KTH - Royal Institute of Technology

RobotDog – A Soft Actuated Quadrupedal Robot

Spring Term Report

MF2121 – Mechatronic Capstone Course

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1 Introduction

This section will serve as an introduction to the project, including the background, the goals the project aims to achieve, the scope of the work, the requirements for the final product, and a description of the project's organization.

1.1 Background

In recent years, the field of soft robotics has seen a sharp uprising in popularity, partially due to the rapid deployment of cheaper 3D-printing technology [1]. By making use of soft robotics instead of traditional rigid robotics, different outcomes can be achieved; by losing some of the predictability inherent in rigid robotics, soft robotics gains enhanced flexibility. This can be useful in many different applications, but for the purpose of this project, soft actuation in legged robots can provide improved ability to navigate unpredictable terrain.

This project is conducted as part of the Mechatronics Capstone course under the supervision of Prof. Lei Feng, with the main goal being improving the design of an existing soft-legged quadruped robot. It serves as a continuation of the work of several previous students, such as the master's thesis work of Seshagopalan Thorapalli Muralidharan and Ruihao Zhu [2], David Danelia and Shuo Fu [3], and Xuezhi Niu [4]. Throughout these projects, several design flaws have been identified, one being the structural stability of the legs. Therefore, this project aims to optimize the topology of the leg design and choose an actuation method that solves these issues while maintaining or enhancing performance, as specified in section 1.5. A picture of the current KTH design can be seen in the following figure.

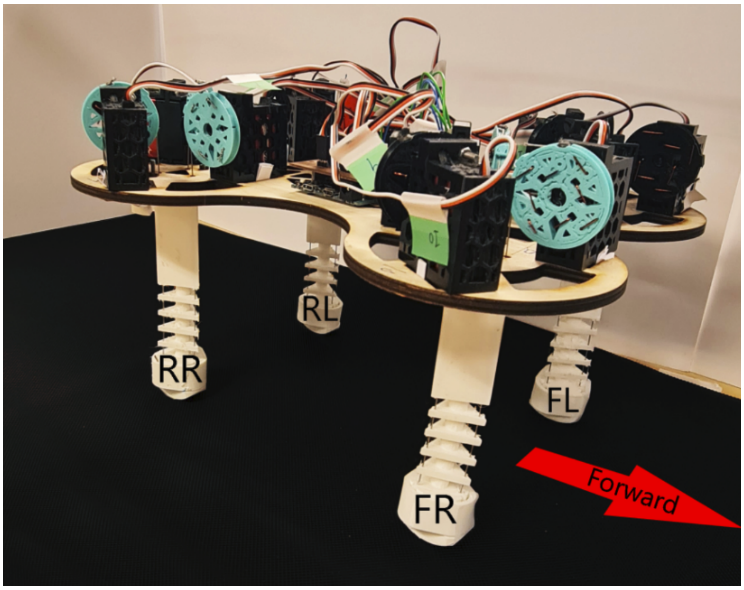

Figure 1.1: Existing soft-legged quadruped robot

1.2 Scope

The scope of this project includes the construction of a soft quadruped robot inspired by the design of a prototype built previously. The robot dog should be able to walk autonomously from point A to point B.

1.3 Goals

The general goal of this iteration of the robot is to optimize the leg topology and the actuation method to improve speed and durability.

More specifically, this means:

- Optimize the leg design by modifying the leg topology, materials and printing parameters
- Explore soft robot simulation tools
- Build at least one prototype
- Develop or modify the gait controller according to new leg design

1.4 Delimitations

The main focus of the project is on the leg itself, as well as the gait controller. Pathfinding, 5G and edge computing will only be implemented if time allows. If this is the case, code from the previous KTH robot, provided by our stakeholder, will be reused to do so.

1.5 Requirements

The project requirements are as follows:

- Soft-Legged Robot: This involves the selection and integration of soft materials and actuation mechanisms.
- Exploration of Simulation Tools and Environments: Investigate and utilize simulation platforms suitable for soft robotics and actuation modeling.
- Topology Optimization of the Leg Design: Perform topology optimization to determine an efficient and functional leg geometry.
- Untethered Robot: Design the robot to operate independently by eliminating tethered dependencies.
- Multi-Directional Mobility: Ensure the robot can move in multiple directions; full omnidirectional capability is not a strict requirement.
- Prototype Construction: Build and test at least one working prototype based on the developed designs and simulations.
- Allowed 10% change in size compared the current design.
- Allowed mass increase by 10% compared to current design.

1.6 Project Organization

The project kicked off in P4 (spring semester) with an initial State of The Art (SOTA) analysis, exploring the problem and existing solutions. The nine-person group split into three subgroups: Soft Robotics, Actuation and Software. Five people in Soft Robotics, due to its broader scope and two in each remaining subgroups.

After completing the SOTA phase, new subgroups were formed to leverage the insights gained during the initial SOTA. One Mechanical Design (5 members) and Topology Optimization (the remaining 4). After this, several concepts were developed and one was chosen for deeper investigation in the autumn semester in regards to topology optimization, control methods, mechanical design and as well as simulations based development.

The group coordinated the day-to-day plans via WhatsApp, share files on Google Drive, schedule activities with a shared Google Calendar, and will in autumn manage further code and files in a GitHub repository. Roles are clearly defined: Project Coordinator, Project Manager, GitHub Manager, and two Report Managers.

2 State of The Art

This section will provide the SOTA for relevant technologies and methods of use when developing a soft legged robot. The research found while conducting the SOTA will then be used in development for the concept designs and eventual physical prototype. The following diagram presents the areas that were studied as a part of the SOTA analysis.

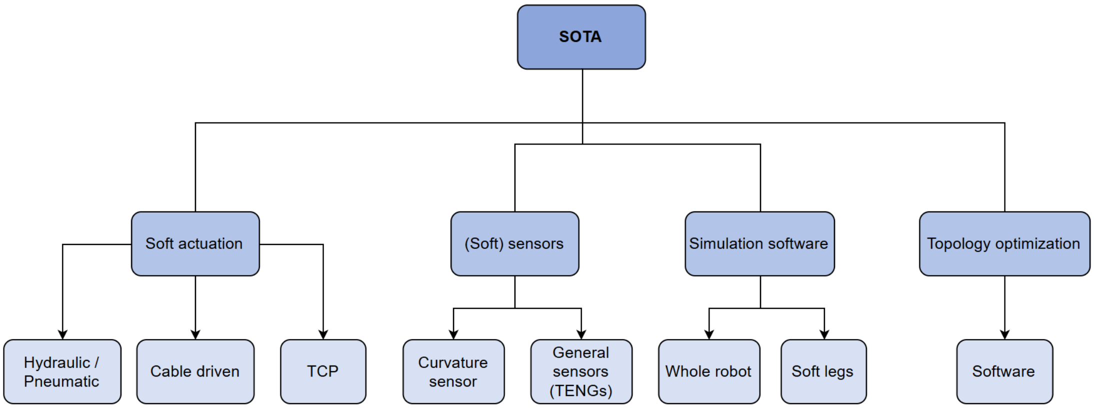

Figure 2.1: Diagram of fields studied in SOTA research

2.1 KTH's Soft Quadruped Robot

The current iteration of the robot, mentioned in section 1.1, utilizes a compressible tendon-driven soft actuator design. This design incorporates three cable tendons per leg, actuated each by a separate servo motor. In total, there are four legs and the coordination of these legs create the walking gait. The robot employs AI to perform tasks such as computer vision, environment perception, obstacle identification and avoidance, trajectory planning, gait control, feedback shape and speed control for each leg. 5G communication is used to offload all these AI computational tasks to an edge server [5].

