Autonomous Robot for Pavement Cleansing

A Personal Project

Christian Lykke Jørgensen

Lykke - Be Happier

AALBORG UNIVERSITY
STUDENT REPORT

Department of Electronic Systems
http://www.aau.dk

Title:

Project:
Autonomous Robot for Pavement Cleansing

Project Period:
Fall 2024

Project Group:

Participants:
Christian Lykke Jørgensen

Supervisor:
Kirsten Mølgaard

Page Numbers: 53

Date of Completion:
October 7, 2024

Abstract:

Howdy

Contents

Preface

This report searches to develop a Roomba-like autonomous robot capable of exterminating weeds in pavement for private users.

Aalborg University, 19-12-2023

Christian Lykke Jørgensen
cljo22@student.aau.dk

1 Introduction

Every homeowner with some variation of pavement has a common thorn in their eye; weeds, moss, and grass. It is a prevailing problem experienced by homeowners, city councils, public buildings, etc. Currently, the only "easy" solutions are harmful to the pavement, water reservoirs and/or release a wide range of greenhouse gasses. Apart from their environmental impact, most of these methods are fairly time-consuming and labor-demanding.

Without a doubt, a better solution is needed. However, these must first be examined and analyzed in depth to understand how to improve upon existing solutions. The individual environmental impact of each solution must be examined before a new approach can be proven a better solution. Therefore this project's initial problem statement can be expressed as:

"What is the currently most efficient method for removing unwanted plants and plantlike material from pavement, and what are its environmental impacts?"

2 | Problem Analysis

2.1 Existing Solutions

Before a new solution can be developed, current methods must be investigated, to understand their benefits and shortcomings. Each method will also be evaluated regarding its environmental impact and average time used to clean one square meter of 14x21cm "herregårdssten". The environmental impact will be a subjective scale of "small/medium/large" based on public guidelines set by Miljøstyrelsen and public consensus from institutions such as Bolius, Taenk, and Idenyt. Aforementioned guidelines and consensus can be accessed at: [1, 2, 3, 4, 5, 6, 7, 8, 9]. The average time used to clean one square meter of pavement will be based upon numbers from appendix A.1 on page 44 containing personal data collection from using different methods in my own driveway. Furthermore, a secondary number based upon Miljøstyrelsens numbers from their paper "Ukrudsbekæmpelse på Belægninger" will be available in cursive for some methods, [1].

2.1.1 Manual Pavement Cleaning

Manual pavement cleaning refers to dragging a stick such as seen in figure 2.1 through every groove between the individual paving tiles. This is an incredibly time-consuming task, as it requires the user to cleanse every mm of groove by hand. However, it is rather effective for cleaning pavement and is one of the most popular modes of cleaning pavement for private users.

Figure 2.1: Manual brush for cleaning pavement, [10].

Pros	Cons
Effective	Hard labour
Thorough	Not efficient
	Time consuming
Environmental Impact	Average Minutes Used to Clean $1m^2$
Small	1.554

Table 2.1: Pros and cons of manually cleaning the pavement.

2.1.2 Pressure Washer with Patio Cleaner

Using a pressure washer with a patio cleaner is one of the most effective methods of removing anything unwanted between tiles in the pavement. Unfortunately, it is almost impossible not to remove the wanted parts as well, as the washer jets are strong enough to remove the sand between the tiles while removing weeds and algae. A positive byproduct of using a pressurewasher correctly on pavement is, that the pavement is cleaned and most of the time given a "new" look. This only occurs if and when the pressure washer is used correctly, as incorrect use can damage the pavement to such an extent, that it has to be replaced.

After treating pavement with a pressure washer, it will need to be re-sanded, and in some cases will benefit from having preservatives added, to discourage algae growth in the future. This part of the process is rather expensive, as new sand has to be bought, and the preservative coating has to be distributed correctly. Another downside to using preservatives is, that some products still contain substances, that are damaging to the environment

Pros	Cons
Effective	Need to refill with sand afterwards
Thorough	Expensive (new sand)
Quick execution	Dirty
Very easy	Loud
	Damages the pavement
Environmental Impact	Average Minutes Used to Clean $1m^2$
Small - Medium[1]	5.197, *0.2, without refilling sand*

Table 2.2: Pros and cons of pressure washing the pavement.

2.1.3 Rotating Steel Brush

Like with manual pavement cleaning, using steel brushes is quite effective at removing unwanted plants. There even exist motorized versions, minimizing the amount of manual labor necessary, and further improving the effectiveness. However, steel brushes are prone to damaging the surface of the pavement, especially if used incorrectly or if it is overused. Apart from the risk of damaging the pavement, steel brushes still require a lot of manual labor to be an effective method for removing unwanted plants in the pavement. Furthermore, cheap steel brushes could lose bristles while being used, leaving steel wires in the vicinity of the cleaned area, which will eventually create rust stains if they are not removed. At a larger scale products such as the Kwern Greenbuster exist, but are generally aimed at professional use rather than the average homeowner.

Pros	Cons
Thorough	Hard labour
Easy to execute	Not efficient
	Time consuming
	Damages the pavement
	Possible rust patches from damaged wires
Environmental Impact	Average Minutes Used to Clean $1m^2$
Medium	1.479, *0.12*

Table 2.3: Pros and cons of cleaning the pavement with a rotating steel brush.

2.1.4 Chemicals

Chemicals are sadly one of the easiest and most widely used methods for handling unwanted plants in pavement. The chemical glyphosate found in many weed-removing solutions is illegal for private people to use. Apart from commonly approved chemicals, it is fairly common that homeowners use a mix of water and salt, vinegar, or other chemicals found in the cleaning cabinet. These homebrewed elixirs and remedies are in most cases more damaging to the environment than people think. Salt and vinegar is so harmful, that they're illegal to use for weed extermination in Denmark.

Even though most of the chemical solutions do a good job at killing the plants, they have to be applied several times over such long periods of time, that they are practically inefficient compared to manual removal. Furthermore, solutions such as salt is damaging to the water reserves and could possibly ruin the pavement as well, leading to premature replacement of the pavement.

Pros	Cons
Effective	Not efficient
	Damage to natural water reserves
	Damages the pavement
Environmental Impact	Average Minutes Used to Clean $1m^2$
Large	0.496 * number of passes for the plant to perish

Table 2.4: Pros and cons of using chemicals to clean the pavement.

2.1.5 Sweeping

The easiest way of keeping pavement free from weeds is to not let the weeds settle and sprout. By this, it is meant as sweeping the pavement at least once a week, if not more often, to disrupt any seeds settling into the crevices, and if any succeed, stressing them by continuous sweeping. However, this method is most effective at the early stages of any weed's life cycle.

Pros	Cons
Thorough	Hard labour
Easy	Not efficient
	Time consuming
	Mostly efficient against new weeds
Environmental Impact	Average Minutes Used to Clean $1m^2$
Small	0.346

Table 2.5: Pros and cons of sweeping the pavement.

2.1.6 Weed Burning

Burning weeds is the prevalent method used in private homes, professional cleaning services, and public institutions. The reasons being ease of use, low labor commitments, and instant results (if used wrong). When it comes to burning off weeds, most solutions have a large area of effect, which may not be optimal. In some cases, the effective area is quite a lot larger than the greenery being burned off.

Pros	Cons
Barely any labour	Fire
Very efficient if used correctly	Not efficient if used wrong
Easy	Time consuming
	Needs several passes to kill the plant
Environmental Impact	Average Minutes Used to Clean $1m^2$
Large	1.376, *0.12* * number of passes for the plant to perish

Table 2.6: Pros and cons of burning off weeds.

