Grover - A Forest Seedling Transporter

Skogforsk & SCA

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Abstract

300-400 million seedlings are planted manually each year by the Swedish forest industry. During this process workers walk an average distance of 20 km a day, in rough terrain, to resupply seedlings from the closest road. Due to this, Skogforsk in association with SCA, has given the task to develop and construct a seedling transporter capable of traversing rough terrain on primarily electric power. This report contains a state of the art of current technologies deemed relevant to this project as of 2022, a concept design for the proposed solution and a description of the implementation of the project, as well as discussion concerning the results. The parts of the vehicle were all designed using CAD software, and were then either ordered or manufactured in house with a laser cutter, water jet or a lathe among other tools and methods. The final solution is a hybrid of the designs studied in the state of the art. For suspension it utilizes pendulum arms with springs. It uses a split chassis for increased stability. The wheels are large enough that the individual ground pressure is less than that of a human. The chassis and four wheel drive combination enables efficient differential steering, driven by electric motors. The final rover is able to carry over 100kg of load. Not all requirements on the vehicle were met, but it can still provide its basic function.

Acknowledgments

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Contents

List of Figures

List of Tables

1 Introduction

This part of the report covers the background and scope of the project, as well as the metrics which the project will evaluated on at the end of the report.

1.1 Background

The Swedish forest industry is the world's fifth largest exporter of pulp, paper and sawn timber. Planting at least 380 million seedlings annually, a large majority of the planting process is done by manual labor. Today seedlings are delivered to a drop-off point at the forestation sites by traditional vehicles using gravel roads going through the forests. The seedlings are carried from the drop-off point by humans either in backpacks or satchels across the site to be planted. This means that a large part of a planter's day consists of walking back and forth between the drop-off point and the site.[14]

Skogforsk is the forestry research institute of Sweden whose mission is to develop and communicate knowledge, services and products to support greater sustainability in forestry, now looking into improving the tree planting process on site. There are many projects which investigate possibilities for improving the planting process, such as using automatic planting vehicles or drones for the transportation of seedlings. At the request of Skogforsk this report will evaluate and develop a land vehicle for transporting seedlings. [1]. The goal is to alleviate the load on the workers currently completing this task by letting them operate a remotely controlled vehicle carrying a part of the load.

1.2 Scope

The scope of this project is to design and manufacture a remote controlled vehicle capable of carrying seedlings through rough terrain. To this end the final design should aim to have the ground pressure be as low as possible while having good mobility and stability. The vehicle should be able to operate under normal working conditions for an extended period of time. It should also have the means to extract itself or easily be extracted by hand, should it become stuck in the terrain.

There are several limitations placed upon this project which are presented in the requirements section in full. However, there are several points of lesser importance to the stakeholders that can still be pursued, time and budget allowing. This is due to this project being part of a larger push from Skogforsk to develop a fully automated forest industry. To this end, room could be allocated on the vehicle to support the implementation of sensors and cameras to be used by another project down the line.

1.3 Requirements

Skogforsk provided several technical requirements which proved not to be exhaustive and left a lot of room for different solutions. Additionally, it became apparent in talks with Skogforsk that some of these requirements were considered more as guidelines, and that as long as the primary purpose of the vehicle was met, some requirements could be ignored.

1.3.1 Stakeholder Requirements and Guidelines

The stakeholder requirements were simply to design and construct a remote controlled vehicle capable of carrying seedlings across rough terrain. The vehicle should have good mobility, stability, reliability and be able to keep up with walking pace. To that end, a list of **requirements** was given:

- The speed of the vehicle should be in the interval of 0 to 3 m/s, i.e. walking pace.

- Ability to operate on soft soil (peat soil).
- Maximum unloaded weight of 200 kg.
- Load capacity matching or exceeding 50 kg.
- Remotely controlled by user in close proximity.
- Utilizing the ROS interface.
- Maximum hardware cost of 50 000 SEK.
- The vehicle should fit inside a standard trailer.
- The vehicle should be electric.

These were accompanied by a list of **guidelines**:

- Diameter of each wheel must be more than 300 mm.
- The vehicle should be capable of a ground clearance of at least 500 mm.
- All wheel drive (or at least 75 percent of the wheels).
- Operational temperature of 0 to 40 degrees Celsius.
- Weather protection of at least IP54 for parts exposed to the ground and IP44 for higher placed parts.

1.3.2 Technical Requirements

After considering the two lists made by the stakeholders, and an analysis of the problem, the final technical requirements were decided as follows:

- The speed of the vehicle should be in the interval of 0 to 3 m/s, i.e. walking pace.
- The vehicle should be capable of a ground clearance of at least 500 mm.
- All wheel drive (or at least 75 percent of the wheels).
- Ability to operate on soft soil (peat soil).
- Operational temperature of 0 to 40 degrees Celsius.
- Maximum unloaded weight of 200 kg. It should be easily recoverable if it gets stuck.
- Load capacity matching or exceeding 50 kg.
- Weather protection of at least IP54 for parts exposed to the ground and IP44 for higher placed parts.
- The vehicle should be remotely controlled by user in close proximity.
- Maximum size while transported of 250x130 cm.
- The vehicle should be able to climb a slope of 20°.
- The vehicle should utilize the ROS interface.

2 State Of The Art

The State of the Art includes an analysis of previous work concerning similar projects with potential applications for our concept design.

2.1 Mars Rover

Mars rovers are moving vehicles used for exploration on the surface of Mars. Until now, seven rovers around the world have successfully landed on Mars and conducted exploration work. Mars rovers are typically used to travel over uneven terrain, climbing over rocks and other obstacles, while maintaining vehicle balance and moving smoothly. The difficulties that the rover needs to overcome are in line with what this project is looking for. Therefore, a design similar to the Mars rover could be an option for this project. Figure 1 shows a typical 6-wheel Mars rover.

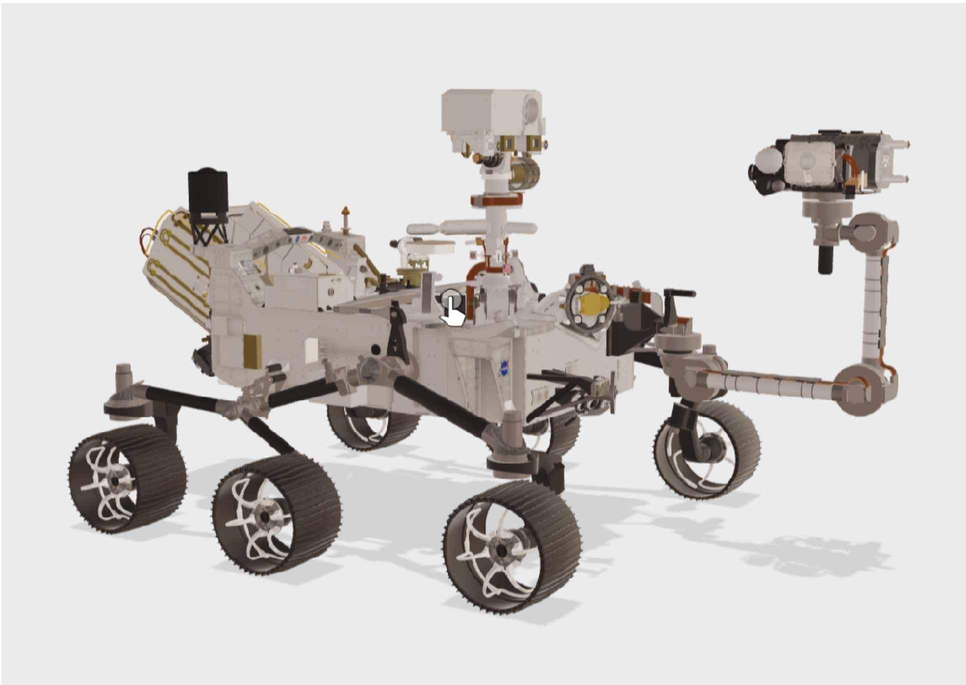


Figure 1: Overall figure of the Mars Perseverance Rover.

According to Cox et al. [3] there are three essential driving mechanisms typically used by Mars rovers in order to be capable of traversing obstacles: rocker-bogie suspension system, differential pivot, and 6-wheel Ackermann steering.

The rocker-bogie suspension system allows all six wheels to maintain contact with the ground when encountering an obstacle. If some of the wheels are unable to stabilize when an obstacle is encountered, the rest of the wheels can still maintain the balance of the body. The rocker-bogie design allows the rover to have maximum contact area with the ground when the angle of the wheels is different, thereby increasing the friction to keep the vehicle in balance.

Moreover, differential pivot is an essential mechanism for the design of the rover. Differential pivot can mechanically offload the weight from one side of the rover to the other side while it is climbing. The last required driving mechanism for the Mars rover is the 6-wheel Ackermann steering. Each wheel is a separate entity, and each wheel has its own individual motor for driving and steering. Using the Ackermann steering geometry, the speed and angle of each wheel can be calculated from the radius of the turn.

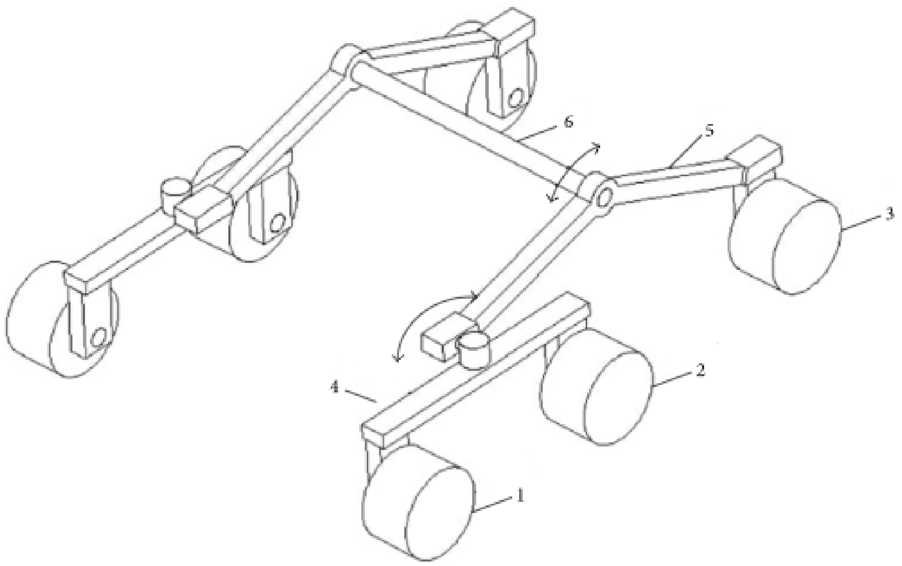


Figure 2: Rocker-Bogie suspension system

However, the Mars rover also has some drawbacks. The construction of the rover has many articulated joints, and in the actual application of this project there are puddles, swamps, and other types of terrain where a Mars rover may not be able to fulfill the requirements.

2.2 Chassis with an articulated body with 3 degrees of freedom and installed luffingwheel-legs

The first report by Zhu et al. [17] presents the design of a chassis with three degrees of freedom. The separation between the front and back of the chassis improves the effectiveness of differential steering by allowing the front and back sections to align similarly to Ackermann steering. Additionally, the construction allows the individual parts to handle rotational movement when surmounting one sided or tilted obstacles.

The second report by Zhu et al. [4] presents a solution which consists of taking the chassis from their first report, and adding luffingwheel-legs to increase the suspension capabilities of the vehicle seen in Figure 3. The luffingwheel-legs, which are the main focus of the report, utilize a knee joint to manage the height of the wheel relative to the chassis. This construction enables the vehicle to keep the chassis stable, keeping the connected parts relative displacement significantly lower than the construction using no suspension.

The separation of the chassis into several parts greatly increases the vehicle's capability to handle a series of different sided obstacles without tilting the entire vehicle one way or the other. This is greatly applicable when crossing uneven surfaces such as those expected from the requirements.

The utilization of luffingwheel joints can be applied to most chassis, and enables an efficient control of the pendulum arm between the chassis and the wheel, enabling controlled suspension. Applying such a design to the project vehicle would greatly increase the stability of the chassis, even if the chassis is different from the one in the reports by Zhu et al.