2.2 Industrial Quadrupedal Robot Dog

2.2.1 Boston Dynamic Spot

Boston Dynamic's robot dog Spot was a pioneer in quadrupedal robot industrial. The robot dog consists of a compact body part and four rigid legs. Each leg is composed of an upper limb and a lower limb. One end of the lower limb touches the ground while the other end connects to the upper limb through ball screw mechanism and linkage system. As shown in 2.2, the knee motor drives the ball screw, converting rotary motion into linear displacement, thus the lower limb is either lifted or lowered, mimicking leg extension or retraction. The upper limb attaches to the body of robot dog via two independent motors, a tilt motor and a hip motor. The tilt motor controls the inwards or outwards rotation of the leg while the hip motor governs the forward or backward motion of the leg. The combination of these motors endows the robot dog with three degrees of freedom and enables it to stabilize on uneven terrain and more diverse features.

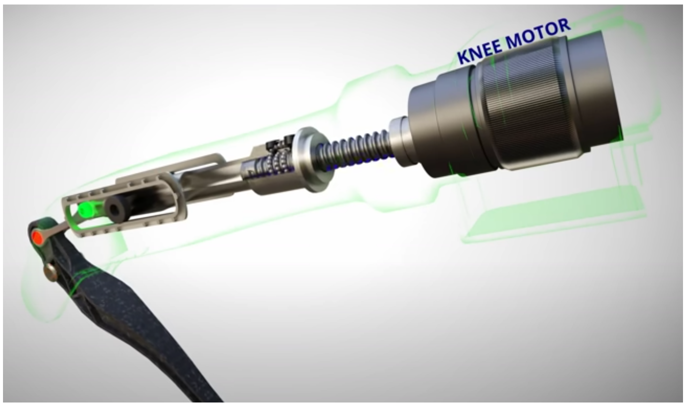

Figure 2.2: Connecting mechanism between upper limb and lower limb [6]

2.3 Soft Actuation

Soft robotics refers to robots designed to perform a task while having a soft body, where ”soft” is defined as materials with a Young’s modulus of $10^4 - 10^9$ [1]. Soft actuation refers to the mechanism used to actuate the robot (i.e wheels, legs, arms), which consists of soft materials. One common example is called ”grippers” which are composed of an arm paired with a gripping hand that can hold and manipulate objects. While some inspiration could have been drawn from this, the SOTA has primarily focused on soft actuation for locomotion and more specifically, walking.

2.3.1 Pneumatics & Hydraulics

The general solution for hydraulic & pneumatic actuation is the same. The pressure generated from the liquid or gas is used to inflate and deflate a flexible and hollow body as can be seen in Figure 2.3 One advantage of this actuation-method is that a lot of force and, therefore, actuation-power can be generated. Another advantage is that this method is not sensitive to elements and can be implemented in under-water applications. The disadvantage of the method is that the movement of the actuator is limited to one DoF.

When comparing pneumatics and hydraulics, hydraulics are often considered the more effective option, particularly in applications requiring high force output and precise control. One of the main challenges of using pneumatics in soft robotics is keeping the system untethered or suitable for extended use. This issue is illustrated in the previous work by R. Katzschmann et al. on a hydraulic fish robot [7], where tethering and the use of pneumatics significantly limited the robot’s autonomy. In our case, a tethered design would greatly reduce the robot’s usability. Additionally, pneumatic actuators tend to be more difficult to control than hydraulic ones, as demonstrated in the comparative study by Y. Feng et al. on soft robotic muscles [8].

What allows hydraulic actuation to be untethered is the ability to easily reuse the liquid. A very effective way to do this to use a peristaltic pump, which is bidirectional and also eliminates the need for valves [9]. An illustration of how the pump works can be seen in Figure 2.3.

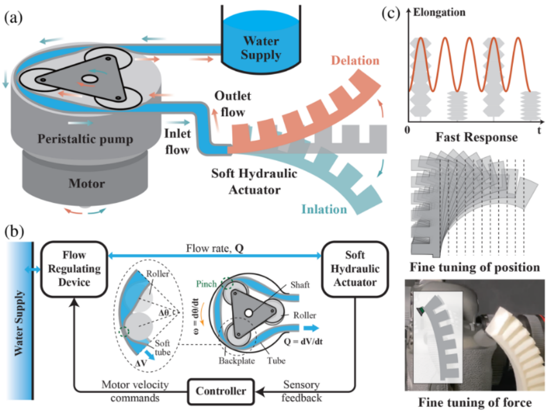

Figure 2.3: Peristaltic pump and how it works [9]

2.3.2 Wire Driven Tendon Actuation

A majority of wire driven soft actuation implementations are in the form of grippers or arms, with very few implementations in locomotion [1]. These implementations typically follow the same principle as the KTH robot, using two to three compressible wires, contracted by servo motors, that function as tendons for the dynamic actuation. There are some exceptions to this, with one in particular utilizing a hybrid approach of supercoiled polymer artificial muscles in conjunction with a servo motor to create the same principle as the tendon driven approach described previously, but with the wire acting as an actuator in and of itself alongside the servomotor[10].

Wire driven soft actuation differs from other forms of actuation by decoupling the force generation components from the point of motion. This brings some inherent advantages, namely a more stable center of mass during motion since the legs remain lightweight composed primarily of passive material and the embedded wires for actuation. Another advantage is the ability to use electrical servo motors for actuation, providing the possibility of untethered movement with onboard batteries [2].

One notable disadvantage of wire driven actuation is the limited durability of the wires. Continuous contraction and extension make them susceptible to fatigue-related failure, making this a likely point of maintenance.

2.3.3 Twisted String Actuation

Twisted cables have been used for centuries to convert rotational motion to linear actuation. The principle of twisted string actuation is quite simple: by twisting two or more wires which are parallel to each other, they form a helical structure. Seeing as the strings are of a predefined set length, when they are twisted, the projected length of the strings necessarily have to be shorter when twisted if no elongation has occurred as can be seen in Figure 2.4 [11].

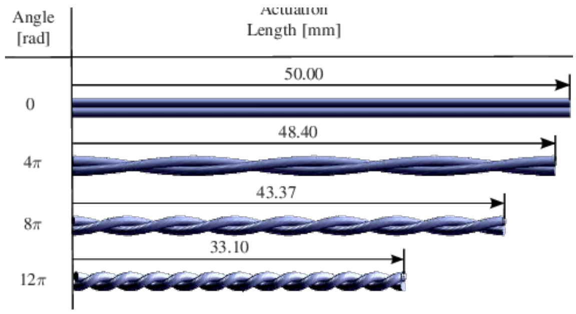

Figure 2.4: Basic concept of twisted string [11]

Compared to a regular pulling wire system, the contracted wire doesn't have to be stored anywhere seeing as system itself will simply shorten. The twisted string actuation also allows for more wires to be easily added for added strength.

However, the twisted wire actuation faces a problem when it comes to the contraction length compared to regular. If the cable is contracted to the point where the projected length of one rotation is shorter than the diameter of a single strand, the twisted wire may twist around itself, leading to unpredictable behavior.

2.3.4 TCP Actuation

Recently, Twisted and Coiled Polymer (TCP) muscles shown in Figure 2.5 have emerged as a promising class of thermally driven actuators for use in soft robotics, due to their high strain capability, low operational voltage, and cost-effective fabrication process. Mature TCP-based systems, such as SoroAgilHand-1 [12], have demonstrated integrated modeling, fabrication, and control for stable and repeatable actuation.