2.1.7 Laser-weeding

Laser-weeding is mostly known in agriculture, and still such a new concept that it has barely got a foothold. The first commercial laser weeding solution is made by Carbon Robotics based in Seattle and was launched during the summer of 2023, [11]. Their flagship product, the "LaserWeeder" is a carriage pulled by a tractor, with 30 150W CO2 lasers, 12 high-resolution cameras, and the capability of killing up to 300.000 weeds every hour, [12]. The "LaserWeeder" is currently the only commercially available technology designed to kill weeds with lasers, while WeedBot and WeLaser are alternatives still in the prototype stages, [13, 14]. Nevertheless, the effects of using lasers to kill weeds are being examined to a great extent across different use cases and under different circumstances. In general, laser weeding is scientifically approved as a concept, but is constrained by several factors such as limited knowledge regarding the long-term effects of using laser on plants and affiliated subjects, such as insects being hit as a byproduct, [15]. Another constraint regards machine learning and the current stage of artificial intelligence, which is mostly relevant for agricultural use where a machine has to discern between plants in different growth cycles and in different substrate compositions, [16]. It is consensus that laser-weeding is most efficient early in the growth cycle, especially at the cotyledon stage and two-leaf stage, [16, 17, 18]. A final constraint is the lack of established safety procedures following new technology. Even though lasers by no means are new technology, equipping autonomous robots with lasers capable of damaging organic matter, is quite new.

Pros	Cons
Barely any labour	Laser
Very efficient if used at optimal growth stages	Not as efficient on established plants
Easy	Expensive
Autonomous	Needs several passes to kill the plant
Fast	
Very eco-friendly	
Environmental Impact	Average Minutes Used to Clean $1m^2$
Small	0.0074^2

Table 2.7: Pros and cons of burning off weeds.

2.2 Private Autonomous Robots

Observing pavement de-weeding as a chore that has to be done, makes it possible to observe other chores that have been automated in a private home. Autonomous lawn mowing and Roombas are common in increasingly more homes, as they undertake a fairly simple, but time-demanding chore.

Autonomous lawn-mowing robots have evolved from bumping into everything and getting stuck in tall grass, to being adaptable and fit for almost any garden. Top-of-the-line robots is fit with GPS coordination, Bluetooth, rain sensors, four-wheel-drive, and batteries large enough for more than a thousand m^2 per charge. Combined with the newest advancements within the control of autonomous robots, they are capable of obstacle avoidance, rain-detection, optimizing routes, and dividing a lawn into multiple zones, including "no-go" zones, all within perimeter cables or other physical "restrictions". An example could be the LUBA 2 AWD 5000, which has all of the above features, [19].

Changing the focus to indoor use near people, pets, and other predicaments, robotic vacuum cleaners have advanced a lot as well. As with autonomous lawnmowers, top-of-the-line vacuum cleaners has evolved from "simple" robots bumping into everything and getting stuck in socks, to an "intelligent" robot. A Roomba Combo 10 Max has many of the same features as the LUBA 2, but with the addition of more advanced AI, capable of categorizing rooms, changing settings to fit a certain cleaning task, and schedule cleaning to fit a lifestyle, such as cleaning the kitchen after dinner each night, [20].

Both system types have integrated safety systems. Such a system could be the automatic blade-stop on the LUBA 2 or the scrub-stop in the Roomba, where it shuts down operation if a sudden change in slope or other suspicious movement is detected. Another safety feature available in both systems is obstacle avoidance. As neither system has to bump into objects before a change in direction is done, the chance of them tipping stuff over or hitting a person is minimized drastically.

Both systems are made to continuously do a simple task, in a semi-static environment near objects and beings. This draws several similarities to the task of cleaning pavement from weeds, and it is possible to draw inspiration from both areas, especially if they could be paired with the autonomous weed-killing available in the "LaserWeeder".

2.3 Problem Statement

Based upon current existing solutions, none of them pose as the most efficient method, without several drawbacks having varying importance dependent on the end-user. Returning to the initial problem statement:

"What is the currently most efficient method for removing unwanted plants and plantlike material from pavement, and what are its environmental impacts?"

The currently most efficient methods available to private users are pressure washing or burning the weeds if the determining metric is time used to remove the weeds (using Miljøstyrelsens numbers). Looking at personal experience with cleaning pavement of weeds, the most effective method is sweeping. However, sweeping pavement clean requires constant cleaning routines, rather than fewer routines of higher intensity for extended periods, such as manual cleaning. If the prosperity of the pavement is not important, faster results can be achieved by pressure washing or using a rotating steel brush. Chemicals are the sore thumb when it comes to common methods, as they are easy to use and mostly very effective, but ecologically not sound, as most users tend to overuse the chemicals.

This leaves burning the weeds and laser-weeding as the remaining methods. As both methods similarly stress the plant, another metric to determine superiority has to be used. Using price, the simple gas-burning solution is far superior, at least on initial cost, but using cost will eventually become larger than the combined acquisition and use cost for a laser system, based upon current gas and electricity prices. If time spent matters most, the possible autonomy of a laser-based system far outperforms a gas-burning solution. As shown by companies such as Carbon Robotics, it is possible to make a system capable of identifying weeds and discerning between different plants. Now, their solution is driven by a tractor and far from a private house-owner use case, but what if it could be adapted to fit the needs of a private individual? Combining the laser-weeding element with known solutions within lawn care such as the LUBA 2 AWD 500 and the iRobot Roomba Combo 10 Max could potentially be a solution, resulting in the following problem statement:

"How can an automated laser-weeding robot be developed to fit the needs of a private user wanting to clean their pavement from weeds?"

However, there is a catch regarding this, as only one person is working on this project. To make it more reasonable, the problem statement is reduced significantly. Nevertheless, the demand specification and general idea will still regard a complete system, until the technical analysis and system design is started, whereafter the project scope will be limited to fit the final problem statement:

"How can an automated pavement-following robot platform be developed?"

3 | Demand Specification

3.1 Limitating the Project

As this project only stretches for a single semester and is being done by a single student, some limitations must be made. Instead of focusing on developing a full system meeting a large number of demand specifications from the start, the project will be divided into iterations - A demand specification for a full system is available in the appendix at sections A.2 and A.3. Therefore each iteration will have its own distinct goal(s) and specifications that it should meet. The first iteration will be the minimum viable product (MVP) and goal of this project. Further iterations will contain increasingly advanced features not described in depth in this project.

3.2 High Level Specification

This section describes a high-level overview of the functionality desired for the pavement cleansing robot. It is written as seen by a private person wanting to ease cleaning their pavement. Detailed specification can be found in section 3.3 starting page 9.
As a house owner looking to ease removing weeds from my pavement, I want:

- *An autonomous robot capable of moving around.*
- *A charge point/home at which the robot can dock when not in use/when it has to charge.*
- *An autonomous robot that updates me of its whereabouts and I can call "home" in case it is in my way.*
- *An autonomous robot that returns "home" before the battery dies.*
- *An autonomous robot that systematically cleans my driveway and other pavement, and therefore does not just bump around like a Roomba.*
- *An autonomous robot that detects cars, outdoor furniture, and the like, so that it will only operate around objects where it is safe.*
- *An autonomous robot capable of mapping what parts of the driveway that has been cleaned.*
- *An autonomous robot avoiding obstacles without bumping into them.*

A high-level specification for a complete system can be found in appendix A.2 on page 45 along with a functional specification in appendix A.3 on page 46.