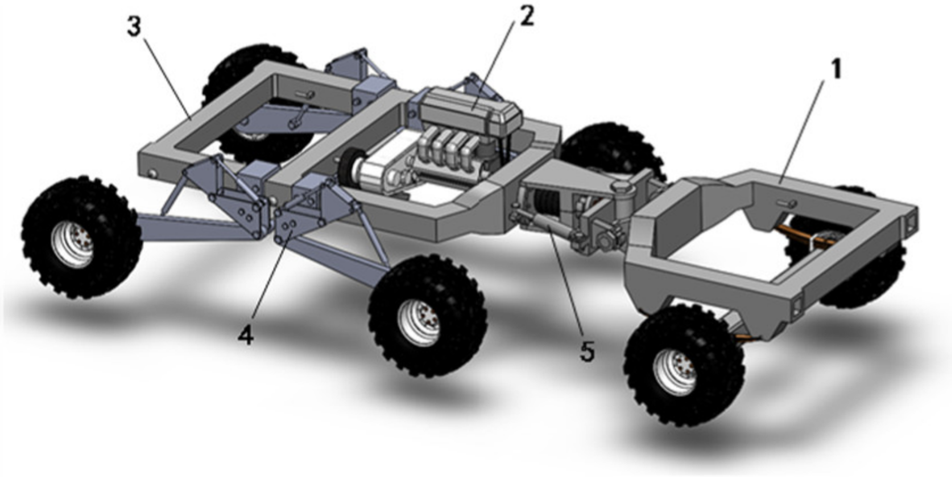


Figure 3: 1. Front frame; 2. Powertrain; 3. Rear frame; 4. Luffing wheel-leg; 5. Articulated structure.

2.3 3D Printed Robot Dog Climbs Over Obstacles

The concept of walking robots is based on biomimicry. The intention of such mimicry is to mirror the movement of animals in nature to overcome obstacles that occur in their environment. There are many reports discussing walking robots, such as that by Zhong et al. [16] which compares different design concepts for quadruped robots. An advantage of most quadruped designs is that they provide significant ground clearance, and high mobility. Thus, the robot provides the necessary tools to traverse terrain. The possibility of crossing difficult terrain for quadruped robots is further explored in the article by Raibert et al. [11] where a quadruped robot is built for crossing rough terrain. The article shows that the robot can cross several types of rough terrain. However, it is also mentioned that the load is limited, and that the terrain it is able to cross is not very complex.

Conclusively, it would be possible to create a quadruped robot which satisfied the requirements. However, the time required to create such a robot is not available, so it is not feasible to use such a construction. It is also most likely that the components required for such a construction do not fit within the available budget.

2.4 TRIDEC - All Terrain Hydraulic Axle Suspension

The TRIDEC hydraulic axle suspension is a solution intended to handle a large variety of problems that arise when designing and using larger vehicles. The suspension is built using one hydraulic piston on each side of the vehicle for every axis as seen in Figure 4 which are used to manage terrain and improve driving conditions. [6]

For example, the suspension can help level the cargo and cab of the vehicle to improve corner stability, it enables retraction of wheel pairs when they are not used. But the most relevant usage of this suspension is of course its ability to handle varying terrain. As every wheel has a piston there is a lot of versatility. The hydraulics acts as a passive suspension while also giving the operator the option to extend each piston independently to surmount difficult obstacles. This could come in handy if larger obstacles are encountered in the forest. Another great thing about this solution is the use of axles as it enables the possibility for geometric steering, in this case Ackermann-steering as seen in Figure 5.

Even though the axles create a great solution for steering, it also becomes the largest drawback due to ground clearance. Unless some other contraption is used to transfer torque between the axles and wheels, the axles will limit the ground clearance to approximately the radius of the wheel. A wheel with large enough radius and width to achieve appropriate ground clearance and ground pressure could prove to become too large or too heavy to be feasible, especially as every wheel will be fitted with a piston and

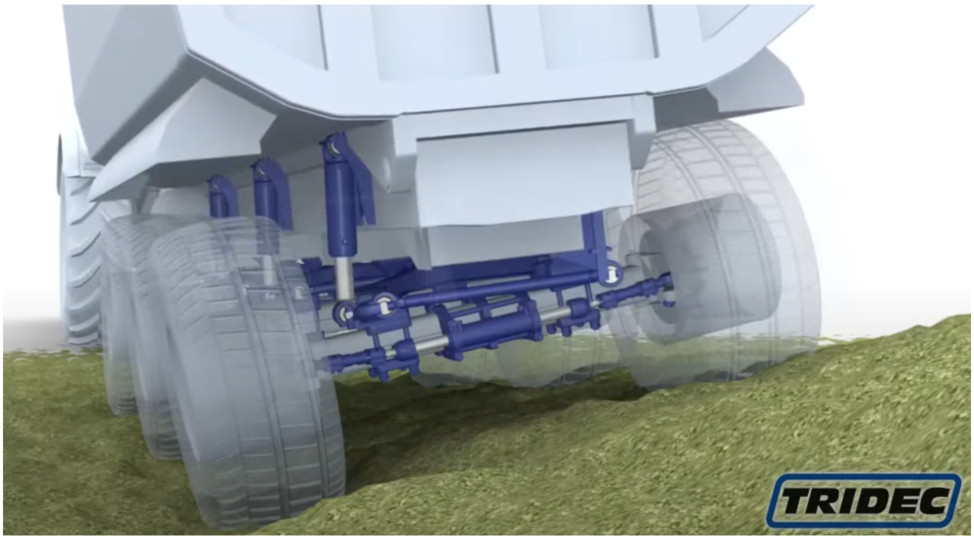


Figure 4: TRIDEC - Hydraulic pistons on each side of every axle.

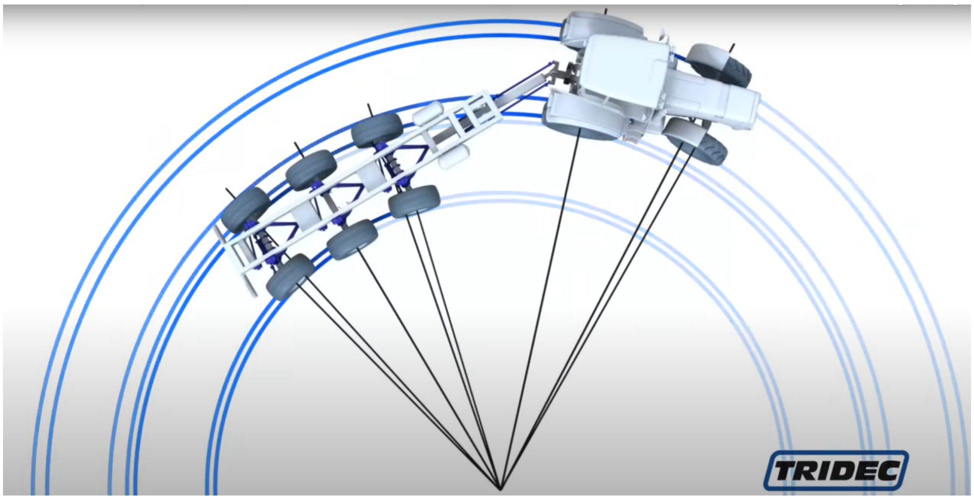


Figure 5: TRIDEC - Ackermann-steering

associated components. Although, given that it is possible mechanically, the solution is feasible both from an economical and a labor-intensity stand point.

2.5 Hyundai Ultimate Mobility Vehicle Concept

Though the specifications are missing in Hyundai's presentation of their Ultimate Mobility Vehicle Concept [7] seen in Figure 6, there is still much to be gained from analyzing it. The presented robot utilizes a construction of legs with wheels, thus gaining both the advantages of having wheels when crossing simple terrain, and the advantages of having legs when crossing rough terrain. However, there are several parts of the design which seem vulnerable to branches and bushes and other such things that can get stuck in the joints. This means that the concept is workable, but that changes to the design would have to be made to avoid the before mentioned problems.

Figure 6: Hyundai Tiger - Ultimate Mobility Vehicle

2.6 Centipede robot for uneven terrain exploration

The centipede robot for uneven terrain exploration [9] presents an additional solution to the issue of rough terrain mobility. The report shows how the robot could navigate very rough terrain relative to its size. An image of the terrains and the navigation of the robot through one of them is shown in Figures 7 and 8 respectively. The construction of a larger version of such a robot would ensure that the terrain could be traversed. However, many changes would have to be made to achieve the desired functions of the final vehicle. The robot has no steering built into it, and the construction would have to be modified to ensure that it can carry load. Since the construction is modular, it is feasible economically, labor intensively and technically to design a vehicle based on the centipede concept as its length can be adjusted.

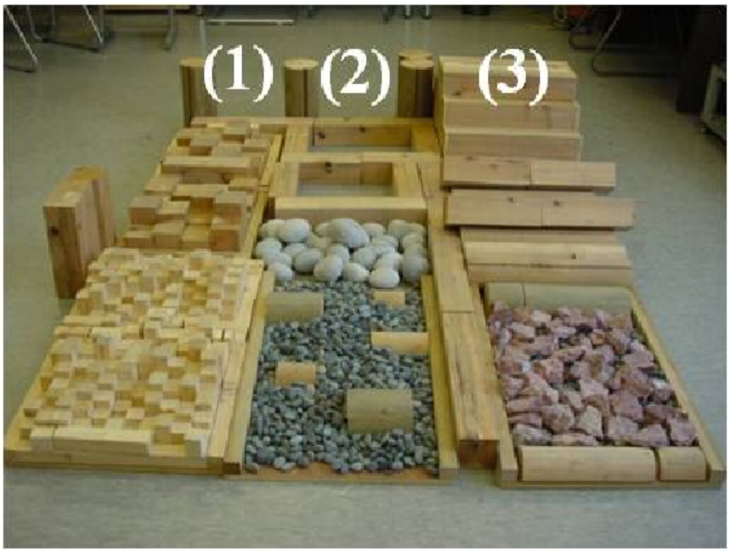


Figure 7: Terrains navigated by the centipede robot.

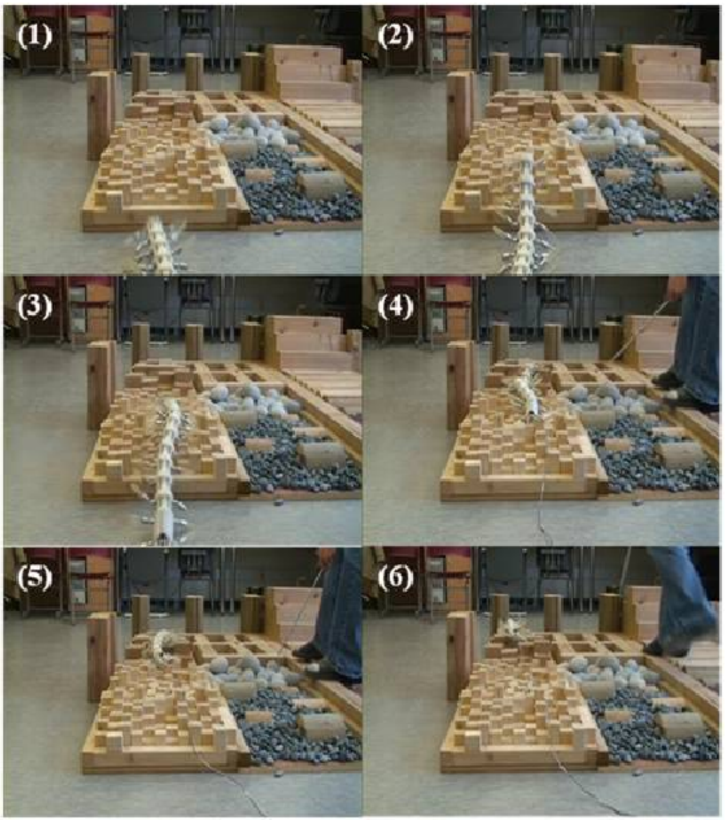


Figure 8: Centipede robot traversing one of the terrains.