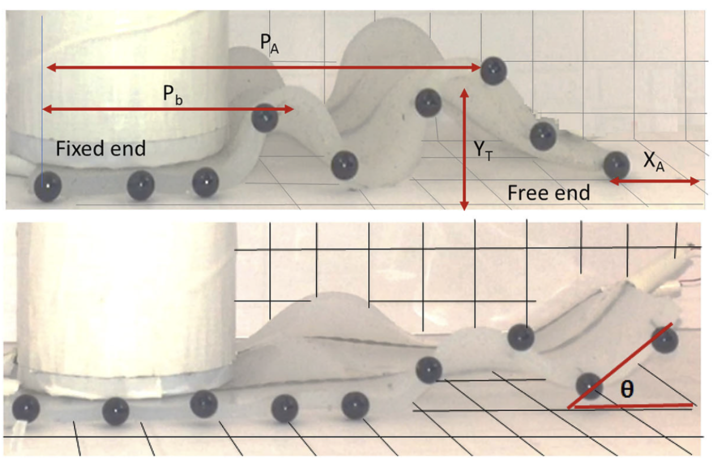

Figure 2.5: Deformation of TCP muscles [13]

Compared to other smart actuators, TCP muscles offer several advantages including silent operation, relatively low input voltage, lightweight design, and compatibility with soft elastomers. Moreover, the fabrication of TCPs involves low-cost materials like silver-coated nylon and standard mechanical twisting, making them accessible for scalable implementation. Additionally, recent work [14] has shown that functionally graded materials (FGMs) can be directly 3D-printed to create soft robotic joints with tunable stiffness, enabling smooth transitions from rigid to flexible regions for improved deformation control.

Nevertheless, TCP actuators face several challenges. Most notably, they suffer from slow actuation speeds due to their reliance on resistive heating and natural convection for cooling. Their energy efficiency remains low. Almubarak and Tadesse [13] demonstrated that the performance of TCPs may vary significantly depending on the uniformity of the precursor fibers, degree of coiling, and annealing/training procedures, contributing to inconsistencies in strain output and actuation force across different fabrication batches.

2.4 Sensors

In soft robotics, sensors play a key role in helping robots sense their environment, adapt to changes, and move intelligently. Because soft robots are built from flexible materials, they often operate in unpredictable settings and need sensors that can bend, stretch, and keep working under significant deformation. Unlike rigid sensors, soft sensors have to be embedded directly into the robot's flexible body without interfering with how it moves. For a soft robot, these sensors are especially important for knowing the position of its limbs (proprioception), controlling its gait, and avoiding obstacles. This section looks at recent progress in soft sensing technologies that help make movement more adaptive and reliable.

2.4.1 Curvature Sensors

Curvature sensors are soft sensing devices designed to detect bending, deformation, and shape changes in flexible robotic structures. By providing real-time feedback on limb or body curvature, they are essential for enabling proprioception in soft robots. This capability is particularly important in soft quadruped robots, where continuous joint deformation occurs during locomotion and must be tracked to maintain coordination, balance, and terrain adaptability. These sensors operate by transducing mechanical curvature into measurable signals, typically electrical resistance or light intensity. Several types have been developed for soft robotics applications.

An example is optical curvature sensors, which are sensors that incorporate optical fibers within soft substrates. When the material bends, the fiber bends with it, causing changes in light intensity, usually due to loss or interference. These changes can be measured and linked to how much the sensor is bending. The connection between curvature and light intensity is usually determined through experiments or computer simulations, depending on how the sensor is designed. The advantages of optical curvature sensors are their high resolution and sensitivity, which make them suitable for complex shape estimation and tracking of limb position. However, on the other hand, they tend to be expensive, require precise alignment, and are more fragile than other types. This makes integration into dynamic soft robotic systems more challenging [15] [16].

Resistive flex sensors are another widely used type. These sensors change its electrical resistance as it bends. As the sensor bends, the material stretches, causing a proportional increase in electrical resistance. This change is then converted into a voltage signal that represents the degree of curvature. The resistance R increases with curvature due to elongation of the conductive path, typically modeled using the following:

$$R = R_0(1 + \epsilon) \tag{1}$$

where R_0 is the initial resistance and ϵ is the strain induced by bending. The strain can be related to the curvature κ by the following approximation:

$$\epsilon = 2t\kappa \tag{2}$$

with t being the thickness of the sensor. This makes it possible to estimate the curvature by voltage measurements in a voltage-divider circuit. These sensors are low-cost, easy to integrate and suitable for real-time feedback systems. But, they are also less precise than optical sensors and subject to mechanical fatigue over time, which can affect long-term stability [17].

2.4.2 Triboelectric Sensors

Triboelectric sensors are self-powered sensing devices that convert mechanical stimuli such as pressure, touch, vibration, or motion into electrical signals between two dissimilar materials [18]. They use the coupling effect of contact electrification (CE) and electrostatic induction, and they have the advantages of low cost, easy fabrication, diverse choice of materials, and broad range of applications. Based on the direction of polarization change and the configuration of the electrodes, four different operation modes have been proposed for the TENG: vertical contact-separation (CS) mode, lateral-sliding (LS) mode, single-electrode (SE) mode, and freestanding triboelectric-layer (FT) mode [19], as illustrated in Figure 2.6 . Recent advances have demonstrated their integration into wearable electronics, artificial skin, and soft robotics, where they effectively detect pressure, touch, motion, and even subtle biomechanical signals [20].

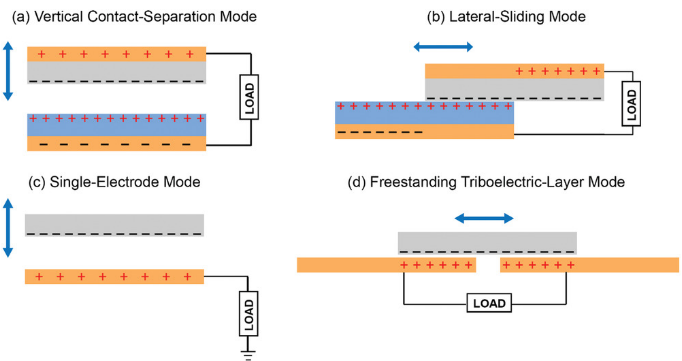

Figure 2.6: Four working modes of TNGs [19]

For quadruped robots, particularly those designed for dynamic locomotion or rough terrain traversal, triboelectric sensors offer an ideal solution for footpad sensing. Their thin and flexible form factor allows seamless integration into the robot's feet, while their high responsiveness to contact and force enables real-time feedback for gait analysis, terrain adaptation, and balance control. Moreover, the self-powered nature of triboelectric sensors reduces the energy burden on the robot, which is crucial for untethered or long-duration operation in field environments.

2.5 Topology Optimization

The concept of topology optimization can be summarized as finding the optimal shape for a part based on its intended use. The definition of optimal depends on how we measure it; it could be minimizing the size, mass, deformation or other factors. To determine what is optimal, the objective must first be defined, and then optimality must be determined in relation to that objective. This leads to the formulation of an optimization problem.

Furthermore, to help us solve this optimization problem, constraints must be determined. In the context of topology optimization, constraints correspond to physical rules and conditions, including but not limited to loads, boundary conditions, and other requirements [21].

There are several software available for topology optimization; ANSYS [22], Fusion 360 [23], SolidWorks [24], and Abaqus [25] all include topology optimization modules. Generally, topology optimization is performed by specifying constraints, objectives, or loads. The software uses Finite Element Method (FEM) to evaluate each element and to determine its rigidity, compliance, or redundancy. Elements are assigned a value between 0 and 1, where 0 indicates removed material and 1 indicates solid material [21]. The software can then construct the optimized part based on these values.

Another approach to topology optimization is to use MATLAB, either with custom code [26] or toolboxes such as FreeTO [27]. Different optimization methods can be implemented, including SIMP, MMA, or others.

2.5.1 SolidWorks - Topology Study

SolidWorks Topology Study has been widely used by researchers for the purpose of topology optimization of both rigid body and soft structure. Using SolidWorks Simulation toolbox, users can optimize the geometry of 3D models to meet specific design criteria. The workflow begins by importing a 3D model and assigning a specific material to the body. Next boundary conditions such as fixture, mechanical connections and external forces are applied as demanding. To balance computational efficiency and accuracy, the mesh quality can be adjusted accordingly. Finally, the goals of optimization can be defined from various constraints including minimize maximum displacement, minimize mass, best stiffness to weight ratio, and factor of safety constraint. SolidWorks iteratively converges toward an optimal solution by simultaneously prioritizing at least two of these objectives. As illustrated in Figure 2.7, yellow indicates the area that must be kept while blue areas can be removed.