3.3 Functional Specification

This section describes the functional criteria of the product. The criteria are seen from an end-user perspective and made as user stories, where accept criteria (AC1 & AC2 e.g.) must be fulfilled. A test of the functional specifications is made in section 7.

3.3.1 Operate the Robot

As a house owner, I want an autonomous robot capable of moving around.
Accept Criteria:
AC1:
The robot should be able to drive forward.
AC2:
The robot should be able to drive backward.
AC3:
The robot should be able to turn around its own axis (Z-axis).

3.3.2 A Home for the Robot

As a house owner, I want a charge point/home at which the robot can dock when not in use/when it has to charge.
Accept Criteria:
AC1:
The charge point should be able to contain the robot.
AC2:
The robot should be able to charge when not in use.
AC3:
The robot should be able to communicate with the charge point.

3.3.3 User-interface

As a house owner, I want an autonomous robot that updates me of its whereabouts and I can call "home" in case it is in my way.
Accept Criteria:
AC1:
At all times the robot should broadcast its whereabouts.
AC2:
If the robot is in the way, a user-interface should enable me to send it "home" or to another area.

3.3.4 Robot Go Home

As a house owner, I want an autonomous robot that returns "home" before the battery dies.
Accept Criteria:
AC1:
At all times enough battery power is left to drive "home" + 10% extra distance, meaning that a 20-meter travel home, requires power for at least 22 meters.
AC2:
The robot should be capable of mapping a route "home" with obstacles such as corners, cars, and lawnchairs added, to accommodate non-direct routes.

3.3.5 Systematical Procedure

As a house owner, I want an autonomous robot that systematically cleans my driveway and other pavement, and therefore does not just bump around like a Roomba.
Accept Criteria:
AC1:
The robot has to map out all paved areas.
AC2:
A systematic approach following lines in the pavement has to be used.
AC3:
If several types of pavement are present, different areas must be mapped to distinguish and optimize routes for each area.

3.3.6 Spatial Awareness

As a house owner, I want an autonomous robot that detects cars, outdoor furniture, and the like, so that it will only operate around objects where it is safe.
Accept Criteria:
AC1:
The robot must be capable of determining whether or not, it can fit within a space.
AC2:
The robot must keep a minimum clearance of 10cm to anything above, so as to not wedge itself beneath anything.

3.3.7 Memory Capabilities

As a house owner, I want an autonomous robot capable of remembering what parts of the driveway have been cleaned.
Accept Criteria:
AC1:
The robot must map out which areas have been cleaned at which point, to rotate between areas.
AC2:
The robot must be capable of increasing its speed when no greenery is present.

3.3.8 Obstacle Avoidance

As a house owner, I want an autonomous robot avoiding obstacles without bumping into them.
Accept Criteria:
AC1:
The robot must not hit anything to change its course.
AC2:
The robot must not be closer than 5cm to anything in any direction, other than the pavement below it.
AC3:
The robot must not drive off of a ledge and tumble down.
AC4:
If the robot cannot turn around its own axis, it must reverse out from its current spot.
AC5:
If presented in a corner with no way out, the robot must turn off and notify the owner.

3.4 Electrical Specification

The electrical specification is currently based on preliminary assumptions and will remain flexible until a comprehensive technical analysis and system design is completed. The following initial specifications are proposed, based on similar systems and available reference manuals:

- Battery Capacity: 10 Ah (capacity may be adjusted based on measured energy consumption requirements).
- Battery Voltage: 12-18V (for compatibility with motors and auxiliary systems).
- Operating System Voltage: 3.3V (suitable for microcontrollers and low-power electronics).
- Motor Voltage: 12-24V (standard voltage for robotic drive motors).
- Auxiliary Equipment Voltage: 12V (for components such as cooling fans, lights, etc.).
- Sensor Voltage: 3.3V (common voltage for environmental and navigation sensors).
- Laser Power Supply: 5-24V (assuming a low-power solid-state laser for weeding, power requirements will depend on the specific laser selected).
- Charging System Voltage: 24V (for rapid charging circuits, depending on battery chemistry).
- Power Consumption: Estimated at 200-250W during peak operation (including motor, sensor, and laser operation).
- Communication Voltage: 3.3V or 5V (for wireless modules such as Wi-Fi, Bluetooth, or LoRa).
- Power Management Unit: 5V/3.3V DC-DC converters to manage voltage distribution efficiently across different subsystems.

These specifications are informed by reference data from "Dr Robot's" manual for the Jaguar Lite robot, which the prototype is modeled after, [21]. Similar robotic platforms such as autonomous lawnmowers and vacuum cleaners generally operate at 12V with battery capacities ranging from 2.8-8.8Ah, [19, 22]. Future adjustments will depend on detailed load analysis and testing.

4 Technical Analysis

In an effort to analyze the technical needs of the project, the demands set for the 1st iteration have been revisited. This identified the following areas of interest:

Area of Interest	Associated Functional Specification
General Control of Autonomous Robots	Operate the Robot
Sensors	Spatial Awareness, and Obstacle Avoidance
Machine Vision	Systematical Procedure, Obstacle Avoidance, and Memory Capabilities
Mapping	A Home for the Robot, Systematical Procedure, Robot Go Home, Memory Capabilities, and Obstacle Avoidance
Power Monitoring	A Home for the Robot, Robot Go Home and Memory Capabilities
Wireless Communication	A Home for the Robot, User-interface, Robot Go Home, and Memory Capabilities

Table 4.1: Overview of which areas will be covered in the technical analysis and their relation to various functional specifications.

With this overview, it is possible to analyze large parts of the system, before implementing the knowledge into the system-design phase. It should be noted that machine vision has been chosen over other methods for analyzing surroundings, as the environment in which the platform will operate is natural, and therefore poses situations where "simpler" methods have been deemed insufficient. Moreover, vision-based navigation is a passive method, whereas lasers, sonar, IR, etc. are active methods, possibly "altering" the environment by introducing waves or light, [23]. With increased computing power, a vision-based system could also extract far more information, than most unifications of other sensors, cheaper and more reliably, provided an effective algorithm is in place, [23].

4.1 General Control of Autonomous Robots

To narrow the subject down to relevant information, this section will focus on operating and designing the operation of autonomous wheel-driven vehicles. Furthermore, this section will incorporate knowledge for creating stable and smooth systems. At first, a consensus on how autonomous vehicles move will be reached, with corresponding describing terms.

To break the control of autonomous robots even further down, their operation can be broken down into five segments:

1. Mapping: Even the simplest autonomous robots require some form of mapping in order to perform their task. Coordinates or physical boundaries could represent the mapping.
2. Data Acquisition: The robot has to "observe" the environment, and collect data from sensors.
3. Feature Recognition: Extracting distinct features will in most cases be significant for the operation, ensuring that certain textures, colors, or physical constraints are avoided or approached.
4. Landmark[1] Identification: Related to mapping, the robot should be able to match landmarks to coordinates or other preset criteria (mostly relevant for vision-based systems).
5. Self-localisation: As most autonomous robots move around, they have to know where they are. This can be achieved by measuring the distance traveled, or better yet, measuring distances to known landmarks. Paths can also be derived from knowing the current location.

A good basis for autonomy is made with the above segments in place. However, navigating the now-known environment requires the robot to solve four subproblems more, before embarking on its task:

1. World Construction: The above segments have to be combined to create a world perception wherein the robot can operate.
2. Path Planning: Based on the perceived/constructed world, the robot needs a task, which it can divide into an ordered sequence of subtasks.
3. Path Generation: With the ordered sequence of subtasks, a path between them must be made, considering the environment.
4. Path Tracking: While it may seem simple to "move 1 meter forward", the robot must at all times reassess its position with regard to known landmarks, as it could otherwise believe it has moved 1 meter, while in reality not moving at all.