2.7 The Multiscope UGV

The Multiscope UGV, made by the Estonian company Milrem Robotics [15], is a remote controlled multi-purpose tracked vehicle. The system is based on the military vehicle THeMIS by the same company. The vehicle utilizes a hybrid diesel electric power solution to drive its two tracks by electric motors. Due to the use of tracks and the relatively powerful motor, the vehicle demonstrates good off-road performance and maneuverability in challenging terrain.

The adaptability of the platform is also demonstrated well by the company in a wide array of roles. This is due to the design of the cargo area seen in Figure 9. One of these adaptations is a forest machine carrying seedlings and associated planter very similar to the final design goal of this project.

Figure 9: Multiscope UGV by Milrem Robotics

Due to the two above stated key performance aspects and the fact that a version capable of carrying seedlings already exists, this vehicle is highly relevant to this project. However, the system does have some noticeable drawbacks. First is the weight, which at 1630 kg exceeds our own limit by 1400 kg. Second is the size, where no data is provided but from videos the vehicle can be observed as much wider than our own limit. Third is the lack of adjustable suspension, which provides a bumpy ride across uneven terrain.

From this system we can make some observations of the performance and implementation of a tracked vehicle. Namely that tracks provide good mobility, lower ground pressure and the advantages of differential steering. These advantages come at the cost of weight, complexity and the need of at least two more powerful motors compared to wheeled designs.

2.8 XT28 - Self leveling pendulum arm terrain transport vehicle

The XT28 [12][13] is a terrain transport vehicle that uses pendulum arms to level itself in order to stabilize and reduce ground pressure to be more gentle on terrain. This vehicle is a prototype developed in 2016 by the same organization as the one funding this project and features many of the requirements set on this project but with a different scope. The self leveling is done by using built in pressure sensors in the hydraulics that control the lifting of the wheels together with a gyroscope. This also allows for the vehicle to "step" over obstacles by lifting the wheels on at a time, in some cases making it possible to pass an obstacle without any pitch or roll change of the cabin/payload.

Figure 10: XT28 climbing over a rock.

The vehicle is made up of several modules with two wheels mounted on pendulum arms on each module, where the front module has the steering cabin mounted and the middle and rear module share a payload bed. Figure 11 shows how the XT28 steers.

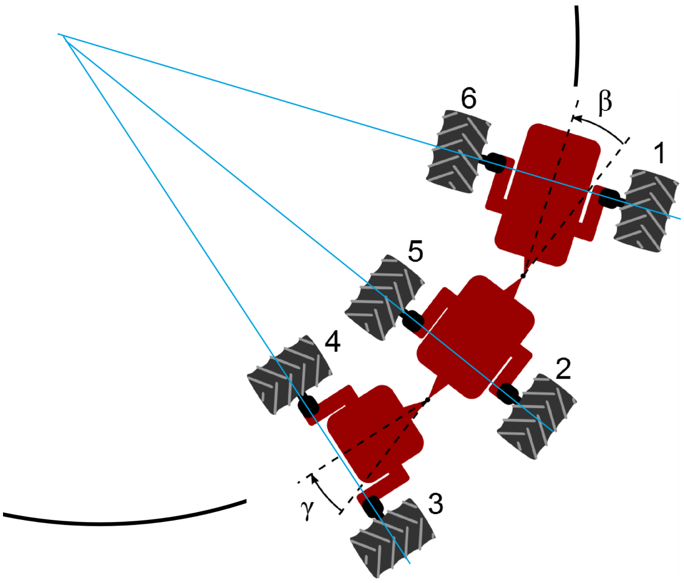


Figure 11: XT28 - Sketch of steering geometry.

The XT28 is of great relevance to this project even though this vehicle was designed for a different purpose. Much of the design could be simplified for this project as the payload will be smaller and more rectangular rather than very long and thin. The suspension should then be very feasible to build both from a technical and labor standpoint, as well as from an economical standpoint.

2.9 Kyosho Optima Mid 4WD - Single motor 4WD RC Car

The Kyosho Optima Mid [10] is an RC vehicle that uses a single DC motor to achieve 4WD with a scale 1:10 car model, shown in Figure 12. The driving mechanism combines one motor with a central belt drive that connects the motor to the rear and front axis, see Figure 13. There are two pulleys that can be manually adjusted with two screws, to keep the desired tension in the belt, reducing friction and slip.

Figure 12: An overview of the Kyosho Optima Mid 4WD.

Use of one motor while still producing 4WD is feasible from two aspects. Firstly, it reduces both cost and weight as one large motor generally is cheaper and weighs less than four equivalent, smaller motors. Secondly, the central belt drive is a simple way to obtain 4WD and only requires one motor driver.

Figure 13: The belt drive of the Kyosho Optima Mid 4WD.

However, 4WD with only one motor for all four wheels comes with a few drawbacks. Firstly, that the single motor has to be powerful enough and produce enough torque to replace four motors. Secondly, that control of each wheel's movement is limited, if not non-existing. The third is that with a central belt drive, the vehicle settles with a low ground clearance or requires additional shafts on both rear and front axis to distance the chassis from the ground, such as in the Kyosho Optima Mid, seen in Figure 14. Finally, this solution requires Ackermann steering, which is discussed in earlier sections.

Figure 14: The rear shaft of the Kyosho Optima Mid 4WD.

2.10 Suspended forestry machines for sustainable forestry

There are many different existing solutions for handling tough and uneven terrain, and the designs are all suited for particular cases. Abbos Ismoilov concluded in his doctoral thesis [8] from previous research that forest machines should make use of either tracks, bogie or pendulum arms. This is necessary to satisfy stability requirements while encountering large obstacles and steep slopes as well as maintaining a functional vehicle without damage from intrusive branches and the like.

Another aspect to consider when designing an unmanned terrain vehicle is to minimize its impact on the environment. A common problem with heavy forest machines is rutting and soil compaction which can be reduced by lessening the ground pressure through an increase in contact area and by evening out the pressure throughout that area. Tracked vehicles tend to have a larger contact area than their wheeled counterparts [2] but with the drawback of causing large sheering of the ground, notably when driving in rough terrain or changing the driving direction.

2.11 Rating the solutions

The solutions above were evaluated based on three criteria:
Technical - Does it solve the problem? Does the competence exist to build it?
Economical - Are the parts too expensive? Does it need a lot of specialized parts?
Labor - Is there enough time to build it? Would constructing it be difficult?

Topic	Tech	Economical	Labor	Sum	Additional comments
Mars Rover	7	3	5	15	Possible solution
3 DOF chassis	8	6	6	20	Useful chassis concept
- with luffingwheel-legs	6	4	6	16	Possible suspension solution
Quadruped robots	4	2	2	8	-
TRIDEC	6	8	8	22	Limited terrain adaptability
Hyundai	4	4	4	12	-
Centipede	4	4	6	14	Useful chassis concept
Multiscope UGV	8	6	8	22	Useful tracked and steering concept
XT28 pendulum arms	8	8	8	24	Useful suspension concept
4WD RC car	4	6	6	16	Problem with ground clearance

Table 1: Feasibility ratings of each design discussed in the SOTA, rated from 0-Impossible to 10-Perfect.

3 Methodology

This chapter provides a detailed description and analysis of the project, including the overall approach of project planning, working process, scheduling and communications.

The project began in the spring of 2022 and was divided into two phases. The first phase started in the spring and was completed in the summer. This phase focused on the search for state-of-the-art research, aiming to understand and study the required knowledge in preparation for the following phase in the fall semester. The first phase was finished by making a decision on a design concept. Work during the first phase was mainly completed in smaller groups. Each sub-group was given a designated research area and attempted to find reasonable solutions that could be discussed at the weekly group meeting. In addition, the other main thing accomplished in the first phase was the selection of the appropriate components. The part selection was based on the defined design concept. Each component was determined by the whole group based on data and recommendations made by each sub-group. Some changes were made to the design at this stage, due to the limited budget. By the end of the first phase most of the crucial parts were decided on, approved by the coaches and ordered. A preliminary budget was also created to create an idea of where the money should go.

The second phase began after the summer, when the ordered components had arrived. The work was executed in the same way as the first phase: The project team was divided into sub-groups, most of the work was done in the sub groups, all decision were made with the whole project group based on information presented by the sub-groups. The sub-groups were: electronics, software, and mechanical. Each group consisted of 2 or 3 members. Depending on the weekly workload, the number of members in each sub-group was flexibly adjusted, thereby ensuring that the workload of each sub-group was kept at similar levels. The main objectives of the second phase were: to refine the design concept to make sure that all parts were possible to manufacture, design and validate the electronics and software, manufacture parts and assemble the vehicle.

3.1 Project Management

There was no appointed group leader meaning all decisions were made by the entire project group, usually based on the information gathered by the relevant sub-group and extensive discussion. Group meetings were held weekly, as far as exams and other courses allowed. During meetings, each member gave an update on the weekly progress and problems that they had identified. The work load and goals for the next week were set when all progress and problems were reviewed and properly evaluated. Meetings with coaches and stakeholders were usually held once every 4 or 5 weeks, to ensure that the project was on the right path and that the project can be completed within the time plan.

3.2 Communication and Documentation

Discord was used for all communication purposes, where a range of channels were set up. The main channels used were:

- A general text chat where the entire project group could communicate.
- A general voice channel used for digital and hybrid meetings.
- A text channel used as an announcement board where contact information, team building events etc. were posted.
- A text channel where the meeting protocols, assigned workload, upcoming meeting dates and deadlines were posted.
- A text and voice channel for each sub-group to discuss relevant topics.

In order to make planning meetings easier, the web page when2meet.com was used to find suitable meeting times.

When it comes to files such as presentations, SotA reports, CAD files, data sheets etc. All files were organized and saved using Google Drive for easy access by everyone in the group.

3.3 Engineering Tools

In the development of this vehicle several digital and mechanical tools were used. The main digital aids were:

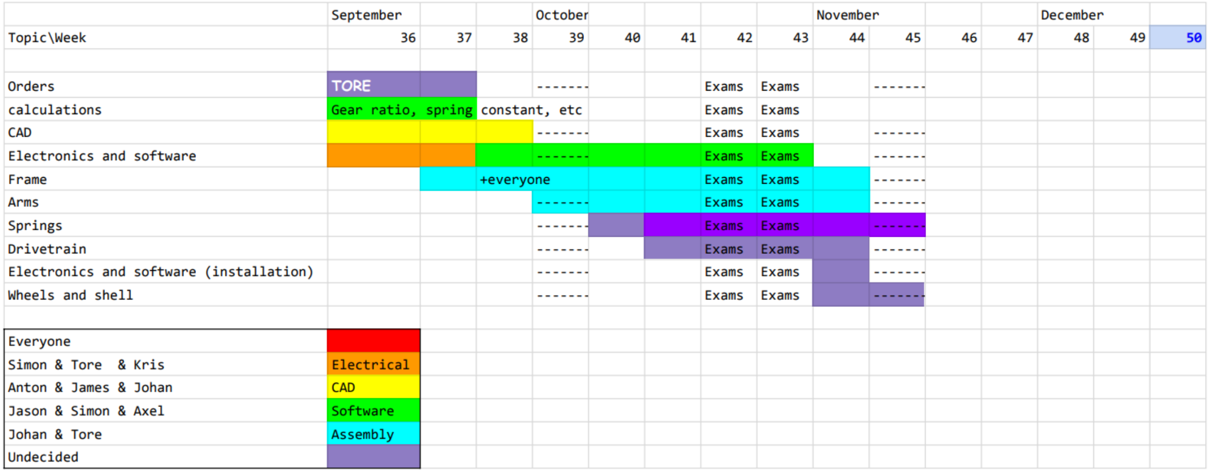
- Solid Edge 2022 and Fusion 360 to create all CAD models.
- Linux and ROS were used to manage the microcontroller communication.
- VESC was used with the ESC's to control the motors.
- Matlab was used to make calculations, mainly to estimate the power and torque needs.
- Cura to slice the 3D prints.
- Arduino IDE was used to program the Arduino board.

