Work Breakdown Structure (WBS)

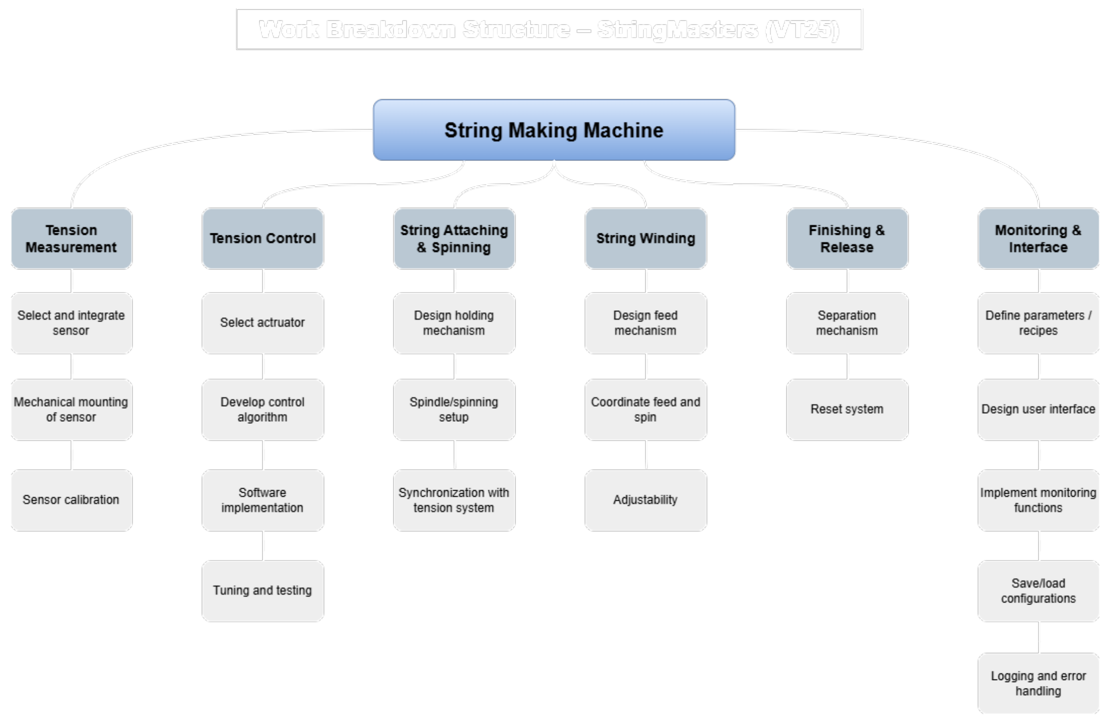

Figure G.1: Work Breakdown Structure (WBS) diagram for the project.

Appendix H

Team Structure

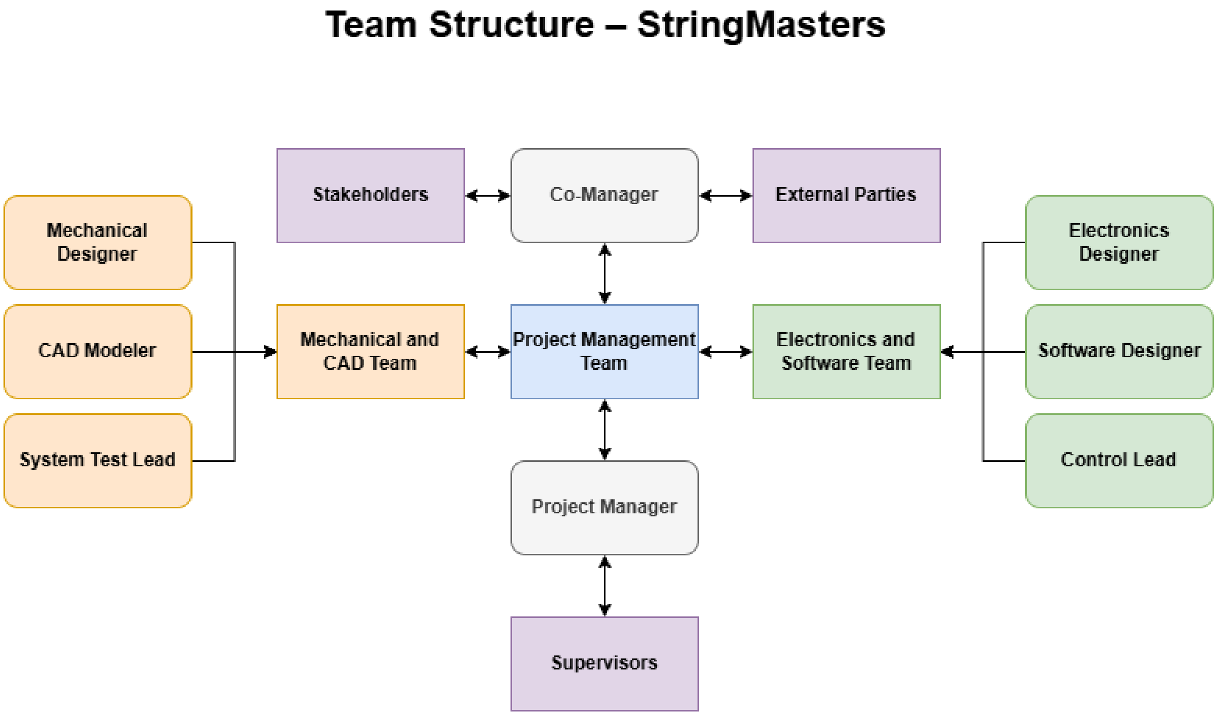

Figure H.1: Overview of the team structure, including subgroup division and individual roles during the spring term.

Appendix I

Responsibility Matrix

Responsibility / Role	Project Manager	Co-Manager	Mechanical Designer	CAD Modeler	System Test Lead	Electronics Designer	Software Designer	Control Lead
Project Planning and Coordination	Responsible	Supporter						
Stakeholder Communication	Supporter	Responsible						
Documentation and Reporting	Responsible	Supporter						
Mechanical Design (Concept and Build)			Responsible	Supporter	Supporter			
CAD Modeling and Mechanical Calculations			Supporter	Responsible				
System Testing and Validation			Supporter		Responsible	Supporter		
Electronics Design and Wiring						Responsible	Supporter	
Software Development (Programming)							Responsible	Supporter
Control System Design and Tuning							Supporter	Responsible
Procurement	Supporter	Responsible						

Figure I.1: Responsibility matrix outlining task distribution and role assignments within the project group.