Even with the added steps of constructing and following a path made to fit a task, autonomous robots can still meet obstacles hindering their operation. Avoidance of such obstacles will be discussed more in-depth in section 4.3 starting page 18. The above lists are derived from the first chapter of [23].

4.1.1 Electrical Systems in Autonomous Robots

All vehicular autonomous robots share the same basic electrical elements. While most robots contain far more elements than the 6 mentioned below, these 6 broad elements are present in all vehicular robots.

[1] In this case, a landmark could be anything, such as a doorway, charge point, etc., and not necessarily a landmark such as a statue or a monument.

- Battery
- Motor(s)
- World Interpreting Sensors
- Memory (for mapping purposes)
- Wireless Communication
- Computing

4.1.2 Movement

The movement of an autonomous robot requires knowledge of its steering and wheel topology. To avoid discussing subjects unrelated to a final design, the reader should note that a tracked topology has been chosen for this project, and the reasoning behind can be found in section 5.10.2 starting page 32. Nevertheless, a short introduction to various platforms will be made.

Typical platform topologies are:

- Two-wheel with a nose wheel
- Four-wheel with steering in one end.
- Multi-wheel with fixed axles.
- Articulated steering.
- Tracked.
- Steering at all wheels.

While these six topologies vary wildly from each other when observed, their steering and general movement are similar for at least three of them. The two-wheel, multi-wheel, and tracked topology all rely on different motor speeds at each side to steer, while the articulated and four-wheeled topology steers by orienting a set of wheels differently to the other set. The only true outlier is robots with the capability of steering at all wheels. In figure 4.1 the six topologies are shown turning to the left, exemplifying that to obtain the same movement, similar but still different approaches are needed.

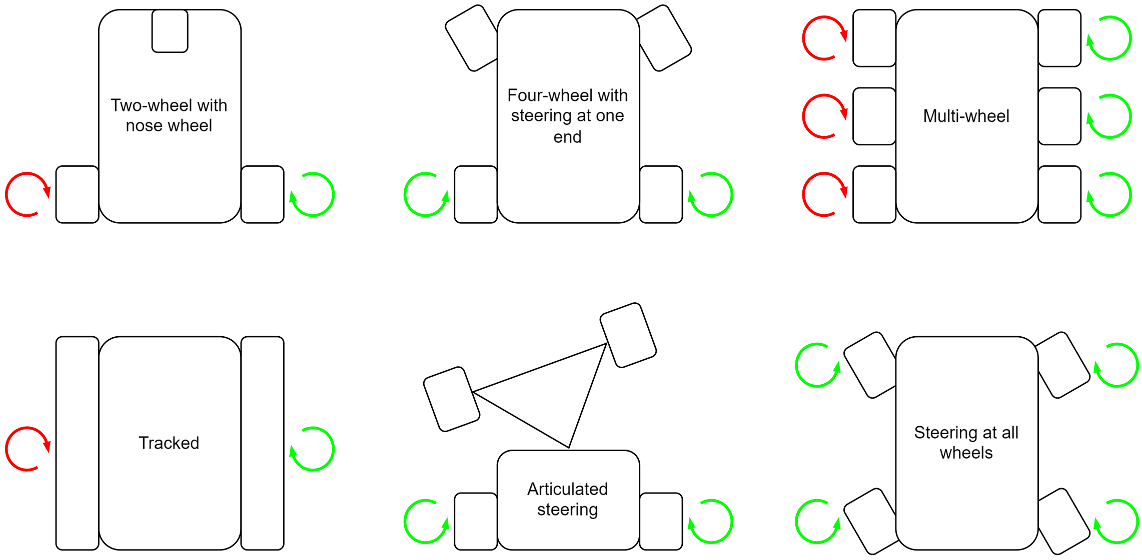

Figure 4.1: The six most common steering topologies used for vehicular robots. Arrows signify driving wheels, with green arrows signifying a forward movement and red signifying a backward movement. All six topologies are steering left in this drawing.

From here, the focus will lie on a tracked vehicle's movement and proprietary behavior. As can be seen from figure 4.1, the tracked topology relies on either moving each track in opposite directions or at least at different speeds to steer in any direction.

A benefit posed by sufficiently strong tracked vehicles is the ability to turn around its z-axis if the tracks are rotating opposite. Unfortunately, an innate side effect is that when moving forward, the turning circle becomes rather large, dependent on the speed. In figure 4.2 different operations on a joystick are paired with the steering of a tracked vehicle.

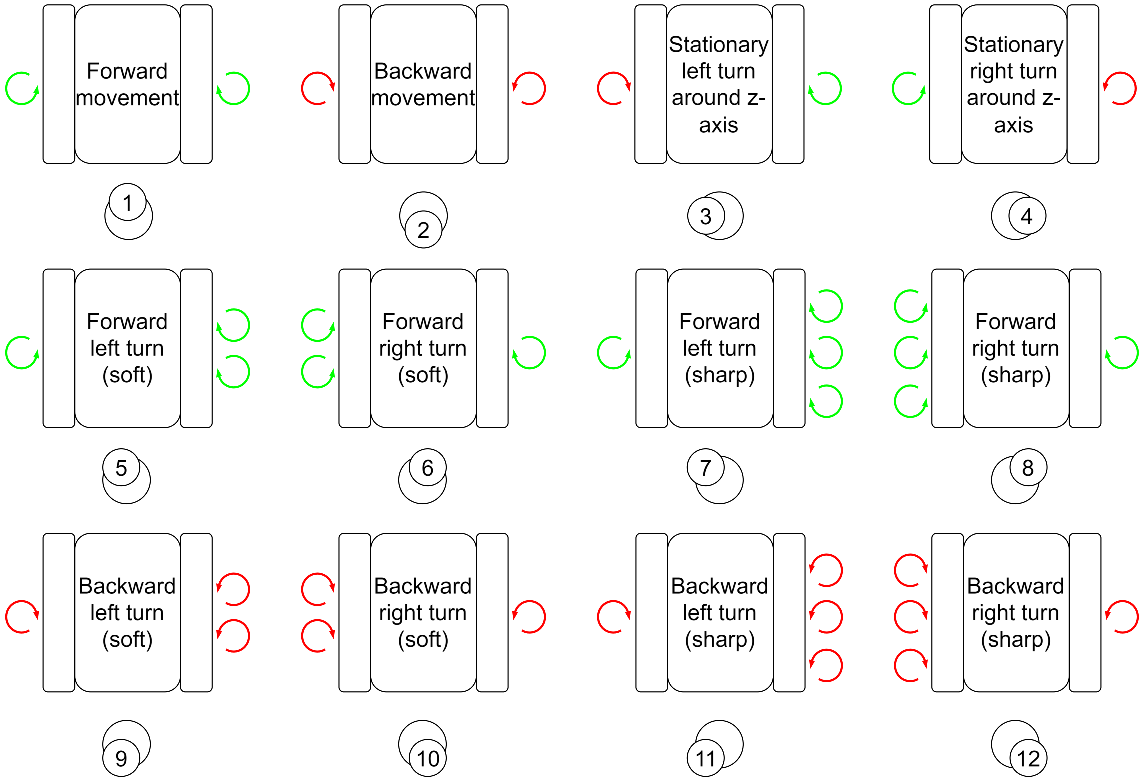

Figure 4.2: Twelve common operations for a tracked vehicle. Beneath each operation, a corresponding joystick placement is found. The number of rotating arrows signifies the speed of each track, and as in figure 4.1, red is backward and green forwards.