On the mechanical side a range of tools were used to manufacture different parts like axles, arms, shoulder joint etc. Excluding manual ones, the following tools were used:

- Lathe
- Mill
- Band Saw
- Water Jet
- Laser Cutter
- Drill Press
- 3D Printer
- TIG and MAG welding
- Soldering tools

3.4 Time Plan and Execution

During the first phase in the spring no extensive time plan was created. There was only set deadlines for when the literature review should be finished, when the design concept should be finalized and when the orders should be sent before the summer. Upon the group returning after the summer, a time plan to finish construction in week 45 was created, as seen in Figure 15, leaving the rest of the semester to solve unforeseen issues.



	September			October					November				December		
Topic\Week	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Orders	TORE			-------			Exams	Exams		-------					
calculations	Gear ratio, spring		constant, etc				Exams	Exams							
CAD				-------			Exams	Exams		-------					
Electronics and software				-------			Exams	Exams		-------					
Frame			+everyone				Exams	Exams		-------					
Arms				-------			Exams	Exams		-------					
Springs				-------			Exams	Exams		-------					
Drivetrain				-------			Exams	Exams		-------					
Electronics and software (installation)				-------			Exams	Exams		-------					
Wheels and shell				-------			Exams	Exams		-------					
Everyone															
Simon & Tore & Kris	Electrical														
Anton & James & Johan	CAD														
Jason & Simon & Axel	Software														
Johan & Tore	Assembly														
Undecided															

Figure 15: Fall Time plan

The time plan held up until week 41 where some design flaws arose that had be solved, mainly concerning the "shoulder" of the vehicle where an outer axle has to be connected to the arm and an inner axle transfer power from the motor to the chain. The amount of needed for manufacturing had been severely underestimated, while workshop access and mentoring was limited. This lead to a lot of the development being run in parallel after week 41 in order to meet the final deadline.

3.5 Budget and Costs

The total budget for the project was 50 000 SEK, which was to be used to order the necessary components for the project and pay for manufacturing labor of certain items. The approach to purchasing parts for this project was based on a strategy of saving as much as possible. This was due to the uncertainties of the parts needed in the pre-production phase. As a result of this, when a part was identified, the first option was to try to find the part on campus, or find a part that could work as an alternative solution and as a last resource purchase it. This would maximize the budget available for unexpected situations at the end of the project.

The frame and arms of this project were constructed from aluminum profiles, aluminum plates and steel plates. All of this material was found in house at the mechatronics department. The same goes for the three pipes/cylinders used as axles. The full details of the budget can be found in Appendix C.

4 Design Concept

After researching and reading about different concepts in a state of the art analysis, the most useful and feasible solutions were condensed to a design concept for the project, seen in Figure 16. This chapter covers the different parts of the vehicle and what design solutions that were chosen to solve the problems at hand. Note that these choices were made early on in the project and some changes were made for different reasons, which is further explained in the next chapter Implementation.

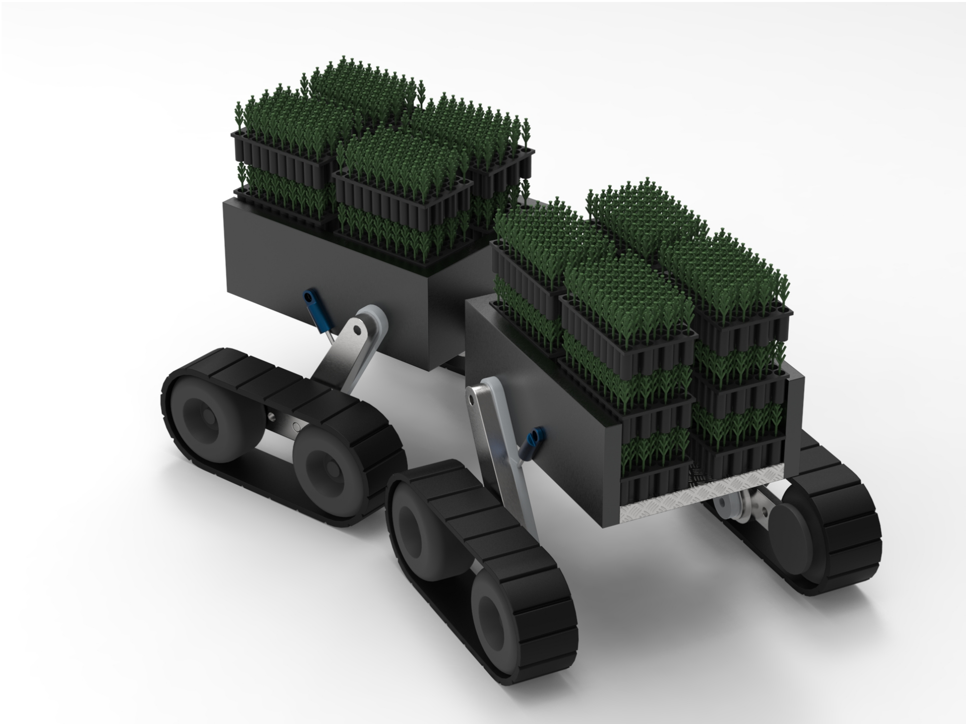


Figure 16: Design concept after state of the art analysis.

4.1 Suspension

There are three main types of suspension, passive suspension, active suspension and a hybrid of these two. Passive suspension is most often comprised of springs and dampeners while active suspension usually uses some kind of linear actuator like a hydraulic piston, often including some built in dampening. For the purposes of this project, passive suspension would be quite trivial to implement as there would be no additional computational logic to implement for after installation and the system would work all by itself. The main reason this type of suspension is used in vehicles is to absorb most of the forces generated from driving over uneven road or terrain for the comfort of the driver, where the springs absorb the forces and the dampeners limit oscillations generated from those forces. Although that is great, if the vehicle were to stand still on an incline the suspension would settle at an equilibrium where the vehicle would be tilted in the same direction as the incline. This together with the low target speed of the vehicle to be constructed in this project would mean that there would not be a need to absorb a large amount of forces. With active suspension, the length of the suspension arm has to be continuously calculated and would probably not be ideal for faster road vehicles as the computer would have to be very fast and rely on very accurate sensors in order to absorb those forces. However, when going slowly or standing still, even a slow computer with minimal use of sensors would be able to accurately make the vehicle keep level with the horizontal plane and keep equal ground pressure between all wheels and the ground. For these reasons both passive and hybrid suspension will be discarded from this project in favor of active suspension as it will better fulfill the stability and ground pressure requirements. An example of active suspension can be seen in Figure 17.

Figure 17: Active pendulum suspension on the XT28 showing ability to control each wheel individually.

4.2 Steering

For this project there were two different types of steering considered. The first type of steering would be turning the front wheels of the vehicle like a road car and the second type would be differential steering. Differential steering would not require any additional parts other than the suspension holding the wheels in place and the ability to power each wheel independently. Together with the turning radius being smaller and being able to steer it equally in both the forward and backward direction makes it the best candidate for this project.

4.3 Electronics

The overall electronic layout will consist of a Raspberry Pi, a Pixhawk microcontroller, electric motors, ESCs, a receiver, a DC-DC converter, and a battery, using the preliminary electronic diagram shown in Figure 18.

As in the diagram, the battery bank will have a 24V output, which will be converted to 5V by the DC-DC converter for all the low power electronics and a direct connection to the power input to the ESCs to drive the motor.

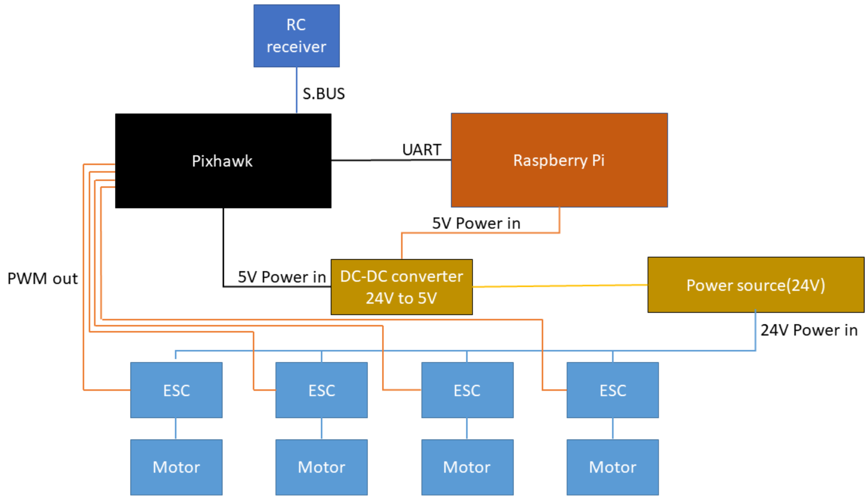


Figure 18: Preliminary electronic diagram

4.3.1 Microcontrollers

In the design concept, a high level microcontroller like Pixhawk will be used for its ROS compatibility. The Pixhawk 4 was chosen with its 8-16 PWM outputs for the drive of motor, and a S.Bus for the RC receiver. It also has a telemetry port for connection to the companion Raspberry Pi to enable ROS as per the requirement.

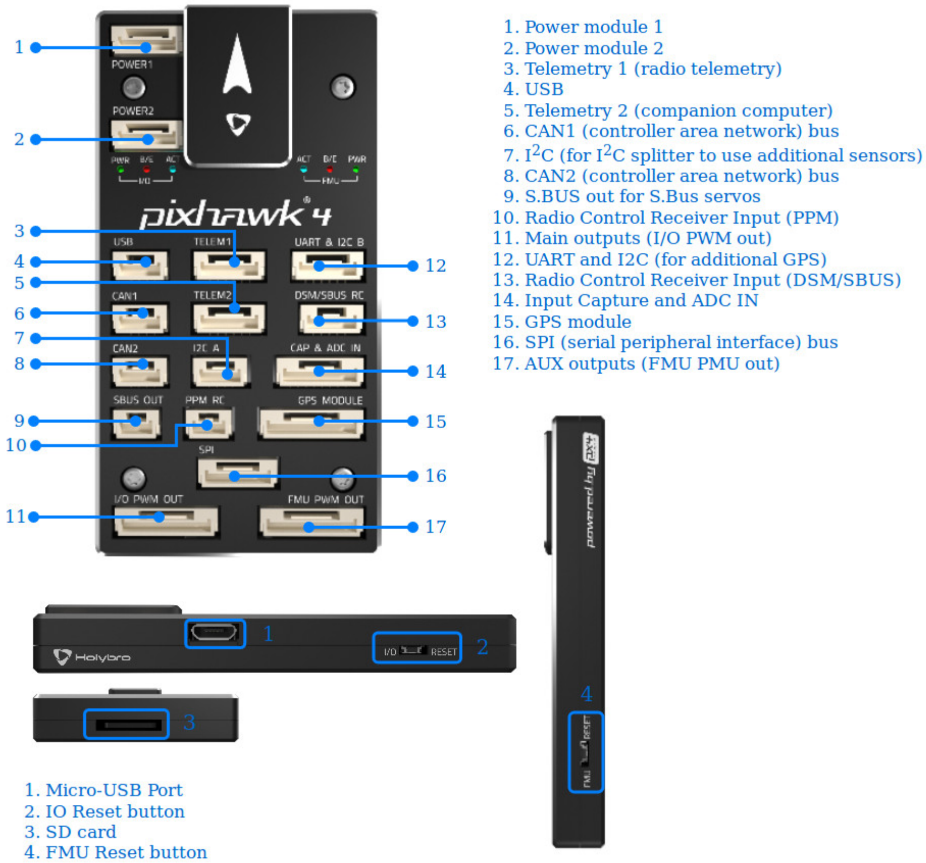


Figure 19: Connectors for Pixhawk 4

As shown in Figure 19, multiple configured ports are built in Pixhawk 4, which can favor future expansion.

4.3.2 Software

The Pixhawk will be deployed and tuned using the ground station software Q-Ground-Control(QGC), where each parameter can be tuned in the GUI. Without additional modules, QGC can already map an RC controller and tune the motor settings, such as PWM output and PID value. Live ground station would also be achievable with an additional telemetry module if required.