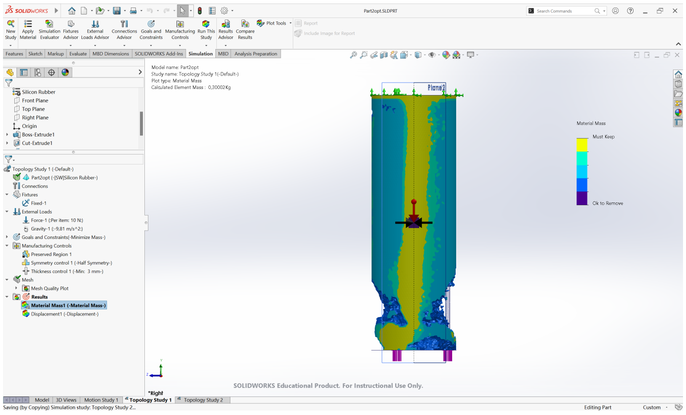

Figure 2.7: SolidWorks topology study

2.5.2 Fusion 360

Fusion 360 includes a topology optimization module that uses generative AI, integrating finite element method (FEM) simulations to refine part geometry. Users define critical design constraints, such as preserved geometry, material properties, boundary conditions, and load cases. The solver evaluates the structural response under the specified conditions and optimizes the topology based on performance objectives such as minimizing mass or deformation. The result is a set of design alternatives, from which the user can select a final concept for refinement or fabrication.

2.5.3 ANSYS

ANSYS supports topology optimization to a much greater degree and offers more freedom than the other software mentioned. Additionally, ANSYS provides more in-depth finite element method (FEM) analysis, eliminating the need to use multiple software tools. All steps, from topology optimization to generating 3D-printable shapes, can be performed within the same software [22]. The work process in ANSYS occurs in similar way as in SolidWorks, see section 2.5.1. It is important to note that this comparison was made between software options available to the project members and KTH.

2.6 Simulation Software

The scope of this section is to focus on the simulation tools for soft robotics instead of general robotics. Unlike traditional rigid robots, simulation and control of soft robot is more complicated due to its nonlinear deformation, time dependency, and larger computation cost. Choosing the right simulation software that can accurately show the motion of the soft robot is the key concern.

The criteria for selecting simulation software are considered from three aspects. Firstly, the simulator should model realistic soft-body instead of spring-damper-mass approximations, which potentially cause deviation from reality and simulation. Secondly, it is expected that the software can support for reinforcement learning since it could be a suitable candidate for gait controller design. Also, since the previous prototype used ROS as the host computer, the simulation software should be compatible with ROS to inherit from the existing design.

In this section, software that can perform simulation on one soft leg will be introduced first. After that, whole body simulation platform will be discussed.

2.6.1 Soft Leg Simulation

SOFA Soft robotics is a relatively new research area, which means that dedicated software is not yet widespread, and only a few platforms support fully soft materials. The most promising one is the SOFA Framework [28], which is "an open-source framework for interactive mechanical simulation, with emphasis on biomechanics and robotics."

This software emphasizes applications in medical technologies, which is also where many advances in soft robotics are currently applied. It is open-source and compatible with any operating system. The SoftRobot plugin [29] enables the simulation of fully soft and deformable materials, making it suitable for modeling fully soft legged robots. Various actuation methods, such as tendon-driven and pneumatic, can be simulated, and a built-in simulation environment allows users to visualize the results.

MATLAB Another simulation tool that can be used for simulating fully soft materials is MATLAB, specifically the SoRoSim [30] and Sorotoki [31] toolboxes. SoRoSim uses a Geometric Variable Strain model, which is less computationally expensive than FEM. One of the advantages of this toolbox is its compatibility with other MATLAB toolboxes, which can be used for optimization or parallel computation. Cable actuation is also supported.

Similarly, Sorotoki is an open-source toolbox for the design, modeling, and control of soft actuated robots. Its modeling is based on FEM, which provides high accuracy but can be slow to run on a computer. Sorotoki is also more focused on pneumatic and hydraulic applications.

2.6.2 Whole Robot Simulation

MuJoCo More researchers in the field of soft robotics are adopting MuJoCo as their physics simulation engine due to its robust support for soft-body dynamics, including soft contact constraints, muscle- and tendon-based actuation, and compliant materials such as ropes and cloth [32], [33]. Reinforcement learning is a widely used method for designing gait controllers. MuJoCo integrates seamlessly with several popular reinforcement learning frameworks, such as OpenAI Gym. It is proved that the simulation accuracy of MuJoCo, especially when used in reinforcement learning applications is quite high compared with real world force data [34]. One of the most significant advantages of MuJoCo is that it can deal with complex dynamical systems in contact-rich behaviors. It is the first full-featured simulator designed from the ground up for the purpose of model-based optimization, and in particular optimization through contacts. While MuJoCo is not natively compatible with ROS/ROS2, it can still be integrated with ROS through custom interfaces or third-party tools.

NVDIA Isaac Sim In contrast, NVIDIA Isaac Sim is also widely used in soft robot simulations due to its native ROS/ROS2 intergration for control and data streaming. Therefore, it has more advanced functions, such as validating sensor fusion algorithms, supporting sensor simulation of cameras, LiDAR, RGB-D, and performing path planing using SLAM. Although PhysX 5 and Omniverse extensions theoretically enable soft body simulation within Isaac Sim, not much available material can be found online. In practice, instead of simulating soft material, the soft components are typically approximated by a mass-spring-damper system, which may introduce inconsistency between simulation and the real robot. Notably, Isaac Sim has access to over 1,000 SimReady 3D assets, including conveyors, boxes, and pallets to build the simulation scene [35]. One worth noting advantage over MuJoCo is that NVIDIA Isaac Sim supports GPU-Accelerated RL Training for Robotics, which significantly speeds up the training.

Gazebo Gazebo is another open source 3D robotics simulator designed to model and test complex robotic systems in realistic environments. Compared with MuJoCo and NVIDIA Isaac Sim, it supports a wide array of sensors, including cameras, LiDAR, IMUs, GPS, and more with realistic noise models [36]. The modularity enable Gazebo extends its functionality through C++/Python plugins in simulation, transport distributed message, sensor integration, physics engine, and rendering engine. Similar to NVIDIA Isaac Sim, Gazebo can seamlessly work with ROS/ROS2 for real-world robot control and data pipelines, making it suitable for hardware-in-the-loop testing and real world deployment. However, Gazebo's support for soft body dynamics is limited when compared to MuJoCo and SOFA. While reinforcement learning is feasible in Gazebo, it generally requires more manual setup and lacks the GPU acceleration and native RL support in Isaac Sim.

MATLAB Lastly, MATLAB can be used to simulate the whole robot, as it has been done with current KTH robot. A series of spring-damper-mass is used to represent the soft legs of the robot. This is the main disadvantage of using a simple Simscape model: the non-linearity of the material cannot be properly modeled. However, this approach is the most simple and straightfoward for our project, since a reference model already exists.

3 Concept Development

3.1 Leg Actuation

In this section, design concepts for the leg design will be presented. The initial concepts for the robot which is to be designed originated from the current robot made by previous years master students for their respective master thesis [2–4]. The process of concept development started with a brainstorming session where some ideas were brought up by the group. During the semester, the ideas were further refined and some more concepts were brought up. Finally after a meeting with the stakeholder of the project, the ideas were brought more in line with the previous project design.

3.1.1 Iteration on Current Design

The first concept is an iteration of the current leg as it stands after the work done in the master thesis by David Daniella & Shuo Fu. The main idea for this concept is simply to optimize the topology of the leg while integrating twisted wire actuation as discussed in section 2.3.3.

Advantages:

- Comparability: Seeing as the design would be very similar to previous years, the direct comparison between the two in several metrics would be easy to perform.
- Simplicity: There would be a greater possibility to reuse some code and simulations, saving the team some time.

Disadvantages:

- Limited movement and speed: The current design has some speed limitations based on the limited angle of the leg rotation.
- Robustness limitations: The current design has some inherent issues regarding long term durability which causes parts to stop working.