4.1.3 Reacting to the Environment

Now that movement of an autonomous robot has been described, it has to move intelligently around, meaning it has to take its surroundings into account - machine vision and its corresponding benefits, disadvantages, and uses will be described in detail in section 4.3 starting page 18. This section strives to explain common control loops related to the operation of an autonomous robot posed with a more demanding environment, than an empty floor. The first control loop worth mentioning is also the simplest, as it does not relate to any autonomy yet, but rather input made from a joystick.

In figure 4.3 a flowchart can be seen showing the steps used to manually adjust the movement of a tracked vehicle. In the flowchart, the user isn't directly controlling the speed at each track as a controller maps the joystick position to a signal that the motor at the left/right track can translate into movement unless the current speed matches the joystick position. What this flowchart does not contain, is assurance of the actual state of each track, nor any information of whether or not the tracked vehicle moves as instructed. That knowledge is reserved for the user, observing the vehicle.

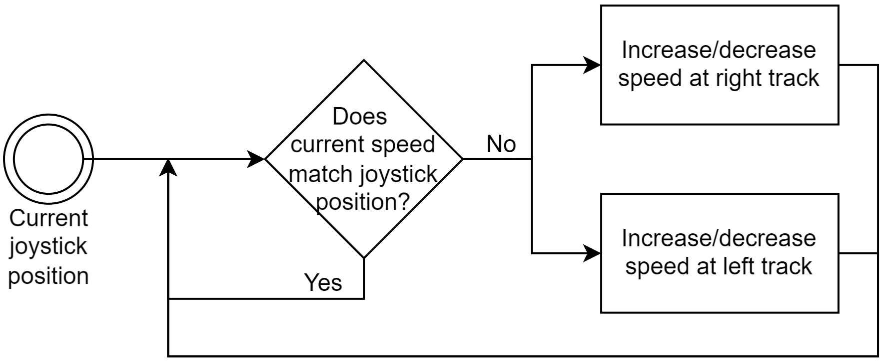

Figure 4.3: Caption

4.1.4 Stable and Unstable Systems

Obtaining a Stable System

Feedback Systems

Feedforward Systems

MIMO Systems

4.2 Sensors

4.2.1 ESPCAM

4.2.2 Distance Sensor

4.3 Machine Vision

4.3.1 Image Processing

4.3.2 Object Detection

4.3.3 Pattern Recogniction

4.4 Mapping

4.4.1 Instantiating a Coordinate System

4.4.2 Localizing a "Home"

4.4.3 Mapping Boundaries

4.4.4 Dividing Into Zones

4.4.5 A Systematical Approach

4.4.6 Remembering Obstacles

4.5 Power Monitoring

4.5.1 Battery Power

4.6 Wireless Communication

4.6.1 Bluetooth

Usage

Protocols

4.6.2 Wi-Fi

Usage

Hosting

Protocols

5 System Design

5.1 System Design Overview for the 1st Iteration

To create an intuitive overview of what elements the 1st iteration will be composed of, it is divided into modules. The modules do not contain specific knowledge at this point. Still, they will mostly serve as an overview of what the different modules are supposed "to do", before the final system design of each module will begin, leading to grounds for designing a system capable of meeting the functional specification.

- Drive motors.
  Motors meant to operate the robot physically.
- Power source.
  A combined power source capable of powering all parts of the robot.
- Power distribution/relay.
  DC-DC converters to match power from the power source to individual systems and relays for switching subsystems on/off.
- Microcontroller.
  The main operating processer, responsible for operating the robot and responding to input from sensors and the Computing module.
- Sensors.
  Sensors meant to enable "spatial awareness" of the robot.
- Camera.
  The main way of determining if the robot is on the correct course through machine vision or other similar protocols.
- Computing.
  The computing module will handle larger computations, such as machine vision/image processing, and possibly be placed externally from the robot.
- Wireless communication.
  The communication module will enable communication between the robot, the charge point, and the user.
- Physical platform (Dr Robot Jaguar Lite).
  The physical platform on which the prototype will be developed.
- Charge point.
  External housing which contains the computing module, wireless communication, user interface, and in future iterations, charging capabilities

From the above list, a block diagram has been made to show interfaces between the modules. The block diagram can be seen in figure 5.1 on page 23.

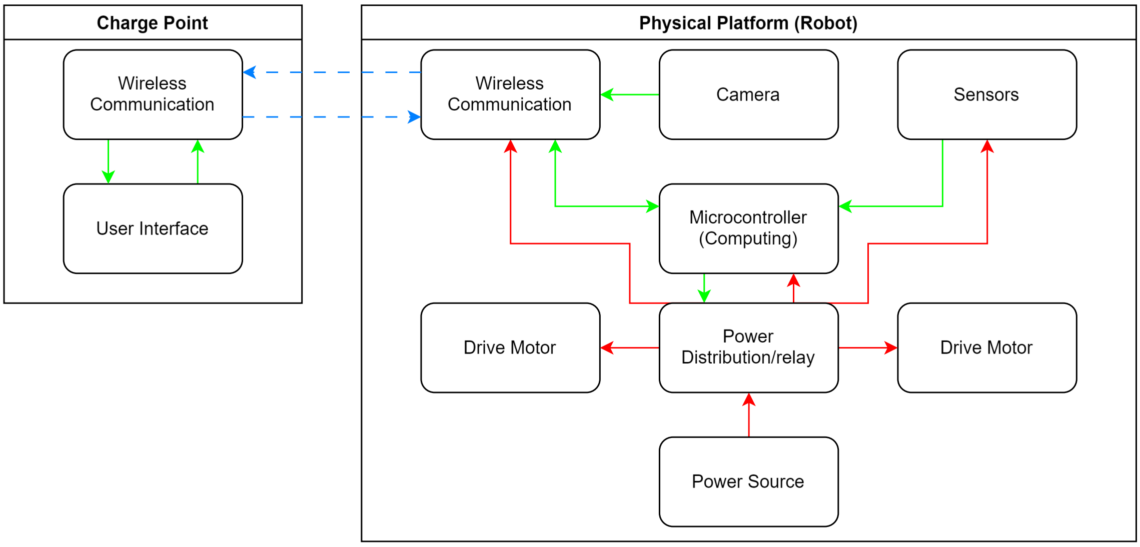

Figure 5.1: Block diagram showing relations between modules of the 1st iteration. Red lines signify power, green signify data, and blue dotted signify wireless data.

From the block diagram, a procedure can be established for determining each module and how they relate to each other. As power distribution requires knowledge of the voltages needed for each succeeding module, it will be the second-to-last module followed by the power source. The first modules to analyze are the microcontroller and camera, as they both determine the needs of connected modules. At the very end, the physical platform and charge point will be analyzed. This leaves the technical analysis sequence as follows:

1. Microcontroller.
2. Camera.
3. Wireless Communication.
4. Computing.
5. Sensors.
6. Drive Motors.
7. Power Distribution/Relay.
8. Power Source.
9. Physical Platform.
10. Charge Point/User Interface.

5.2 Microcontroller Module

The microcontroller has to connect to a supposedly large amount of sensors (at least 5 along the front of the robot) as well as control power distribution and wireless communication, a large amount of I/O pins will be handy, along with integrated wireless communication, and multiple cores for added processing power.