According to the stakeholder, the system should have ROS enabled. Raspberry Pi was chosen for its relatively low cost and power consumption with well-documented guides for integration with ROS while also being easily accessible. Linux and ROS will be installed on the Raspberry Pi. The preliminary connection is shown in Figure 20.

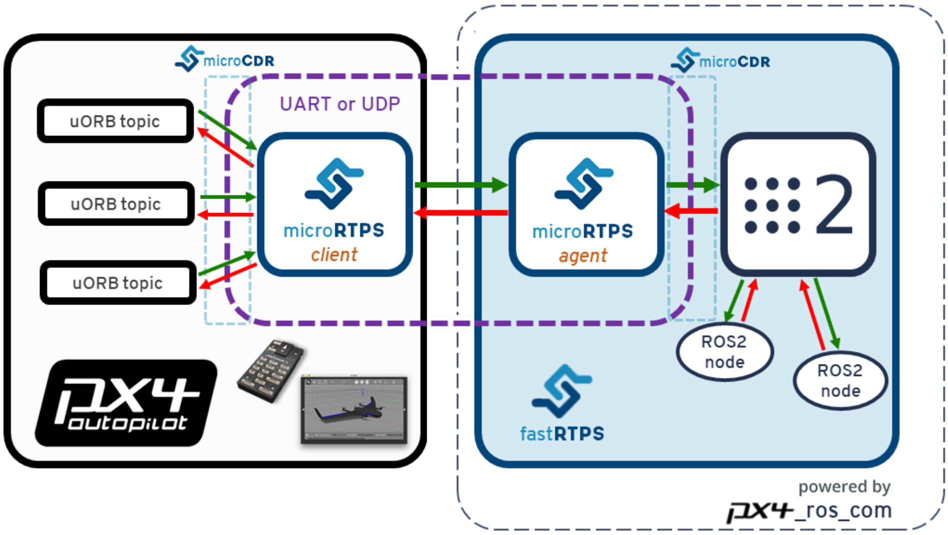


Figure 20: ROS and Pixhawk connection

It shows how a ROS2 node can be built on the Raspberry Pi and be used to control the Pixhawk.

4.4 Driveline

This part of the report covers the implementation of energy, motors and transmission of torque through the vehicle.

4.4.1 Energy Storage

By far the most common way to power electric vehicles is through stored energy in batteries. For this project the most important aspects to consider for the batteries is energy density and cost as well as safety and reliability. Different types of lithium-ion (li-ion) batteries are the most common for their relatively high energy density and continuous decline in cost. For this project the chosen battery type is lithium iron phosphate (LFP) which has many desirable features compared to other types of li-ion batteries such as nickel cobalt aluminum (NCA) and nickel manganese cobalt (NMC). Among the advantages are things like lower cost, longer life cycle and lower chance of explosions and fires as well as not containing any nickel or cobalt which are expensive and have a high environmental impact [5]. The most notable disadvantages are the lower energy density and operating voltage compared to other li-ion types, but the advantages easily outweigh the slight disadvantages in this case.

4.4.2 Motor

Per request by the stakeholders, no fossil fuel is to be used in the primary design of the vehicle. This leaves electric and hydraulic motors as the feasible alternatives. As the maximum speed of the vehicle is walking speed, the ideal motor would be high torque and low speed. Hydraulic motors are often favored in robust designs, especially in high torque low speed applications. But due to the small size of the vehicle, the hydraulic motors are simply too expensive to be economically feasible. And as the vehicle will use a DC power source, the ideal motor would be a high torque low speed brushless DC motor.

To calculate the minimum requirements for the motor a test case is created where the vehicle is considered to be positioned on a slope with the given inclination attempting to climb it. Based on the estimated data of Table 2, given no losses and that all wheels are in contact with the ground, the minimum torque to climb the slope is 42.0 Nm. The required power to climb the slope at 3 m/s is 630.0 W.

Data	Value
Mass [kg]	250
Incline [°]	20
Wheel diameter [mm]	400
Number of wheels [#]	4
Maximum velocity [m/s]	3

Table 2: Estimated vehicle data

Looking at the XT28 as a benchmark for forest vehicles, the torque to mass and power to mass ratio of the XT28 can be seen in Table 3. The values give an estimate of requirements on the motor, given the vehicle's presumed mass, including load $m = 250kg$, the ratios yield a torque of 10.5 Nm and a power of 1.66 kW.

Ratios	Torque	Power
Mass	23.77 [kg/Nm]	0.15 [kg/W]

Table 3: Torque and power to mass ratios of the XT28

As the initial calculations were done regarding no losses and all wheels in contact with the ground a safety factor of 4 gives a more realistic worst case scenario where only two wheels have traction or only half of the energy is translated to forward velocity. This results in a torque requirement of 167.9 Nm and a power requirement of 2.5 kW which is reasonable compared to the XT28 ratio calculations as the inclination can be large for forest terrain.

4.5 Chassis

With differential steering as the most promising option, and the electrical driveline decided, the chassis specifications could be specified. A simplified chassis design can be seen in Figure 21.

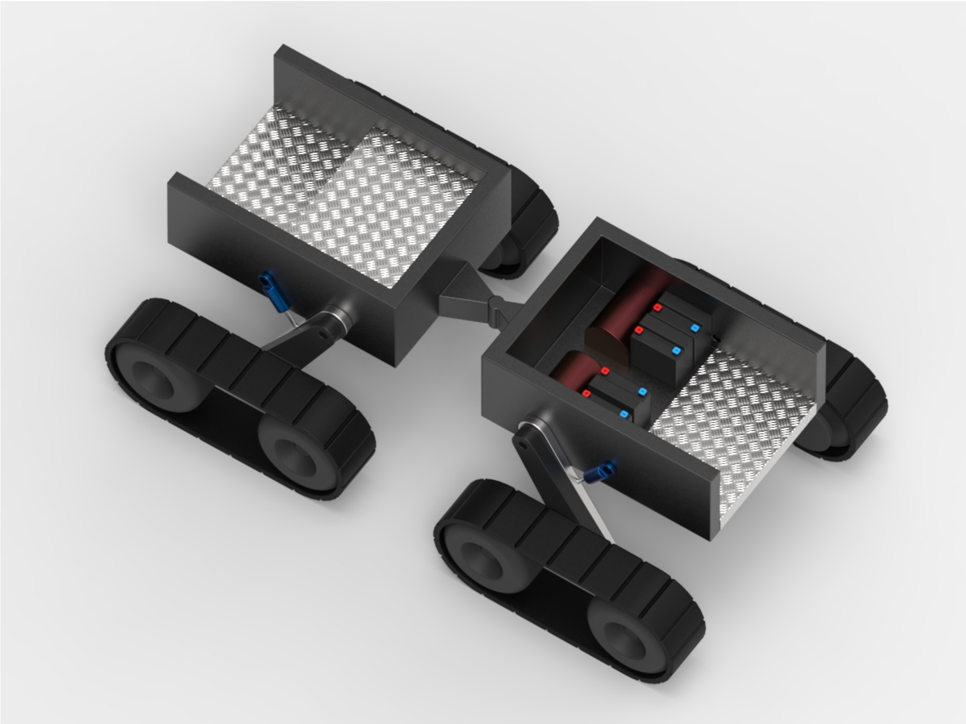


Figure 21: Overview of the chassis design, with battery and motor placement.

4.5.1 Split wagon

In order to increase stability, the weight is preferably distributed over a larger area, and so the vehicle was split into two wagons. This was also advantageous together with differential steering, due to the different carts being able to rotate relative to each other, thus creating an Ackermann-like steering motion between the two wagons. A split wagon-design also enables the vehicle to clear narrower gaps in the terrain, as well as increasing vehicle area, thus increasing stability.

4.5.2 Torque transmission

Electrical motors for this application, as mentioned in section 4.4.2, requires a large gear ratio, thus a gearbox or a line of gears has to be fitted onto the frame. A chain along the arm, to transmit torque, was chosen and gears were chosen to achieve the desired gear ratio. In the potential case that the chain gear ratio is not high enough, a second gear-stage could be added in the bogey.

4.5.3 Low centre of mass

The main components of the vehicle are quite heavy; four brushless DC motors, batteries, gears and a sturdy frame. In order to make a sturdy vehicle, the centre of mass should be as low as possible. Therefore, placing the motors and batteries in the lower part of the chassis is preferable, and for this purpose, hub motors prosper. However, there are a few drawbacks of hub motors compared to motors on the main body. These include the motors having to be more resilient to water and dirt, and a lack of torque with limited gear ratios. For a non-hub motor, the gearing could be placed at the pendulum arms or at the wheels, which also moves weight further down. In this regard, the only components of the vehicle unable to be moved outside of the main frame, would be the batteries and the controlling electronics. During construction further into the project, these things have to be considered.

5 Implementation

The implementation began with creating a list of the crucial components that needed to be ordered, followed by compiling the costs of these components. At this time, a problem arose. Though all of the parts of the design concept seemed affordable individually, as they had been evaluated earlier, they were not affordable together. Many of the component systems were crucial to the design, but some could be replaced by much cheaper, but worse, alternatives. The most expensive system in relation to how it improved the design was the active suspension using hydraulic pistons. To make the project fit within the budget, this active system was replaced by a passive one, using springs for suspension. This change additionally meant that the electronic system was unnecessarily complex, since the feedback control was eliminated. To this end, the Pixhawk was replaced by an Arduino Uno, which is a cheaper alternative, but with less built in functions. The RC control that was previously meant to connect to the Pixhawk was replaced by control via Bluetooth to the Raspberry PI.

5.1 Overview of the physical model

Figure 22 clearly shows the prototype on the side view. A more detailed explanation of each part and how it has been constructed was described below.

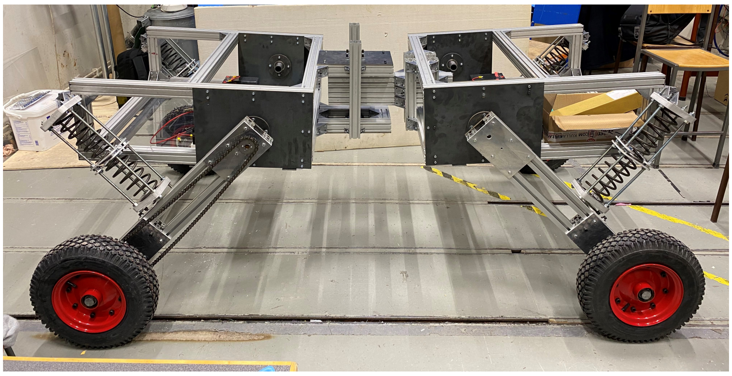


Figure 22: Overview of the physical model.

5.2 Frame

The construction of the framework for this project was composed of two parts, the front frame and the back frame, as shown in Figure 23. According to the stakeholders' requirements, the final product's dimensions were limited to two meters in length and one meter in width. After considering the space required for other parts, the final frame dimensions were determined to be 80x80 cm, and the height was determined to be 30 cm. The distance between the two frames was determined to be 30cm. All aluminum profiles were connected using the type XDFA 44B angle connections with M5 screws and nuts. Three angle connections were used for each corner and each angle connection used 4 screws and nuts. Plastic plates were mounted at the base of the front and back of the frame to place batteries and other equipment.

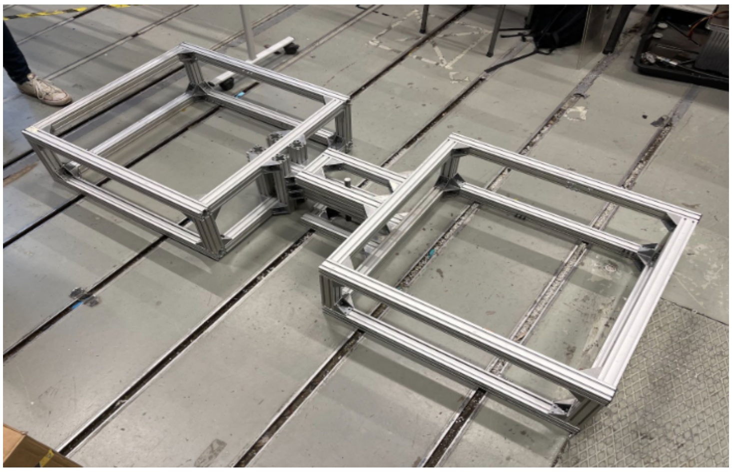


Figure 23: Overview of the frame.