3.1.2 Current Design with Joint

Following the current design, an idea was brought up where the angle of the legs could be increased to allow greater mobility if an additional joint was added to the upper part of the leg as can be seen in Figure 3.1. This design and the previous design discussed in section 3.1.1 could be seen as the same design with regard to the problem of topology optimization of the leg.

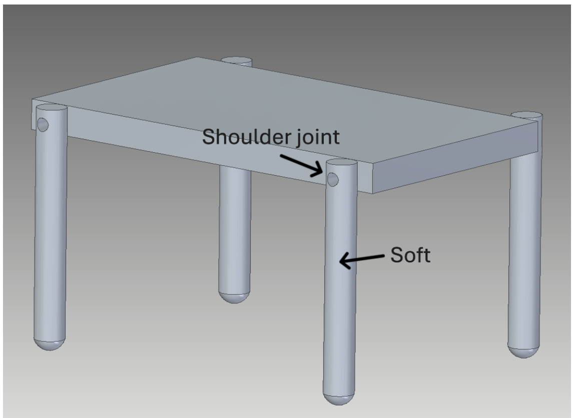

Figure 3.1: Basic CAD model of jointed design

Advantages:

- Increased mobility: Adding a shoulder joint expands the leg's range of motion, allowing it to reach more positions, adapt more easily to uneven terrain, and even climb.
- Improved locomotion control: The additional DoF (Degree of Freedom) allows for more complex gait patterns and dynamic adjustments.

Disadvantages:

- Higher control demands: More degrees of freedom require more complex control algorithms and possibly more sensors and actuators.
- Reduced omnidirectionality: The shoulder joint provides benefits primarily for forward motion and becomes ineffective when the robot moves in other directions.

3.1.3 Rotating Leg

To increase the robots omnidirectional capabilities, a proposed concept is one where the leg part itself would have one degree of freedom, but would be able to freely rotate around its central axis. This can be seen in Figure 3.2. The idea here is that the amount of motors required to drive the leg could be reduced by one, while also simplifying the gait controller.

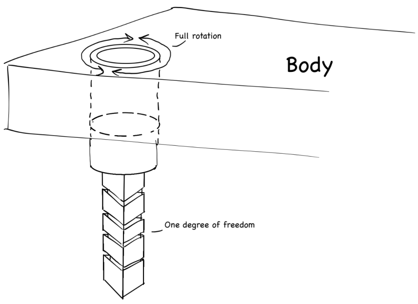

Figure 3.2: Drawing of rotating leg design

Advantages:

- Increased omnidirectionality: Rotation allows for directional adjustments without full body reorientation, improving agility.
- Reduction of number of motors: There would only need to be 2 motors per leg instead of 3, reducing weight and cost.

Disadvantages:

- Mechanical challenges: Implementing a reliable rotating joint that can bear weight and operate smoothly under dynamic loads may be non-trivial.
- Control challenges: The gait controller could be complex, with four legs being able to rotate freely.

3.1.4 Crab Design

The “crab” design follows a similar principle as the design brought up in section 3.1.3. This design however, consists of a two-jointed leg with an “upper” stiff part that can rotate and a “lower” soft part that can be actuated in many different ways. This concept, as can be seen in Figure 3.3, uses the same actuation method as the current robot, meaning cable actuation, but with only one degree of freedom. The lower part would be actuated when the “foot” needs to be lifted up from the ground, and the soft part would not contribute to the forward motion of the robot.

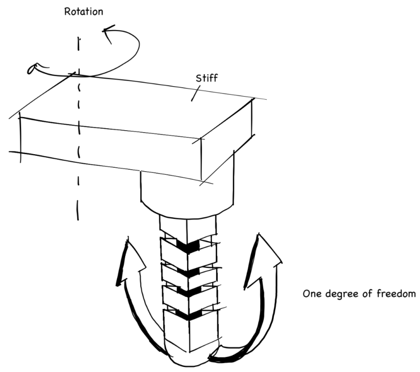

Figure 3.3: Drawing of crab design leg

Advantages:

- Speed: The added hard actuated part of the leg could give the leg a greater stride thus making it go faster.
- Simplicity for control: Having only two separate degrees of freedom simplifies the control.

Disadvantages:

- Not “doglike” enough: After talks with the stakeholder, the design was deemed too different from the previous project design.

3.1.5 Two-Jointed Design

The two-jointed design, as can be seen in Figure 3.4, mimics how a real dog moves. Unlike the “crab” design in section 3.1.4, where the rigid segment extends outward from the robot, this design directs the leg downwards. Both joints would be able to rotate freely, while still controlling the bending of the lower soft leg with cable actuation.

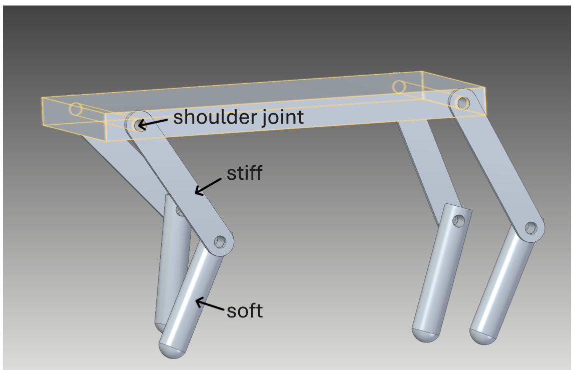

Figure 3.4: Basic Cad of two jointed design

Advantages:

- Biomimetic motion: Closely replicates the natural motion of quadrupeds, making it suitable for dynamic and stable walking or running.
- Greater range of motion: Two rotational joints allow for more precise control of leg trajectory, including swing and stance phases.
- Improved terrain adaptability: With multiple joints, the leg can better conform to uneven surfaces or obstacles.

Disadvantages:

- Added complexity: A double jointed system would possibly require a more complex gait-controller, which could conclude in the final project not having a fully walking robot.
- Actuation: Actuation of the lower soft leg becomes a difficult challenge with this design.

3.1.6 Linear Actuation

This concept is based on the principle of the “crab” design in section 3.1.4.

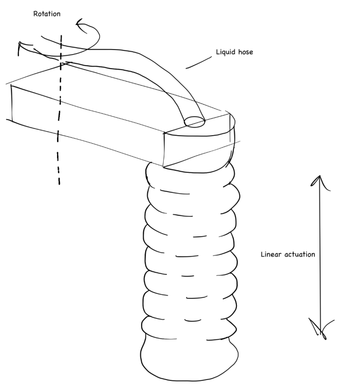

Figure 3.5: Concept idea sketch of linear actuation design

The mechanism shown in Figure 3.5 consists of a soft bellows-shaped actuator responsible for linear actuation (extension and contraction) when fluid is pumped into or out through the liquid hose. A rigid thigh allows rotational motion, enabled by a rotary joint. Fluid pressure controls the actuation, inflating the soft body to extend and deflating it to contract.

Advantages:

- Simple Actuation: The use of fluidics pressure for motion removes the need for complex motors or gears in the leg itself.
- Speed: The added hard actuated part of the leg could give the leg a greater stride thus making it go further with each stride.

Disadvantages:

- Durability and Fatigue: Soft materials are prone to wear and leakage over time, especially under continuous movement and pressure cycles.
- Limited Load-Bearing Capacity: Soft actuators often lack the stiffness needed for supporting heavy loads or fast dynamic motions.
- Limited movement of the robot: Only the hard part of the leg actively contributes to the motion of the robot.

3.2 Control Strategy

The final control strategy will depend on the structural design that is ultimately implemented. The objective would be to reuse the already existing control code, while modifying and adapting the control algorithms according to changes in the mechanical architecture. In the selected design, the control strategy is hierarchically divided into two main parts: Shoulder Joint Control and Soft Leg Control.

3.2.1 Shoulder Joint Control

The shoulder joint plays a key role in enabling the swing motion of the leg, facilitating forward and backward movement. It is planned to be actuated using position control, which ensures precise trajectory tracking during swing phases.