5.2.1 Specification

-

5.2.2 Design

5.2.3 Implementation

5.2.4 Test

Test Setup

Actual Testing

Test Results

5.2.5 Summary

5.3 Camera Module

5.3.1 Specification

-

5.3.2 Design

5.3.3 Implementation

5.3.4 Test

Test Setup

Actual Testing

Test Results

5.3.5 Summary

5.4 Wireless Communication Module

5.4.1 Specification

•

5.4.2 Design

5.4.3 Implementation

5.4.4 Test

Test Setup

Actual Testing

Test Results

5.4.5 Summary

5.5 Computing Module

5.5.1 Specification

-

5.5.2 Design

5.5.3 Implementation

5.5.4 Test

Test Setup

Actual Testing

Test Results

5.5.5 Summary

5.6 Sensors Module

5.6.1 Specification

-

5.6.2 Design

5.6.3 Implementation

5.6.4 Test

Test Setup

Actual Testing

Test Results

5.6.5 Summary

5.7 Drive Motors Module

5.7.1 Specification

-

5.7.2 Design

5.7.3 Implementation

5.7.4 Test

Test Setup

Actual Testing

Test Results

5.7.5 Summary

5.8 Power Distribution Module

5.8.1 Specification

-

5.8.2 Design

5.8.3 Implementation

5.8.4 Test

Test Setup

Actual Testing

Test Results

5.8.5 Summary

5.9 Power Source Module

5.9.1 Specification

-

5.9.2 Design

5.9.3 Implementation

5.9.4 Test

Test Setup

Actual Testing

Test Results

5.9.5 Summary

5.10 Physical Platform Module

GRUNDIG BESKRIVELSE AF HVORFOR PÅ LARVEFØDDER

5.10.1 Specification

-

5.10.2 Design

5.10.3 Implementation

5.10.4 Test

Test Setup

Actual Testing

Test Results

5.10.5 Summary

5.11 Charge Point Module

5.11.1 Specification

•

5.11.2 Design

5.11.3 Implementation

5.11.4 Test

Test Setup

Actual Testing

Test Results

5.11.5 Summary

6 Integration

Blokdiagram over hele systemet, som er virkelig detaljeret

6.1 Physical Platform and Charge Point

6.2 MCU, Drive Motors, Power Source, and Power Distribution

6.3 Sensors

6.4 Camera, Computing, and Wireless Communication

7 Acceptance test

8 | Discussion

9 | Conclusion

Bibliography

[1] "Ukrudtsbekaempelse på belaegninger". In: ().

[2] *Biodiversitet - Miljøstyrelsen*. URL: https://mst.dk/borger/natur-og-fritid/natur-og-biodiversitet/biodiversitet.

[3] *Du må ikke længere bruge Roundup midler med glyphosat på veje, fortove, gårdspladser, terrasser, grusstier og lign. - Miljøstyrelsen*. URL: https://mst.dk/nyheder/2024/februar/du-maa-ikke-laengere-bruge-roundup-midler-med-glyphosat-paa-veje-fortove-gaardspladser-terrasser-grusstier-og-lign.

[4] *Forbud mod at bruge Roundup i indkørsler og på terrasser*. URL: https://www.bolius.dk/slut-med-at-bruge-roundup-i-indkoersler-og-paa-terrasser-97376.

[5] *Sådan bekæmper du IKKE ukrudt | Brug fx ikke salt eller eller eddikesyre*. URL: https://www.bolius.dk/saadan-bekaemper-du-ikke-ukrudt-2959.

[6] *Populært ukrudtsmiddel gjort ulovligt: Her er alternativerne | Havehobby.dk*. URL: https://via.ritzau.dk/pressemeddelelse/13577322/populaert-ukrudtsmiddel-gjort-ulovligt-her-er-alternativerne?publisherId=13559506.

[7] *Naturlig ukrudstbekæmpelse: Derfor bør du undgå salt mod ukrudt | idenyt*. URL: https://idenyt.dk/haven/ukrudt/fa-styr-pa-ukrudtet-inden-det-far-fat/.

[8] *Må du bruge eddike eller eddikesyre til at bekæmpe ukrudt?* URL: https://www.bolius.dk/maa-du-bruge-eddikesyre-som-ukrudtsmiddel-35665.

[9] *Græsplæner - Miljøstyrelsen*. URL: https://mst.dk/erhverv/sikker-kemi/pesticider/anvendelse-af-pesticider/graesplaener.

[10] *Fugebørste med skraber - Freund | BAUHAUS*. URL: https://www.bauhaus.dk/fugeborste-med-skraber-freund.

[11] *News & Media — Carbon Robotics*. URL: https://carbonrobotics.com/news-media.

[12] *Technology — Carbon Robotics*. URL: https://carbonrobotics.com/laserweeding-technology.

[13] *WeedBot Products*. URL: https://weedbot.eu/weedbot-products/.

[14] *We Laser Project: Eco-Innovative weeding with laser*. URL: https://welaser-project.eu/.

[15] Christian Andreasen et al. "Side-effects of laser weeding: quantifying off-target risks to earthworms (Enchytraeids) and insects (Tenebrio molitor and Adalia bipunctata)". In: *Frontiers in Agronomy* 5 (Nov. 2023), p. 1198840. ISSN: 26733218. DOI: 10.3389/FAGRO.2023.1198840/BIBTEX. URL: https://welaser-project.eu/.

[16] Christian Andreasen, Karsten Scholle, and Mahin Saberi. "Laser Weeding With Small Autonomous Vehicles: Friends or Foes?" In: *Frontiers in Agronomy* 4 (Mar. 2022). ISSN: 26733218. DOI: 10.3389/FAGRO.2022.841086.

[17] Christian Andreasen et al. “Laser weed seed control: challenges and opportunities”. In: *Frontiers in Agronomy* 6 (2024). ISSN: 26733218. DOI: 10.3389/FAGRO.2024.1342372/FULL.

[18] Christian Andreasen, Eleni Vlassi, and Najmeh Salehan. “Laser weeding of common weed species”. In: *Frontiers in Plant Science* 15 (May 2024), p. 1375164. ISSN: 1664462X. DOI: 10.3389/FPLS.2024.1375164/BIBTEX. URL: https://welaser-project.eu/.

[19] *LUBA AWD 5000 : Robotplæneklipper uden tråd i perimeteren*. URL: https://mammotion.com/products/luba-awd-5000-perimeter-wire-free-robot-lawn-mower.

[20] *iRobot® Roomba® Combo 10 Max*. URL: https://www.irobot.dk/products/combo-10-max.

[21] *Dr Robot Inc.: WiFi 802.11 robot, Network-based Robot, robotic, robot kit, humanoid robot, OEM solution*. URL: http://jaguar.drrobot.com/specification_lite.asp.

[22] *iRobot Roomba robotstøvsuger | Opdateret 2024-sortiment*. URL: https://www.irobot.dk/collections/roomba-robotstoevsugere.

[23] Amitava. Chatterjee, Anjan. Rakshit, and N. NirmalSingh. *Vision Based Autonomous Robot Navigation : Algorithms and Implementations*. eng. Ed. by Amitava. Chatterjee et al. Elektronisk udgave. Studies in Computational Intelligence, 455. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013. ISBN: 9783642339653.

[24] *TMX1000 - Pris 1 stk. 4.599,- 10+ stk. på eget lager. - texas.dk*. URL: https://www.texas.dk/da/products/robotplaeneklipper/tmx1000/?partno=90070243.