5.3 Frame Connections

The connection between the two frames was held in place by a steel axle, as shown in Figure 24. The front frame has two U-shaped aluminum profiles at the joints, while the back frame has three aluminum profiles at the joints. A steel plate was mounted on the outer side of each U-shaped profile to hold the ball bearings in place. The two frames were connected by a steel axle that passed through the three aluminum profiles of the back frame, and then fixed on the ball bearings on the steel plates located on the front frame.

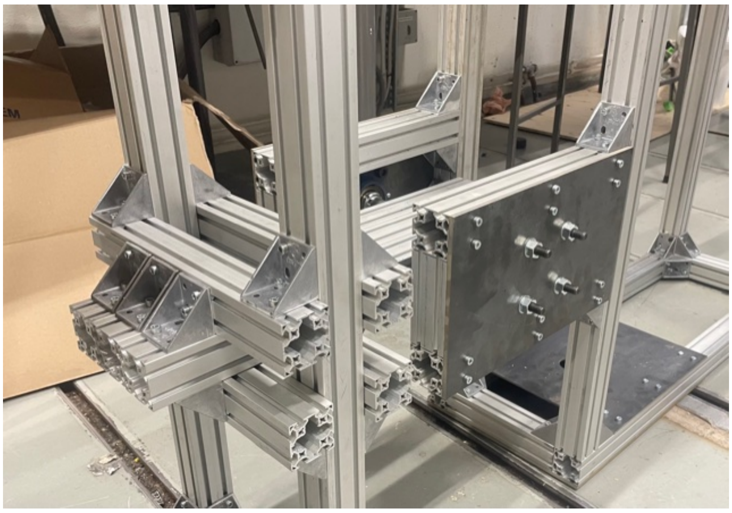


Figure 24: Overview of the connection between two frames.

The frame material selected for the construction was aluminum profiles. According to the stakeholders' requirements, this project has a weight limit on the final product, and the frame has the largest proportion of the overall weight. Therefore, the selection of a relatively low-weight and high-stiffness material was preferred. In addition, there were a lot of aluminum profiles available in the school's warehouse. Thus, after a collective discussion, aluminum was finally chosen as the construction material for the frame part of the project.

5.4 Arm assembly

Figure 25: Overview of arm and spring assembly with drive-line.

The arm is primarily made out of aluminum, just like the chassis, but in a similar fashion also has steel components where more stress would have occurred. Forming the bulk of the arm assembly is 40x40 mm aluminium profiles and water cut plates of 4 mm in thickness.

The profiles in question can be seen in Figure 25, consisting of two 650 mm profiles running from top to bottom, one 300 mm profile onto which the wheel assembly is attached and finally, a small 40 mm profile. The last profile is placed outside of view between the longer profiles at the top of the assembly in order to give the arm more rigidity.

At the bottom of the arm two plates are placed. These are identical and placed on either side of the arm. These are attached via M6 bolt and nut to the outermost profiles, fixing them in place. On the same plates are holes for M8 bolts which are used to mount the shorter profile onto which the wheel is attached. These attachment points are utilizing sliding nuts placed inside the profile rather than through holes. This allows the profile to be moved up or down in parallel to the longer profiles. This provides the means to tighten the chain appropriately.

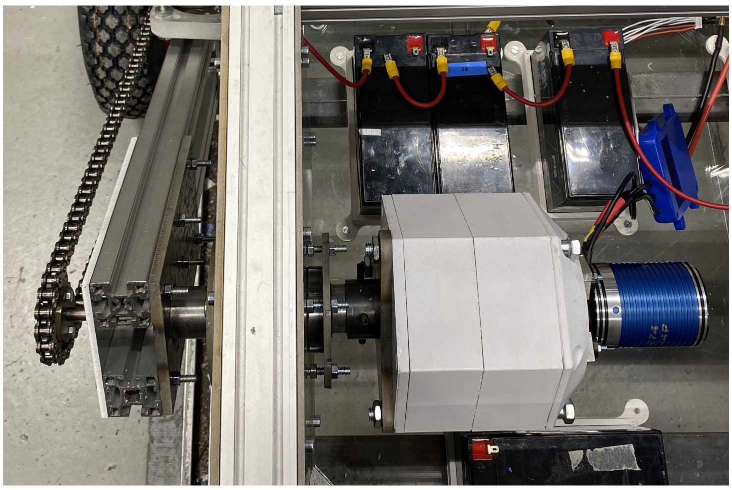


Figure 26: Topside view of arm-frame connection and arm-gearbox connection.

At the top of the arm two different plates are placed. The outermost, and visible in Figure 25, is made out of aluminum. The inner part is the shoulder component, which can be seen in Figure 26. This part consist of two components, a steel plate, near identical in design to the outer plate visible in Figure 25, and a steel cylinder. The latter of which has been extensively processed and cut to handle all experienced forces the arm could encounter. These two parts are welded together. The schematics for this component can be found in project files. This part is connected to the frame though ball bearings placed on the steel frame plates.

At the inside of the frame another part is attached to the shoulder axis. This is the gearbox mount plate. This component consists of a metal plate and a cylinder welded together. To the plate the gearbox is attached and though the cylinder tightening bolts are placed in order to lock the rotation of the gearbox to the arm.

At the bottom end of the arm is the wheel assembly. This consists of a wheel onto which a series of spacer plates are attached. To these spacers the large sprocket wheel is attached. The wheel rests on a fixed axle and rotates on two ball bearings fitted to the wheel. Axial movement is restricted by use of multiple stop rings.

Finally, on the lowermost profile there is small metal plates placed on the profile in order to give additional support, this due to concerns about high stresses on the aluminum extrusion when such a large hole was drilled through it.

5.5 Spring assembly

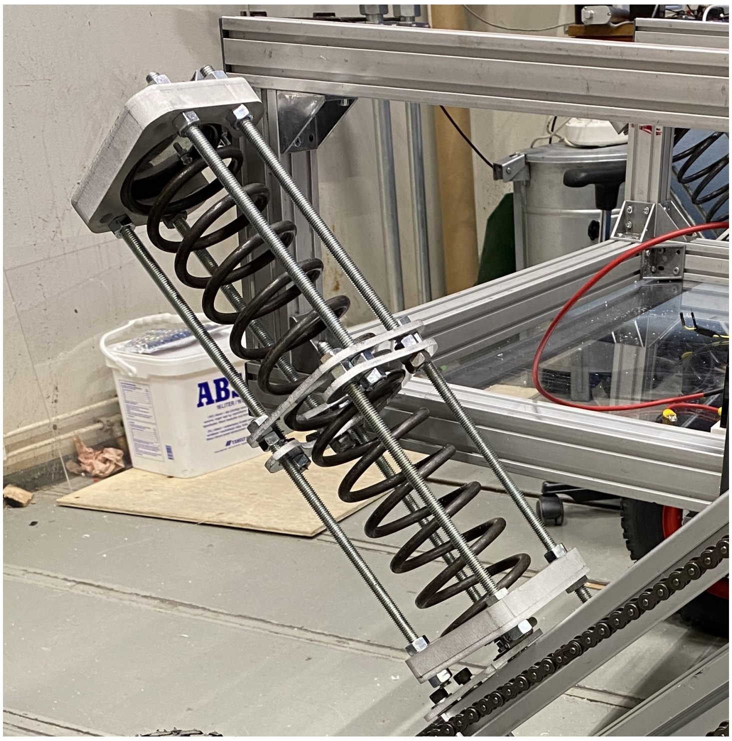


Figure 27: View of the spring assembly.

The spring assembly can be seen in Figure 27.This connection between the arm and frame via spring is meant to give the vehicle adequate suspension in harsher terrain. To this end a large spring is placed in the middle of the assembly. On the top and bottom of the spring there are plates with holes for mounting to the frame and arm. At the top this is done though an angular connector piece with a bolt running though it. At the bottom this connection is handled via a hinge.

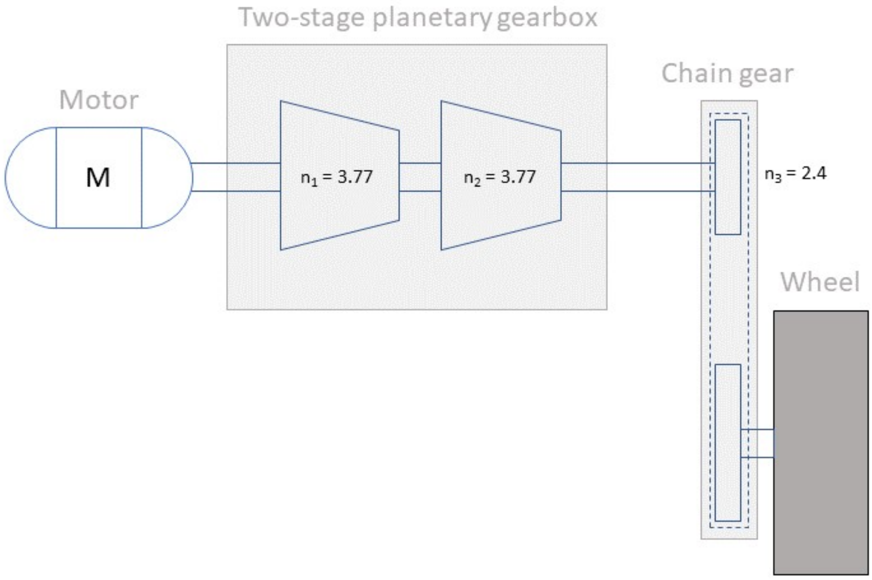


Figure 28: Overview of the driveline.

In order to prevent the spring, and arm in extension, from over-extending, and to provide rigidity to the assembly, a series of aluminium plates and long bolts were used. The two middle plates are identical and feature a large centre hole for the spring as well as eight M10 holes for the bolts. Through four of these, threaded rods are run either to the top plate or the bottom one. When assembled this allows for compression of the spring since the two center plates are not attached to each other. One additional, much thicker, plate is positioned at the top and bottom plates. The purpose of these thicker plates is to hold the spring in place. Other than thickness they are identical to the middle plates. Schematics for these parts can be found in attached project files.

5.6 Driveline

The driveline has five main parts, the motors, the two-stage planetary gearbox, the driving axis inside the arm, the sprocket chain gear and finally the wheels, see figure 28. Each of these parts are explained in the subsections below.

5.6.1 Motors

For this project, hobby grade brushless DC motors were chosen due to their high versatility and controllability with ESCs. BDCMs provide a relatively low torque and high rpm, and therefore a high gear ratio was required to convert low torque, high speed to high torque, low speed, which the application required. More on the specific motors and ESCs is explained in Electronics, further on.

5.6.2 Two-stage planetary gearbox

Early on it was established that the vehicle had to be resilient to harsh weather conditions, not excluding rain and other sources of water. The IP-classification requirement prohibited exposed electronics, and exposed moving parts that could get stuck should be kept to a minimum. Therefore it was concluded that the best option was to keep as many of the components as possible well protected within the vehicle's chassis. This, combined with the high gear ratio required, resulted in a planetary gear. A planetary gear has a high gear ratio relative to its volumetric footprint and could therefore be placed directly connected to the motor, inside the chassis. To receive an even higher gear ratio, two planetary gears were stacked, thus creating a two-stage planetary gear. Each stage had a gear ratio of 1:3.77, resulting in a ratio of 1:13.44 for the entire gearbox.

5.6.3 Axis and chain gear

Torque from the gearbox's output shaft was transmitted via a steel axis, placed inside of the arm-cylinder, freely rotating in relation to the arm. This driving axis emerges at the outside of the arm-frame connection and ends with a 15 teeth sprocket. This sprocket is connected via a chain, which runs along the outside of the wheel-arm, down to a receiving sprocket by the wheel of 36 teeth. This results in an additional gear reduction of 1:2.4, resulting in a total gear ratio of 1:32.266.