3.2.2 Soft Leg Control

The soft leg is controlled using a closed-loop impedance control strategy, which uses feedback from foot pressure sensors. This approach continuously regulates mechanical impedance, specifically stiffness and damping, in response to varying ground contact conditions:

- Low stiffness is applied when increased compliance is desired, e.g., during contact with uncertain or uneven terrain.
- High damping is employed to absorb shocks, particularly during landing or sudden load changes.

By leveraging feedback from foot pressure sensors, the robot can achieve the balance between stability and compliance, which is essential for real-world unstructured environments.

3.2.3 Foot Pressure Sensors

To enable effective closed-loop impedance control, capacitive pressure sensors will be used, and they will be placed at the bottom of robot's foot. Capacitive pressure sensors operate based on changes in capacitance caused by the deformation of a dielectric material under mechanical load. These sensors are selected for their high sensitivity and flexibility, and it is able to conform to the soft structures of the leg. Moreover, this type of sensor is technically mature, which makes it easy to integrate into embedded systems and to write control code.

In the soft leg's control loop, these pressure sensors are embedded in the foot pads to monitor ground contact forces. The real-time data is mapped to modulate stiffness and damping parameters using a pre-calibrated impedance model. Furthermore, if time allows, other sensors could be added, such as inertial sensors or joint encoders, in order to enhance system robustness. The multi-sensor fusion strategy can contribute to better slippage detection and terrain adaption. The details of control strategy and algorithms still remain to be further discussed in the next stage.

3.3 Concept Evaluation

A concept evaluation stage was done to determine the best leg design, simulation software and topology optimization software. These evaluations have been done by making matrices containing relevant criteria, each assigned an importance rating from 1 (least important) to 5 (most important). Each concept was scored from 1 to 5 for each criterion. The total score for each concept was calculated by multiplying the importance rating by the assigned score for each criterion. The concept with the highest total score is considered the most suitable.

3.3.1 Leg design

For the leg design, different concepts ideas were compared based on various relevant aspects such as stability, speed, safety, complexity, predictability, and cost.

Initially, the two-jointed design, as can be seen in Fig 3.4, was favored, as it incorporates both fast operating speed and good stability. However, after meeting with the stakeholder, it was emphasized that the new design should not deviate significantly from the current dog-like shape. As shown in the evaluation matrix in Table A.1, the best solution is the design of adding a shoulder joint to the current design, shown in Figure 3.1. This approach maintains the overall shape while the rotating shoulder increases the range of leg movement, thereby improving both speed and robustness.

3.3.2 Topology Optimizer

For the topology optimizer, the criteria are the following: access, learning curve, accuracy, topology optimization toolbox, flexibility and force tracking capabilities. The definition of these criteria, as well as the evaluation table, can be found in Appendix A. With the highest score, ANSYS seems to be the best option.

3.3.3 Whole Body Simulation

In this section, the different simulation software programs and toolboxes were compared to decide on the main platform at which the robot simulations will take place. The criteria are similar to the previous evaluation: access, learning curve, accuracy, soft leg simulation, flexibility, inheritability, ROS compatibility and reinforcement learning toolbox. Matlab Simulink has been selected, since the score is the highest, mainly due to the fact that the team can modify and build upon already existing code. This gave an advantage to this software. The table, and definition of criteria, can be found Appendix A.

4 Discussion and Conclusions

Based on the information gathered over the course of the SOTA and discussions with stakeholder, as well as evaluating different concepts, a choice was made to continue with the “Current design with joints” 3.1. Notably, this design was the preferred concept for the stakeholder, as it extends the existing Royal Institute of Technology (KTH) robot, which is a key criterion, and it also was the concept with the most points in the evaluation matrix, meaning that it was the concept which fulfilled the most project requirements.

It is important to note that although the selected concept is the “Current design with joints”, the selection and design process was multi-step and iterative, with not all steps being documented in this report. Due to an iterative process of determining clear requirements and project goals for the project, this process has been extra time consuming and challenging.

Regarding topology optimization and leg shape selection, the majority of the work so far has been about determining the best approach, so using software, apply mathematical methods, or adopt a trial-and-error strategy. The selected methodology that will be applied during the Autumn term is the following: first, the current leg design will be analyzed using FEM to identify potential improvements. Then, various software tools, such as ANSYS, SolidWorks, and Fusion 360, will be used to generate new leg designs through their topology optimization modules. One optimized design will be selected from each software. Additionally, new designs will be introduced by the group, in order to do comparisons in performs between the toolboxes, current design and new group designs. Out of all these designs, the two most promising ones will be 3D printed and further examined by testing different printing parameters. The best-performing model among the two will ultimately be used in the robot.

4.1 Risk Analysis

A risk assessment has been done by the group, based on situations that can occur during the project, and can be found in Appendix B . The analysis has been done to determine risks regarding the robot itself, the completion of the project and finally the safety of the group members.

5 Plan for the Fall

5.1 Project Plan

In the fall term, the goal will be to go from a concept to a fully functioning prototype. To get to this result, the following steps will be followed:

- Finalize the concept and develop it (CAD, schematics and plans, leg design)
- Meanwhile, build the simulations and code the gait controller in parallel
- Build a one-leg setup, verify the gait controller code
- Build the whole robot and adjust gait for walking
- If time allows, add path finding and 5G edge computing

The project Gantt chart, which details when these steps will be arranged and scheduled, is presented in Appendix C.

5.2 Future Organization

For the next phase of the project, comprising of detailing the design of the robot and beginning the simulations, the team will be split into three groups of three: the mechanical design group, which will work on the overall robot structure and actuation; the leg design group, which will focus on finding an optimal leg shape and handle the 3D printing; and the simulation group, which will collaborate with the mechanical group to develop a full-body simulation of the robot. This last group will also begin developing the gait controller so that it is ready to use as soon as the robot is assembled.

Once the leg and mechanical designs are completed, the groups will be divided again. Some members will focus on the physical construction of the robot, while others will work on the coding. If everything goes smoothly and assembly is efficient, all members should be working on the code by the end of the project, either for the gait, path finding or other.

Since all members of the team will have more availabilities next semester, it is expected that the meetings will be held on a more regular basis, at the same time every week. The stakeholder will also be met on a semi-regular basis.

5.3 Purchasing

Since the design has not been finalized, no purchases will be made during the Spring term. However, the most critical components, namely the sensors and motors, have a delivery time of less than two weeks. As the design will be finalized during the first weeks of the Fall semester, the parts will be ordered then and should be available shortly after for assembly. The robot body and legs will either be 3D printed or built using easily accessible materials such as wood or plastics.

References

[1] Seshagopalan Thorapalli Muralidharan Georgios Andrikopoulos, Lei Feng. "A Survey on the Current Trends and Applications of Design Optimization for Compliant and Soft Robotics". In: *Proceedings of the 2023 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*. IEEE, 2023, pp. 47–53. DOI: 10.1109/AIM46323.2023.10196108.

[2] Thorapalli Muralidharan, Seshagopalan and Zhu, Ruihao. "Continuum Actuator Based Soft Quadruped Robot". MA thesis. KTH, Mechatronics, 2020, p. 72. URL: https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-286348.

[3] Danelia, David and Fu, Shuo. "Structure and Gait Optimizationof a Soft Quadrupedal Robot". MA thesis. KTH, School of Industrial Engineering and Management (ITM), 2021, p. 50. URL: https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-305510.

[4] Xuezhi, Niu. "Optimal Gait Control of Soft Quadruped Robot by Model-based Reinforcement Learning". MA thesis. KTH, School of Industrial Engineering and Management (ITM), 2023, p. 97. URL: https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-339056.

[5] Lei Feng. *Digital Futures Demonstrator project proposal*. Accessed: April 13, 2025. 2024.

[6] Vsauce. *The Banach-Tarski Paradox*. YouTube video. Accessed: 2025-05-20. YouTube, Nov. 15, 2023. URL: https://www.youtube.com/watch?v=tfWbE_1eCZk.