Glossary

MVP Minimum Viable Product. 8, 52

A | Appendix

A.1 Average Cleaning Time Driveway

The testing/timing has been done by cleaning the driveway every 3 weeks across the 2024 season with one of the mentioned methods and timing how long each method took. The driveway has had similar growth between each clean, however, do keep in mind that the driveway is being used and identical weed growth cannot be guaranteed, making these numbers a mere guideline rather than strict facts."Aftertreatment" refers to treatment such as refilling pavement with sand, sweeping dead shrubs away, etc.

Method	Area in m^2	Time Used	Aftertreatment	Time Per m^2
Manual Cleaning	106.8	166		1.554
Pressure Washing	106.8	204	351	5.197
Rotating Steel Brush	106.8	128	30	1.479
Chemicals	106.8	53		0.496
Sweeping	106.8	37		0.346
Weed Burning	106.8	117	30	1.376

Table A.1: Average cleaning time per square meter of herregårdssten in my own (Christians) driveway. All times are in minutes.

A.2 High Level Specification - Full System

This section describes a high-level overview of the functionality desired for the pavement cleansing robot. It is written as seen by a private person wanting to ease cleaning their pavement. Detailed specification can be found in section A.3 starting page 46.
As a house owner looking to ease removing weeds from my pavement, I want:

- *An autonomous robot capable of removing dandelions, moss, grass, and other common weeds found in the pavement.*
- *An autonomous robot capable of moving around.*
- *A charge point/home at which the robot can dock when not in use/when it has to charge.*
- *An autonomous robot that updates me of its whereabouts and I can call "home" in case it is in my way.*
- *An autonomous robot capable of climbing my driveway (37%/20°rise).*
- *An autonomous robot that returns "home" before the battery dies.*
- *A fully autonomous robot, meaning that I will only need to do one setup procedure, and then it will work forever.*
- *An autonomous robot only removing weeds within my land.*
- *An autonomous robot that can distinguish between pavement styles, and act accordingly.*
- *An autonomous robot that systematically cleans my driveway and other pavement, and therefore does not just bump around like a Roomba.*
- *An autonomous robot capable of passing an IP56 test.*
- *An autonomous robot that can detect when a puddle is nearby, and go around it.*
- *An autonomous robot that detects cars, outdoor furniture, and the like, so that it will only operate around objects where it is safe.*
- *An autonomous robot that adjusts its pattern, based both on the weather and on previous passes. I.e. if there were a lot of weeds on the previous pass around the driveway, it would schedule a new pass earlier.*
- *An autonomous robot capable of mapping what parts of the driveway that has been cleaned.*
- *An autonomous robot avoiding obstacles without bumping into them.*
- *An autonomous robot making as little noise as possible.*
- *An autonomous robot as small in size as possible, ideally no larger than a Roomba (approximately 45cm), [22].*
- *An autonomous robot that does not get stuck at random places around my land; if it does get stuck, I want it to attempt to get unstuck.*
- *An autonomous robot capable of cleaning a minimum of 500m^2.*

A.3 Functional Specification - Full System

This section describes the functional criteria of the product. The criteria are seen from an end-user perspective and made as user stories, where accept criteria (AC1 & AC2 e.g.) must be fulfilled. A test of the functional specifications are made in section 7.

A.3.1 Weed Removal

As a house owner, I want an autonomous robot capable of removing dandelions, moss, groundsel, grass, and other common weeds found in the pavement.
Accept Criteria:
AC1:
The robot should be capable of burning off several types of weeds, including but not limited to: dandelion, grass, groundsel, moss, thistle, cleavers, and horsetail.
AC2:
The robot should be capable of only burning the necessary intensity to stress the plants, without setting them aflame.
AC3:
All plants should perish within a season of continuous burning.
AC4:
The robot should be able to distinguish between weeds and non-organic items, such as a gardenhose.

A.3.2 Operate the Robot

As a house owner, I want an autonomous robot capable of moving around.
Accept Criteria:
AC1:
The robot should be able to drive forward.
AC2:
The robot should be able to drive backward.
AC3:
The robot should be able to turn around its own axis (Z-axis).

A.3.3 A Home for the Robot

As a house owner, I want a charge point/home at which the robot can dock when not in use/when it has to charge.
Accept Criteria:
AC1:
The charge point should be able to contain the robot.
AC2:
The robot should be able to charge when not in use.
AC3:
The robot should be able to communicate with the charge point.

A.3.4 User-interface

As a house owner, I want an autonomous robot that updates me of its whereabouts and I can call "home" in case it is in my way.

Accept Criteria:
AC1:
At all times the robot should broadcast its whereabouts.
AC2:
If the robot is in the way, a user-interface should enable me to send it "home" or to another area. **AC3:** The interface should enable me to take control of the robot, effectively making it remote-controlled.

A.3.5 Go Anywhere

As a house owner, I want an autonomous robot capable of climbing my driveway (20% rise).
Accept Criteria:
AC1:
The robot should be able to climb a 20% rise.
AC2:
The robot should be capable of traversing poorly laid pavement (up to 30mm height difference between tiles).
AC3:
The robot should be capable of traversing small obstacles, such as a garden hose.

A.3.6 Robot Go Home

As a house owner, I want an autonomous robot that returns "home" before the battery dies.
Accept Criteria:
AC1:
At all times enough battery power is left to drive "home" to a charging point + 10% extra distance, meaning that a 20-meter travel home, requires power for at least 22 meters.
AC2:
The robot should be capable of mapping a route "home" with obstacles such as corners, cars, and lawnchairs added, to accommodate non-direct routes.

A.3.7 Easy Setup

As a house owner, I want a fully autonomous robot, meaning that I will only need to do one setup procedure, and then it will work forever.
Accept Criteria:
AC1:
The robot has to be capable of adjusting its trajectory and routing to changing environments, as long as the outer bounds do not change.
AC2:
The robot "home" has to be connectable to a standard wall socket.
AC3:
The robot has to auto-charge between passes.
AC4:
The robot should be updateable and automatically update at convenient times.
AC5:
The robot should be easy to connect to secondary devices, such as phones, routers, etc..

A.3.8 Stay On My Turf

As a house owner, I want an autonomous robot only removing weeds within my land.
Accept Criteria:
AC1:
The robot should not wander off from assigned bounds.
AC2:
The robot has to stay within its registered land.
AC3:
If placed off of its registered land, it should first ping its "home" to plan a possible route home, or simply send a message to the owner before turning off.

A.3.9 Pattern Recognition

As a house owner, I want an autonomous robot that can distinguish between pavement styles, and act accordingly.
Accept Criteria:
AC1:
The robot should be capable of recognizing the following (danish) pavement styles: herregårdssten (14x21cm), modul fliser (30x30cm, 30x60cm, 60x60cm, 40x40cm, 50x50cm, 25x50cm, 25x25cm, 20x20cm, 20x40cm, 15x30cm, 15x15cm), soldaterfliser (60x90cm, 90x90cm, 60x120cm, 90x120, 30x90cm, 45x90cm), sekskantede fliser (32x32cm), chaussesten (9x9cm) and SF-sten (10.5x19cm).
AC2:
The robot has to adjust its route based on which pavement style it is currently cleaning.

A.3.10 Systematical Procedure

As a house owner, I want an autonomous robot that systematically cleans my driveway and other pavement, and therefore does not just bump around like a Roomba.
Accept Criteria:
AC1:
The robot has to map out all paved areas.
AC2:
A systematic approach following lines in the pavement has to be used.
AC3:
If several types of pavement are present, different areas must be mapped to distinguish and optimize routes for each area.