5.7 Electronics

To fulfill the four wheel drive requirement, each driveline has a Turnigy SK8 6374-192KV motor. The motor is rated for 4400 Watt and 6 Nm of torque before reduction, at 38V. To control each motor a Turnigy SK8 V2 80A 3 12S Single Motor Skateboard ESC is used. The ESC uses the VESC software and is set to actuate by receiving a signal between 0.5 and 3 V. The range corresponds linearly to a transition between full power backwards at 0.5 and full power forwards at 3 V.

Figure 29: Turnigy SK8 6374-192KV Motor

Figure 30: Turnigy SK8 V2 80A 3 12S Single Motor Skateboard ESC

As the ESC is VESC compatible, the VESC Tool is used to setup and configure both the motor and the ESC. The ADC of the ESC will be mapped to the duty cycle of the motor. However, the Arduino used in the project does not provide any DAC for voltage output. As a simplified solution, an RC low pass filter is implemented, consisting of one 10kOhm resistor and a 47uF capacitor, resulting in a cut off frequency of 0.33Hz. The low pass filter is shown in Figure 31. It sufficiently converts the 500Hz Arduino PWM frequency to a rather steady voltage, which has no visible oscillations in the ADC of the ESC when tuning. Regenerative breaking is also enabled for a better breaking performance and overall motor efficiency. The software limits the ESC to 60A at all times, to make sure the ESC is not overloaded.

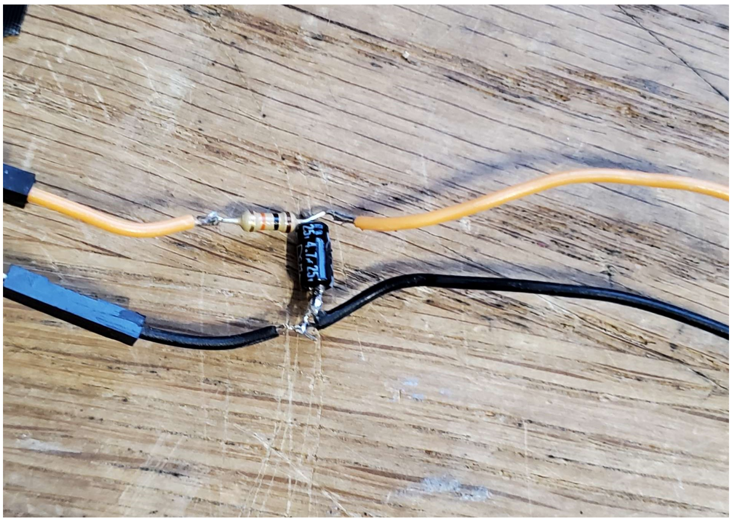


Figure 31: RC Low pass filter without a heat shrink wrap.

Purchasing a new set of batteries for the sole purpose of testing the functionality of the vehicle has been deemed unnecessary as the goal of this project is a proof of concept, and not a fully fledged prototype. Instead a set of batteries has been borrowed from the Mechatronics Department at KTH. On deployment, every motor is using an independent battery pack. Each pack consist of three 12V, 7.2Ah battery. The Micro-controller and onboard computer are powered with a separated battery to avoid sudden voltage surges and drops from motor movement. A DC-DC converter is used to provide 5V from the 12V batteries. All electronics can be run with the electronic diagram shown in Figure 32.

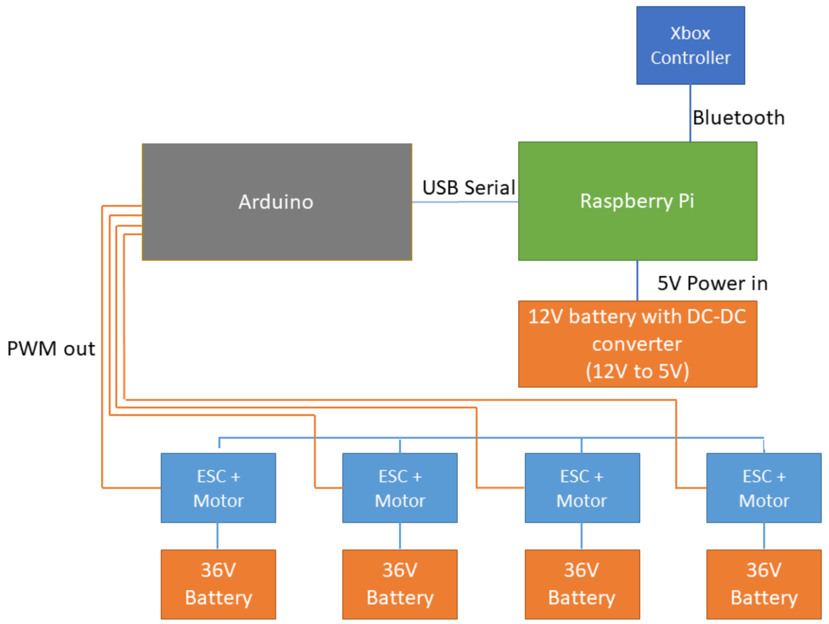


Figure 32: Electronic diagram

5.8 Micro-controller and onboard computer

To fulfill the requirement of ROS compatibility a Raspberry Pi 4 was used. The Pi was connected by a USB serial connection to an Arduino which handled the actuation of the motors. The ROS interface on the Pi currently has two nodes, one which receives a control input and then sends it to a topic. The second node listens to the topic and calculates the appropriate actuation necessary, it then sends this information to the Arduino, which outputs a PWM signal with the corresponding duty cycle. As mentioned in section 5.7, the PWM signal passes through a low-pass filter to the ESC. The ESC was calibrated using this setup to make sure the software and electronics matched. Details explaining how to use the code can be found in the Appendix A.

An important part of the system is that it is able to run outside in the wilderness without any extra controls and monitors, apart from the steering controller. To this end the program was initiated by having it start upon boot of the Pi. The details of this procedure can be found in Appendix B.

6 Verification and validation

Section 1.3.2 outlines the technical requirements agreed upon in order to meet all of the requirements given by the stakeholders. In order to validate if a requirement has been met, each requirement has to go through a verification process. The following lists contain the technical requirements from section 1.3.2 split into 3 sections: **Measurable**, **Testable** and **Implemented**. Requirements in the measurable section can be numerically measured without running the vehicle. Requirements in the testable section can be measured while the vehicle is running. Requirements in the implementable section will either be implemented into the final design or not.

6.1 Measurable

- The vehicle should be capable of a ground clearance of at least 500 mm.
  - Verified by measuring the distance between ground and the lowest point of the vehicle frame, both while the vehicle is loaded and unloaded.
- Maximum unloaded weight of 200 kg. It should be easily recoverable if it gets stuck.
  - Measured by using one or more weight scales. Either 4 scales could be placed under each wheel or the vehicle could be hanged in a hang scale. Testing if the vehicle is recoverable can be tested by having 4 or more people try to lift it.
- Load capacity matching or exceeding 50 kg.
  - Verified by slowly loading the vehicle with pre-weighed items until 50 kg is matched or surpassed.
- Maximum size while transported of 250x130 cm.
  - Verified by measuring the distance between the farthest points of the vehicle length-wise and width-wise respectively.

6.2 Testable

- The speed of the vehicle should be in the interval of 0 to 3 m/s, i.e. walking pace.
  - Verified by either running the vehicle forwards for a certain amount of time, or by letting the vehicle drive a predetermined distance and measure the time it takes to cross that distance.
- Ability to operate on soft soil (peat soil).
  - Verified by operating the vehicle in different terrains and conditions and seeing if the vehicle can cope or gets stuck.
- Operational temperature of 0 to 40 degrees.
  - Requires the vehicle to be run in different temperatures across that range. Verifying the battery life time at different temperatures will also require longtime running.
- Weather protection of at least IP54 for parts exposed to the ground and IP44 for higher placed parts.
  - Done by following the IP54 and IP44 standards verification process/ simulating rain and operating the vehicle in puddles.
- The vehicle should be remotely controlled by user in close proximity.
  - Verified by running the vehicle and testing all assigned inputs.

- The vehicle should be able to climb a slope of 20°.
  - Verified by running the vehicle at different inclines until the vehicle slips and cannot cope with steeper inclines and seeing if it surpassed the desired incline or failed to do so.

6.3 Implementable

- All wheel drive (or at least 75 percent of the wheels).
  - Verify that all wheels (or 75 percent of the wheels) are part of the driveline and can be run together.
- The vehicle should utilize the ROS interface.
  - Verify that the different controllers are communicating using the ROS interface.

7 Results

The results of the project are measured by looking at which of the technical requirements outlined in section 1.3.2 have been achieved.

7.1 Measurable

- The vehicle should be capable of a ground clearance of at least 500 mm.
  - The ground clearance with the vehicle unloaded was measured to 570 mm. The height remained almost unchanged with two people sitting on either side (each person weighing about 75 kg). This requirement has thus been achieved.
- Maximum unloaded weight of 200 kg. It should be easily recoverable if it gets stuck.
  - The vehicle could not be weighed due to lack of equipment. The estimated weight calculated in CAD was approximately 180-190 kg. The vehicle could be lifted, moved around and flipped over with 4 people present. This requirement has thus been achieved.
- Load capacity matching or exceeding 50 kg.
  - The vehicle was capable of holding two people on either end weighing about 75 kg each while standing still. The vehicle was not weight tested while running. This counts as the requirements being partially achieved.
- Maximum size while transported of 250x130 cm.
  - The distance between the hubcaps and the maximum width of the vehicle was measured to to 1290 mm. The distance between the tips of the front and back wheels and the maximum length of the vehicle while standing straight was measured to 2200 mm. This means that the vehicle fits within the bounding box set by the requirements of fitting inside a standard trailer. Thus this requirement has been achieved.

7.2 Testable

- The speed of the vehicle should be in the interval of 0 to 3 m/s, i.e. walking pace.
  - The vehicle could reach the desired wheel speed while lifted of the ground. No running test while loaded or unloaded was able to be performed. Thus this requirement was partially achieved.
- Ability to operate on soft soil (peat soil).
  - No ground performance test was performed. The only assurance is that the ground pressure is less than that of a person. This requirement was not confirmed to be achieved.
- Operational temperature of 0 to 40 degrees.
  - The vehicle performed as expected at room temperature. No further testing was performed. Thus this requirement was not confirmed to be achieved.
- Weather protection of at least IP54 for parts exposed to the ground and IP44 for higher placed parts.
  - Large parts of the electronics was not insulated or sealed. Thus this requirement has not been achieved.
- The vehicle should be remotely controlled by user in close proximity.

  - The vehicle could be operated by, and communicate with a wireless Xbox One controller. This requirement has thus been achieved.

- The vehicle should be able to climb a slope of 20°.
  - No climbing tests were performed. However, the torque is dimensioned so that this should be possible on some grounds. This requirement was not confirmed to be achieved.

7.3 Implementable

- All wheel drive (or at least 75 percent of the wheels).
  - All wheels could be operated at the same time. This requirement has thus been achieved.
- The vehicle should utilize the ROS interface.
  - The software on the Raspberry Pi runs on ROS. Thus this requirement has been achieved.

In summary, very few performance test were performed, but the vehicle platform built meets most of its requirements and could be upgraded to fulfill the rest of the requirements.

8 Discussion

Based on the solutions in the state of the art report in section 2 the conclusion was to build a vehicle according to the the design presented in section 4. As there were several relevant solutions for most problems the reasoning behind the concluded design is separated by function.

8.1 Software

Though the software mostly works, there were a few bugs that were not solved. Most severely one which sometimes caused the program to crash when steering the vehicle from the controller, causing the vehicle to keep going with the latest control input. The rover can however be steered without issue using other control functions in the code.