[7] Katzschmann, Robert K., Marchese, Andrew D., and Rus, Daniela. "Hydraulic Autonomous Soft Robotic Fish for 3D Swimming". In: *Experimental Robotics*. Ed. by M. Ani Hsieh, Oussama Khatib, and Vijay Kumar. Vol. 109. Springer Tracts in Advanced Robotics. Springer, Cham, 2016, pp. 405–420. ISBN: 978-3-319-23777-0. DOI: 10.1007/978-3-319-23778-7_27. URL: https://doi.org/10.1007/978-3-319-23778-7_27.

[8] Feng, Yunhao et al. "Safety-enhanced control strategy of a power soft robot driven by hydraulic artificial muscles". In: *Robomech Journal* 8.1 (2021), p. 10. DOI: 10.1186/s40648-021-00194-5. URL: https://doi.org/10.1186/s40648-021-00194-5.

[9] Wu, Shijian et al. "High-Performance Hydraulic Soft Robotic Control Using Continuous Flow Regulation and Partial Feedback". In: *IEEE Robotics and Automation Letters* 9.8 (Aug. 2024), pp. 6967–6974.

[10] Zhu, Honghui et al. "A Novel Soft Actuator Based on Mini DC Motor and Supercoiled Polymer Artificial Muscle". In: *Proceedings of the 2022 IEEE International Conference on Real-time Computing and Robotics (RCAR)*. Guiyang, China: IEEE, 2022, pp. 244–249. DOI: 10.1109/RCAR54675.2022.9872215.

[11] Palli, Gianluca et al. "Feedback Linearization of Variable Stiffness Joints Based on Twisted String Actuators". In: vol. 2015. May 2015. DOI: 10.1109/ICRA.2015.7139571.

[12] Wang, Man et al. “Design of TCP-actuator-driven, soft-tendon integrated anthropomorphic dexterous hand: SoroAgilHand-1”. In: *Sensors and Actuators A: Physical* 378 (July 2024), p. 115760. DOI: 10.1016/j.sna.2024.115760.

[13] Almubarak, Yara and Tadesse, Yonas. “Twisted and Coiled Polymer (TCP) Muscles Embedded in Silicone Elastomer for Use in Soft Robot”. In: *International Journal of Intelligent Robotics and Applications* 1.3 (Sept. 2017), pp. 352–368. DOI: 10.1007/s41315-017-0022-x.

[14] Hamidi, Armita, Almubarak, Yara, and Tadesse, Yonas. “Multidirectional 3D-Printed Functionally Graded Modular Joint Actuated by TCPFL Muscles for Soft Robots”. In: *Bio-Design and Manufacturing* 2.4 (Nov. 2019), pp. 256–268. DOI: 10.1007/s42242-019-00055-6.

[15] Chen, Wenbin et al. “Fabrication and Dynamic Modeling of Bidirectional Bending Soft Actuator Integrated with Optical Waveguide Curvature Sensor”. In: *Soft Robotics* 6.4 (2019), pp. 495–506. DOI: 10.1089/soro.2018.0061.

[16] Shi, F., Zhang, H., Ye, Z., et al. “Miniature optical fiber curvature sensor via integration with GaN optoelectronics”. In: *Communications Engineering* 1 (2022), p. 47. DOI: 10.1038/s44172-022-00049-w.

[17] Kramer, Rebecca K. et al. “Soft curvature sensors for joint angle proprioception”. In: *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems* (2011), pp. 1919–1926. URL: https://api.semanticscholar.org/CorpusID:2749678.

[18] Wang, Zhong Lin et al. *Triboelectric Nanogenerators*. Green Energy and Technology. Springer, 2016. DOI: 10.1007/978-3-319-40039-6. URL: https://link.springer.com/book/10.1007/978-3-319-40039-6.

[19] Wu, Changsheng et al. “Triboelectric Nanogenerator: A Foundation of the Energy for the New Era”. In: *Advanced Energy Materials* 9.1 (Jan. 2019), p. 1802906. DOI: 10.1002/aenm.201802906. URL: https://onlinelibrary.wiley.com/doi/full/10.1002/aenm.201802906.

[20] Zhang, Baosen et al. “Recent Progress of Bioinspired Triboelectric Nanogenerators for Electronic Skins and Human–Machine Interaction”. In: *Nanoenergy Advances* 4.1 (2024), pp. 45–69. DOI: 10.3390/nanoenergyadv4010003.

[21] *Topology Optimization: A New Frontier in Design*. Accessed: 2025-04-13. 2025. URL: https://formlabs.com/blog/topology-optimization/.

[22] *Ansys Topology Optimization*. Accessed: 2025-04-13. 2025. URL: https://www.ansys.com/applications/topology-optimization.

[23] *What is Topology Optimization?* Accessed: 2025-04-13. 2025. URL: https://www.autodesk.com/solutions/topology-optimization.

[24] *Topology Study - 2021 - SOLIDWORKS Help*. Accessed: 2025-04-13. 2021. URL: https://help.solidworks.com/2021/english/SolidWorks/cworks/c_generative_design_study.htm.

[25] *Abaqus Topology Optimization Module (ATOM)*. Accessed: 2025-04-13. 2012. URL: https://www.3ds.com/fileadmin/PRODUCTS-SERVICES/SIMULIA/RESOURCES/SIMULIA-Abaqus-Topology-Optimization-Module.pdf.

[26] Sigmund, Ole. “A 99 Line Topology Optimization Code Written in MATLAB”. In: *Structural and Multidisciplinary Optimization* 21.2 (2001), pp. 120–127. DOI: 10.1007/s001580050176. URL: https://link.springer.com/article/10.1007/s001580050176.

[27] Ibhadode, Osezua, Fu, Yun-Fei, and Qureshi, A. J. *FreeTO - Freeform 3D Topology Optimization Using a Structured Mesh with Smooth Boundaries in MATLAB*. SSRN preprint. Accessed: 2025-04-13. 2024. URL: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4876754.

[28] *SOFA Framework*. Accessed: 2025-04-13. 2025. URL: https://www.sofa-framework.org/.

[29] *SOFA Plugin*. Accessed: 2025-04-13. 2025. URL: https://softroboticstoolkit.com/sofa/plugin.

[30] MathWorks. *Creating SoRoSim: A MATLAB Toolbox for Soft Robotics Modeling and Simulation*. Accessed: 2025-04-13. 2025. URL: https://se.mathworks.com/company/technical-articles/creating-sorosim-a-matlab-toolbox-for-soft-robotics-modeling-and-simulation.html.

[31] Aasenbrood, B. J. C., Verschoor, J. C. G., and Misra, S. “Sorotoki: A Soft Robotics Simulation Toolkit for MATLAB”. In: *IEEE Robotics and Automation Letters* 9.2 (2024), pp. 1234–1241. DOI: 10.1109/LRA.2024.1234567.

[32] Riddle, Shane et al. “A Dynamic Simulation of a Compliant Worm Robot Amenable to Neural Control”. In: *Living Machines 2023*. Ed. by F. Meder et al. Vol. 14157. Lecture Notes in Artificial Intelligence. Springer Nature Switzerland, 2023, pp. 338–352. DOI: 10.1007/978-3-031-38857-6_25. URL: https://doi.org/10.1007/978-3-031-38857-6_25.

[33] DeepMind Technologies Limited. *MuJoCo: Multi-Joint dynamics with Contact*. https://mujoco.org/. Accessed: April 7, 2025. 2024.

[34] Bálint, Balázs András et al. “Benchmark of the Physics Engine MuJoCo and Learning-based Parameter Optimization for Contact-rich Assembly Tasks”. In: *Procedia CIRP*. Vol. 119. 33rd CIRP Design Conference. Elsevier, 2023, pp. 1059–1064. DOI: 10.1016/j.procir.2023.03.149. URL: https://doi.org/10.1016/j.procir.2023.03.149.