A.3.11 Weather Endurant

As a house owner, I want an autonomous robot capable of passing an IP56 test.
Accept Criteria:
AC1:
The shell of the robot has to pass an IP56 test.
AC2:
The charging/home point has to pass an IP56 test.
AC3:
The robot should notify the owner if temperatures become low enough to damage the battery or other electronics.

AC4:
The robot should be able to drive "home" in severe rainfall i.e. more than 30mm over an hour.
AC3:
The robot should be capable of operation in sub-zero temperatures[1].

A.3.12 Water Avoidance

As a house owner, I want an autonomous robot that can detect when a puddle is nearby, and go around it.
Accept Criteria:
AC1:
The robot must recognize puddles, pits, and other flooded areas.
AC2:
The robot must reroute to navigate around water.
AC3:
If a reroute is unavailable, the robot must turn around and follow its previous route back to "home".

A.3.13 Spatial Awareness

As a house owner, I want an autonomous robot that detects cars, outdoor furniture, and the like, so that it will only operate around objects where it is safe.
Accept Criteria:
AC1:
The robot must be capable of determining whether or not, it can fit within a space.
AC2:
The robot must keep a minimum clearance of 10cm to anything above, so as to not wedge itself beneath anything.

A.3.14 Self-adjusting Scheduling

As a house owner, I want an autonomous robot adjusts its pattern, based both on the weather and on previous passes. I.e. if there were a lot of weeds on the previous pass around the driveway, it would schedule a new pass earlier.
Accept Criteria:
AC1:
The robot must map out every time a plant is hit, and keep that map in memory for the next 5 cycles.
AC2:
The robot must schedule passes based upon the amount of remaining greenery in an area.
AC3:
The robot must be capable of accessing weather information, so as to not plan its next pass when rain is predicted.
AC4:
The robot must be capable of intensifying passes if the greenery percentage does not go down in an area.

[1] In this instance, longevity of the battery is de-prioritized.

AC5:
The robot must be capable of adjusting its pattern to only focus on areas previously containing weeds. I.e. scheduling every second or third pass to only go for coordinates with "known" weeds, rather than traversing the full area.

A.3.15 Memory Capabilities

As a house owner, I want an autonomous robot capable of remembering what parts of the driveway have been cleaned.
Accept Criteria:
AC1:
The robot must map out which areas have been cleaned at which point, to rotate between areas.
AC2:
The robot must be capable of increasing its speed when no greenery is present.

A.3.16 Obstacle Avoidance

As a house owner, I want an autonomous robot avoiding obstacles without bumping into them.
Accept Criteria:
AC1:
The robot must not hit anything to change its course.
AC2:
The robot must not be closer than 5cm to anything in any direction, other than the pavement below it.
AC3:
The robot must not drive off of a ledge and tumble down.
AC4:
If the robot cannot turn around its own axis, it must reverse out from its current spot.
AC5:
If presented in a corner with no way out, the robot must turn off and notify the owner.

A.3.17 Low Noise

An autonomous robot making as little noise as possible.
Accept Criteria:
AC1:
The robot must not make any more noise than comparable lawn mowing robots, i.e. 58dB for a Texas TMX1000, [24].
AC2:
Under extraordinary circumstances, such as traversing small obstacles, volume may be increased to 65dB.
AC3:
Cooling of the robot must not surpass 55dB.

A.3.18 Small Size

An autonomous robot as small in size as possible, ideally no larger than a Roomba (approximately 45cm), [22].
Accept Criteria:

AC1:
The length and width of the robot must be smaller than 45cm.
AC2:
The height of the robot must be lower than 12cm.

A.3.19 Selfrecovery

An autonomous robot that does not get stuck at random places around my land; if it does get stuck, I want it to attempt to get unstuck.
Accept Criteria:
AC1:
If the cameras do not change pictures for 25 cycles, the robot should recognize it is stuck.
AC2:
If stuck and no obstacles are nearby, the robot should try to first reverse, then turn clockwise, then counterclockwise - all operations must be made at half speed to minimize the risk of loosing grip due to speed.
AC3:
If the robot cannot get unstuck on its own, it should notify the owner and turn off.

A.3.20 Area

An autonomous robot capable of cleaning a minimum of 500m^2.
Accept Criteria:
AC1:
By cleaning 500m^2, it is meant as mapping out 500m^2 and cleaning continuously, rather than in one pass.
AC2:
The robot should be capable of prioritizing some areas over others, so a customer can prioritize the terrace higher than the driveway i.e..

A.4 Limitating the Project - Full System

As this project only stretches for a single semester and is being done by a single student, some limitations have to be made. The project will instead of focusing on developing a full system meeting all demand specifications from the start, be divided into iterations. Therefore each iteration will have its own distinct goal(s) and specifications that it should meet. The first iteration will be the minimum viable product (MVP), and further iterations will contain increasingly advanced features.

A.4.1 1st Iteration - Minimum Viable Product/Focus of This Project

The minimum viable product is a version, which only really is an autonomous robot driving around pavement. The 1st iteration will therefore be based on a tracked vehicle available from AAU, and will mostly regard the steering and operation of an autonomous robot, rather than actual weed-removing capabilities. The goals for the first iteration are oriented at being able to follow a line in the pavement, drive around on flat pavement, and avoid hitting objects.
Functional specifications to meet:

- A.3.2 - Operate the Robot
- A.3.3 - A Home for the Robot
- A.3.4 - User-interface
- A.3.6 - Robot Go Home
- A.3.9 - Pattern Recognition, AC2
- A.3.12 - Water Avoidance
- A.3.13 - Spatial Awareness
- A.3.15 - Memory Capabilities
- A.3.16 - Obstacle Avoidance

A.4.2 2nd Iteration

The 2nd iteration will be the first to include actual weed-removing capabilities. At this iteration, a laser[2] and its power source will be added. Furthermore, image processing and recognition will be integrated, enabling the laser to be aimed correctly. On a software-level, systematical procedures for optimising routes and pattern recognition for more advanced kinds of pavement will be added.

Functional specifications to meet:

- A.3.1 - Weed Removal
- A.3.9 - Pattern Recognition, AC1
- A.3.10 - Systematical Procedure

[2]To stay within budget, the first laser will most likely be a laser-pointer, rather than an actual laser capable of burning weeds.

A.4.3 3rd Iteration

At its 3rd iteration, the autonomous robot will be configurable to stay within a designated area, ensuring the robot does not wander off into the wild. Furthermore, the setup/installation procedure should be made easier for the common man/woman to do. A self-adjusting schedule will also be integrated so that the robot optimizes its routing and number of passes to correspond with greenery growth, weather, and personalized preferences.

Functional specifications to meet:

- A.3.5 - Go Anywhere
- A.3.7 - Easy Setup
- A.3.8 - Stay On My Turf
- A.3.14 - Self-adjusting Scheduling
- A.3.19 - Selfrecovery
- A.3.20 - Area

A.4.4 4th Iteration

The 4th iteration will be the first to require a new vehicle, as this iteration will focus on making the robot more comfortable to be around, while also making it weather endurant and capable of being outside for extended periods of time.

Functional specifications to meet:

- A.3.11 - Weather Endurant
- A.3.17 - Low Noise
- A.3.18 - Small Size

A.4.5 5th Iteration

When a 5th iteration is developed, it will focus more on easing use for the consumer by implementing an app, where the user can set up prioritizing for different areas, divide their land into zones, and generally customize the operation of the robot. This iteration will have no functional specifications, as these are not designed within the scope of this project.