8.2 Frame

The frame has been well tested and has not exceeded the maximum weight requirement, while perfectly supporting the required load. Moreover, the frame was constructed to the required dimensions and reached the desired size. The aluminum materials used for the project were taken from the school, which greatly reduced the time needed to order and kept the budget available for other parts of the project. Therefore the selection of materials was made correctly. However, one design flaw in the construction of the frame was that the joint between the two parts sags inwards due to the weight being concentrated towards the center. This has not shown any problems in the current tests, however, it might still have adverse effects in the long run.

8.3 Arm assembly

The pendulum arm assembly, and all of its attached components, has turned out to be one of the more successful parts of this project. It is able to handle the stresses it experiences while providing the technical solution it was designed to resolve. The tension of the chain is handled well, the welding on the shoulder component is sturdy, the connection to the frame plates trough ball bearings is solid and the gearbox mounting plate is solid. All in all, the arm turned out as one of this project's highlights and there isn't much to comment on. One aspect that could however be mentioned is that the time and manufacturing resources needed to produce the four arms was extensive. This reduced resources to other assembly work that would have benefited from more attention such as the suspension and middle joint.

8.4 Suspension

The suspension assembly has a great potential for improvement and potential future work. The initial design included a much more advanced, controllable solution. The original concept was to control each individual arm with hydraulics. This design turned out to be difficult due to the excessive costs it would have meant for the project. Due to this reason, another solution was used, which utilized springs for suspension. This is not an inherently bad idea, as such constructions are used in many other vehicles. However, the implementation into this prototype can be seen an lacking. Due to the use of threaded rods and raw metal in the sliding assembly it was found that the threads of the threaded rods repeatedly jammed against the metal plates. This caused the jamming of the spring, preventing its compression or expansion. This is a major issue in the design.

The reason for this perhaps obvious issue was twofold. First off, during design and assembly, it was assumed that the teeth on the bolts would just be a slight inconvenience rather than issue it turned out to be. Secondly, during manufacturing, when the spring assembly was standing vertical, the spring could still compress and expand, albeit with some friction. However, when mounted at an angle as seen in Figure 25, the issue became far worse. This problem was only exacerbated by the time limit. During the production it was discovered that the current solution was of poor design, and more resources should have been allocated to this part. However, the process of cutting plates, using the lathe, welding and the final fitment left little time for adjustments.

There is however a remedy for this major issue of suspension, by switching to a bolt without threads on the middle section and adding a liner section for the middle plates, this problem could be solved. Thus allowing the spring assembly to function as originaly planned.

8.5 Driveline

Even though a tougher plastic, PETG, was used to print the planetary gears, parts of the gearbox broke during running. Interestingly enough, it was not the gears themselves that broke first, but the holders for the gears. This is good news, since these gear holders can be enforced with aluminum or other metal parts, much easier than the gears themselves. Preferably, the entire gearbox would be manufactured out of metal instead of plastic, and for other projects, with a bigger budget and more iterations, this is a must. The hypothesis is that the failure of the holders was caused by the loosening of nuts due to vibrations which could be solved by using loctite.

The motor and planetary gears were well protected inside the chassis. However, the chain and sprockets were not. This made them vulnerable to branches, dirt and other obstacles that could get caught in the chain and sprockets. An enclosure for the chain drive would have been beneficial. Such an enclosure increases the robustness of the driveline and also helps fulfill the IP-classification requirements. This was featured in the design concept, but was cut out due to time constraints.

8.6 Electronics

Currently, the motor is driven by ADC input. While the motor is connected to the battery and the Arduino is not connected to motor, the capacitor will start charging with the floating ADC voltage, causing the motor to spin during the 0.5-1.5V area. To avoid this problem it is necessary to connect the Arduino first before powering the motor.

The battery is currently separated into 5 sets, four 36V sets and one 12V battery, this induces difficulties to charge the battery and the motor will discharge each set differently causing voltage differences in the long term. There is also a lack of an overall kill switch, which induced a safety concern.

8.7 Testing

Due to manufacturing of parts taking longer than expected, as well as there being no way to bring the vehicle outside due to the path being blocked, proper testing of the vehicle could not be performed. This made it impossible to verify some of the technical requirements mentioned in section 1.3.2, especially the testable requirements mentioned in 7.2. As the vehicle was built with the requirements in mind it should theoretically be able to achieve all of them, but without proper testing it is impossible to confirm those theories. The only requirement that is confirmed not to be achieved is the water resistance, which could be remedied by installing more panels and filling in cracks between the panels with silicone or similar products.

9 Future Work

There were some parts of the original design that could not be implemented for various reasons. This presents an opportunity for a future project to implement these parts. Because of the aluminum extrusions used to create the frame, it would be easy to add or replace parts.

9.1 Linear actuators

An improvement that was considered, but not implemented, was linear actuators between the two different boxes of the frame. This addition would enable a greater control over the joint. Such control could be used both to enable sharper turns, and to assist in balancing the robot.

9.2 Hydraulic suspension

The current suspension leaves much to be desired, and is a good place to start if one wishes to make improvements to the robot. Though it exceeded the budget of this project, adding hydraulic suspension would greatly increase the ability of the rover to traverse rough terrain. The suspension would enable proper balance control for the robot, as well as hinder the oscillations that are to be expected when using a spring. Additionally, hydraulic suspension would enable the robot to execute special movements, such as "stepping" by lifting the wheels individually one at a time over obstacles.

9.3 Gearbox

Due to the nature of planetary gears, 3D printing is not one of the best manufacturing options. Because of the small contact surface between each gear, high stress is induced to the plastic material. The easiest way to improve this construction would be purchasing a metallic gearbox.

9.4 ROS on Arduino

It is possible to setup ROS on an Arduino using existing libraries. Currently the Arduino is not directly connected to ROS, but this improvement might streamline future work if additional information has to be passed from the Pi to the Arduino.

9.5 Waist Joint

While the articulating joint placed between the main frames is able to take loads larger than 50 kg (as specified in the technical requirements), it is one of the weakest points of the vehicle as a large part of the loads acts upon it causing a lot of torque. This makes the vehicle sag inwards and does neither inspire trust nor confidence, as can be seen in Figure 22. Making a better design would be greatly beneficial for both of these aspects as well as being able to carry larger loads.

9.6 Electronics

The problem of the motor spinning uncontrollably before start can be solved completely if the motor is mapped to throttle from 0-3.3V with a triggered reverse. Alternatively, future implementation using communication over a CAN bus between the Arduino and the ESC can be done to improve the overall system response.

The battery system could also be further improved by using one larger capacity battery with a battery management system. This would ensure each motor shares same voltage. It would also be easier to implement a kill switch. Finally it would make it easier to recharge the system, as the batteries have to be charged individually right now.

9.7 Requirements

As mentioned in section 8.7, all requirements could not be adequately tested. Doing proper tests and confirming if the requirements were met or not would be beneficial. Further waterproofing would also be beneficial to fulfill that requirement.

Appendix A Using the software

Both the controller node and the steering node currently have two different options for running the code. The controller node has two functions ”talker” and ”talker2”. ”talker” will require a keyboard input for throttle, direction (forwards or backwards) and turning ratio. ”talker2” uses the input from an Xbox controller connected via Bluetooth to generate numbers for throttle, direction and turning ratio from the controller's inputs. The steering node's two options are either running it from the controller nodes topic, or running it locally using a keyboard input in the same way as ”talker”.

Appendix B ROS launch on startup

Causing ROS to launch on startup was achieved by adding the simple line:

@lxterminal –command:”/home/pi/autolaunch.bash” into the file with the path:

/etc/xdg/lxsession/LXDE-pi/autostart.

This ensures that the terminal is opened on boot and will run the lines in *autolaunch.bash* containing the commands to enter the workspace of the ROS environment and launch the two nodes.

Appendix C Budget and Part List

Budget and Part List						
Purchases						
Part	Name	Quantity	Price each incl VAT	Price each excl VAT	Cost	Link
Screws Aluminum Profile	Skruv M5, MC6S 5x10	300	2.34	1.872	561.6	https://www.alucon.se/product/skruv-m5-mlc6s-5x10-50st
Bolts Aluminum Profile	Spårmutter M5, T-spår 5.5	300	17.48	13.984	4195.2	https://www.alucon.se/product/sparmutter-m5-t-spar-5-xdan-5a
Linear Actuator	LD3-24-10-K3-150-C11-POT-IP54-00	2	1500	1200	2400	https://www.oemmotor.se/produkter/linj%C3%A4ra-st%C3%A4lldon-,-a-,-domkrafter/linj%C3%A4ra-st%C3%A4lldon/ld3-_-692816
Wheels	Tunglasthjul - 250-1100 kg - räfflad eller mönstrad - lufthjul	4	2312.5	1850	7400	https://www.esska.se/shop/search/952932289700?promotedItem=952932289700
Angle Aluminum Profile	Vinkelfäste 42x42x42. M5. T-spår 5.5	40	57.86	46.288	1851.52	https://www.alucon.se/product/vinkelfaste-42x42x42-xdfa-44-b
Bullet connectors (5 pieces)	BULLET CONNECTORS 4MM 5 PAIR (FEMALE-MALE)	8	55	44	352	https://www.kullagergrossisten.se/en/product/bullet-connectors-4mm-5-pair-female-male
Bearing	6007 2Z Kullager Codex	24	49	39.2	940.8	https://www.kullagret.com/product/6007-2z-kullager-codex
Bearing	608 2Z Kullager MSC Ekonomi	50	10	8	400	https://www.kullagret.com/product/608-zz-kullager-msc-ekonomi
Spring	Article nr: 14560	4	1007.46	805.968	3223.872	https://www.fjadrar.se/produkter/tryckfjadrar?n_a_006=250.00-350.00&n_a_009=5.00-40.00
Cog JT 36	Bakdrev JT 36	4	199	159.2	636.8	https://www.skoterdelen.com/cross/drev-kedjor/bakdrev-jt-121436
Cog 15 teeths	Framdrev 15 kugg (420)	4	79	63.2	252.8	https://www.skoterdelen.com/moped/derbi/senda-50-r-sm-drd-00-05/kedja-drev/framdrev-15-kugg-420-78038
Chain	Kedja 420 1/2" x 1/4", 140 länk	4	179	143.2	572.8	https://www.skoterdelen.com/moped/yamaha/dt50-dt50r-98/kedja-drev/kedja-420-12-x-14-120-lank-75296
Chain Lock	Kedjelås 420, 1/2"x1/4"	4	19	15.2	60.8	https://www.skoterdelen.com/moped/yamaha/dt50-dt50r-98/kedja-drev/kedjelas-12x14-420
PETG Plastic	PETG	1	799	639.2	639.2	https://addnorth.se/product/PETG/PETG%20-%201.75mm%20-%202300g%20-%20White
ESC One Directional	T-Motor Flame 60A 6-12S	5	703	562.4	2812	https://cdon.se/leksaker/t-motor-flame-60a-esc-6-12s-p58439988?gclid=Cj0KCQjw2MWVBhCQARIsAIjbwoMeLY-kbA_LA0xOeKcqKnIOLJCSNPXxLsiY4FkAOX_6hNruabjecX4aAmvPEALw_wcB
Motor One Directional	Turnigy Aerodrive SK3 - 6374-149KV	4	1100	880	3520	https://hobbyking.com/en_us/turnigy-aerodrive-sk3-6374-149kv-brushless-outrunner-motor.html/?___store=en_us
ESC Bidirectional	Turnigy SK8 V2 80A 3~12S Single Motor Skateboard ESC	4	1260	1008	4032	https://hobbyking.com/en_us/turnigy-sk8-v2-80a-3-12s-single-motor-skateboard-esc.html?___store=en_us
Motor Bidirectional	Turnigy SK8 6374-192KV Sensored Brushless Motor (14P)	4	2020	1616	6464	https://hobbyking.com/en_us/turnigy-sk8-6374-192kv-sensored-brushless-motor-14p.html?___store=en_us
				Sum Purchases	40315.392	
From the KTH Mechatronics department						
Frame parts	Aluminum profiles, axles, aluminum and steel plates (estimated price)	1			15000	
Raspberry Pi		1			1400	
SD card		1			100	
				Sum KTH	16500	
				Sum Total	56815.392	

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