[35] NVIDIA Corporation. *Isaac Sim on Omniverse*. https://developer.nvidia.com/isaac/sim. Accessed: April 7, 2025. 2024.

[36] Open Source Robotics Foundation. *Gazebo Simulator*. https://gazebosim.org/home. Accessed: April 7, 2025. 2024.

A Appendix A: Evaluation Matrices

A.1 Leg Design Evaluation Matrix

Table A.1: Evaluation Matrix of leg design

Criteria (Weight)	Current design	Current design with joint	Rotation leg	Crab-design	Two-jointed design	Linear actuation
Stability (5)	3	4	3	4	5	3
Speed (5)	3	5	3	3	5	3
Predictability (3)	4	4	4	4	4	4
Safety (1)	5	5	5	5	5	5
Lower Complexity (2)	4	3	2	3	3	4
Cost (1)	5	5	4	4	4	5
Deviation from current robot (5)	5	5	1	1	1	1
Total Score	65	98	60	67	82	65

A.2 Topology Optimization Evaluation Matrix

Table A.2: Evaluation matrix of topology optimizer

Criteria (Weight)	ANSYS	SolidWorks	Fusion 360
Access (5)	4	1	5
Learning Curve (2)	1	4	3
Accuracy (5)	5	3	2
Topology Opt. Toolbox (5)	5	3	2
Flexibility (4)	4	3	2
Force Tracking Capabilities (5)	5	3	3
Total Score	113	70	74

The criteria mentioned in Table A.2 are important when comparing different software programs that provide topology optimization tools.

- ”Access” is regarding the accessibility of the software to students in the project.
- ”Learning curve” is regarding how fast a beginner can start to implement and simulate topology optimization in the software, given the time limitation and the size of the project, a less complex and more easier to learn program is desirable.
- ”Accuracy” is of course in regards to comparison between simulation results and real world results.

- ”Topology optimization toolbox” and ”Flexibility” criteria compare the quality of the topology optimization toolboxes provided by each software as well as how flexible these toolboxes are to be adjusted and integrated to various problems.
- ”Force tracking” compares how well each software can simulate the deformation simulations while performing the topology optimization, in other words a dynamic optimization and not a static construction.

A.3 Whole Body Software Evaluation

Table A.3: Evaluation matrix of simulation software

Criteria (Weight)	Gazebo	Matlab Sorotoki	Isaac	SOFA	Mujoco	Matlab Simulink
Access (5)	4	5	2	5	5	5
Learning Curve (2)	3	3	3	4	4	4
Accuracy (5)	4	4	3	5	5	4
Soft Leg Simulation (5)	1	4	1	4	3	2
Flexibility (4)	4	1	5	2	3	5
Inheritability (4)	1	1	1	1	1	5
ROS Compatibility (2)	4	2	4	3	4	5
Reinforcement Learning Toolbox (3)	5	3	5	3	5	4
Total Score	94	92	83	105	112	125

The logic here in Table A.3 follows the logic in Table A.2. The common criteria in both tables have similar definitions. For the new criteria:

- ”Soft Leg Simulation” quantifies if the software/toolbox can simulate real soft material and soft leg, and to what extent.
- ”Inheritability” is in regards to the current existing design and if the current model can be imported and used in the new software environment.
- ”ROS Compatibility” is as it sounds, meaning how well can ROS be integrated into and work with the software.
- ”Reinforcement Learning Toolbox” aims to see if the software provides reinforcement learning features and to what extend.

B Appendix B: Risk Analysis Table

Table B.1: Risk assessment table

Category	Risk or hazard	Consequence	Probability	Risk impact	Mitigation
Physical	Handling of electrical components	Burn, electric shock	3	2	Handle with care and read datasheets carefully to find the limits and other information about each component.
Physical	Batteries exploding	Burn	2	3	Check limits and battery quality, and beware when charging them.
Physical	Soldering injuries	Burn, breathing in toxic fumes	2	2	Handle with care - always solder two and two. Plan and double check before soldering.
Physical	Robot falls	Components breaking	2	2	Start testing the robot in small step, with no contact to the ground at first, then movement with support from members and finally fully indpendent movement. Have a backup of most important and hard to get parts.
Physical	Unreliable simulations	Delays in implementation of the gait of the robot	2	3	See design techniques for the current robot and or other robots - how is the simulation done for these? How are different components modeled. Discuss with supervisor regarding tips and tricks.
Physical	Unpredictable behavior of the robot	Getting hurt by the robot or robot components breaking	3	1	Restricted and safe area when testing the robot. Both regarding the safty of groupmemebrs and the robot itself.
Organizational	Falling behind schedule	Not being able to finish to project or be force to narrow the scope	4	3	Plan well and organized - every group member has a responsibility to finish and follow the taks in order for the group to succeed. Worst case, the project will be limited and the scope narrowed.
Organizational	Cost of part too high	Going outside the budget, making a expensive robot	1	1	Take care of the components that are purchased. Do calculations and verification of components before purchasing these to ensure each component is usable.
Organizational	Delays in delivery	Delays in the project, may lead to being unable to finish on time	2	5	Purchase as early as possible and see shiping times, as well as companies or websites that provide such components.

C Appendix C: Project Gantt Chart

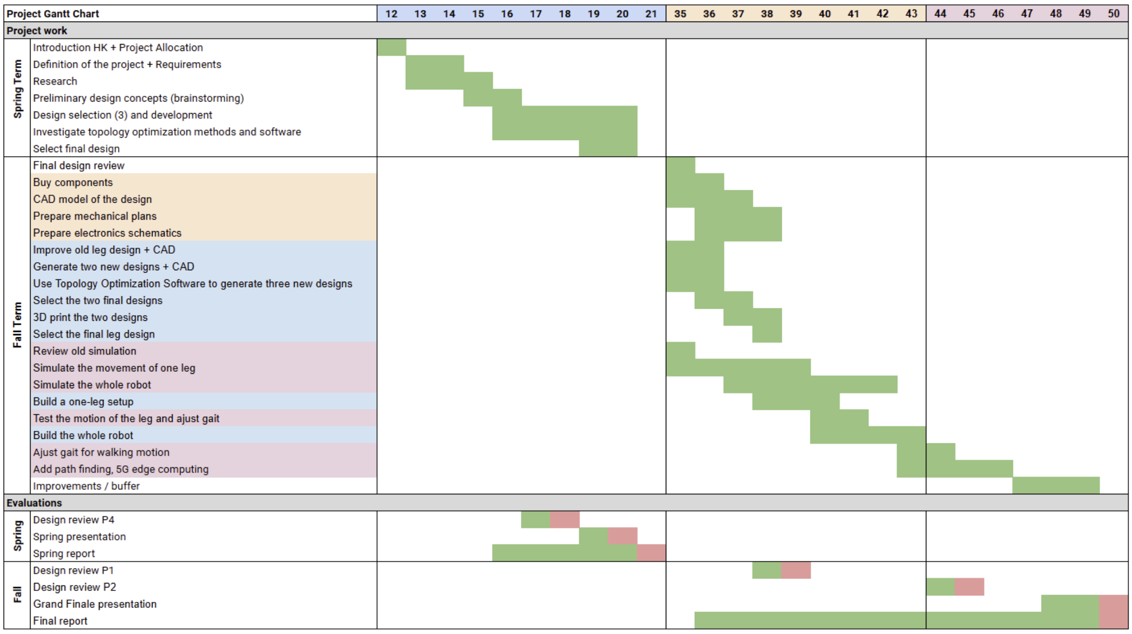

Figure C.1: Project Gantt Chart

As mentioned previously, the group will be divided into three subgroups during the Fall semester: the robot design group, the leg design group, and the simulation and gait control group. The tasks assigned to each subgroup are represented by different colors: yellow for robot design, blue for leg design, and red for simulation and gait control. Once the robot design is complete, its members will join the other subgroups, most likely the simulation group. The objective is for all three subgroups to work in parallel and later come together for physical prototyping. A small buffer has been included in the schedule to plan for potential delays.