FACULTY OF ENGINEERING AND ARCHITECTURE

Design and modelling of a modular robotic system to improve weed management in raised bed organic farming

Rembrandt Perneel
Student number: 01712429

Supervisors: Prof. dr. ir. Francis wyffels, Prof. Jan Devos

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in de industriële wetenschappen: industrieel ontwerpen

Academic year 2019-2020

GHENT UNIVERSITY

Preamble

The development of the Coronavirus Covid-19 pandemic impacted the progress of this master's dissertation in a number of ways. The restricted entry into the grounds of Instituut voor Landbouw-, Visserij- en Voedingsonderzoek (ILVO), the project's main facilitator, complicated practical testing of the developed robotic system. Additionally, the fabrication of the platform has known delays due to suppliers being closed or working at a reduced capacity. However, being able to work on practical and theoretical aspects from a home environment, communicating with the project stakeholders through digital platforms and purchasing components from local suppliers, reduced the impact the pandemic had on completion of this master's dissertation.

Statement of Confidentiality

Confidential up to and including 31/12/2029

Important

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Keywords

Agriculture, Community Supported Agriculture, Robotics, Robotic Vehicles, Raised Bed Farming, Market Gardening, Integrated Weed Management, Precision Agriculture, Industrial Design, Engineering, User Centred Design

Abstract

The introduction of robotics in agriculture may be a radical step away from the current tendencies in farming of increasingly large machines designed to improve productivity. Heavy machinery has a high cost, a greater complexity and causes serious subsoil compaction issues. But unlike large, industrial monoculture farms, small-scale organic farming businesses, specifically within Community-supported Agriculture (CSA), also welcome robotic innovations since many different crops are grown and more manual labour is required to execute tasks such as weed control. The field of agricultural robotics acknowledges these challenges and aims to develop robots that operate with more efficiency, effectiveness and at less cost than traditional farm machinery and labour.

This thesis presents the design process and the prototyping of a modular robotic system to improve weed management in raised bed organic farming. This is to be achieved by the collaboration of multiple autonomous modules in a so-called 'swarm concept', rather than making use of one single, large machine. This configuration may positively impact energy consumption, labour and crop management efficiency.

The outcome of this effort is a lightweight robotic vehicle with a configurable implement unit. The current configuration is capable of undertaking weed mitigation tasks at seedling stage. The realised platform has a four-wheel configuration, driving through the use of two differential steering wheels and two passive caster wheels. Two 200 W electric motors powered by a lithium ion manganese oxide (LiMnO2) battery enable locomotion.The outcome of this project is achieved by using aspects of the engineering field and industrial design practices together according to a user-centred design model, where human factors are interwoven with technical problem-solving thinking.

The images below demonstrate the accomplished prototype of the robotic system.

De introductie van robotica in agricultuur kan een radicale stap opzij zetten van de huidige tendensen waarbij de steeds groter wordende machines in de landbouw ontworpen worden om de productiviteit voortdurend te verbeteren. Zware machines hebben een hoge kostprijs, ze zijn complexer en veroorzaken ernstige problemen met betrekking tot de verdichting van de ondergrond. In tegenstelling tot grote, industriële monocultuurbedrijven verwelkomen ook kleinschalige biologische landbouwbedrijven, met name binnen de Community-supported Agriculture (CSA), innovatie vanuit het roboticadomein aangezien er veel verschillende gewassen worden verbouw den er meer handarbeid nodig is om taken uit te voeren zoals onkruidbestrijding. Het gebied van landbouwrobotica erkent deze uitdagingen en heft tot doel robots te ontwikkelen die efficiënter, effectiever en goedkoper zijn dan traditionele landbouwmachines of handarbeid.

Deze thesis stelt het ontwerpproces en prototype voor van een modulair robotsysteem om onkruidbeheer in biologische beddenteelt te verbeteren. Uiteindelijk wordt dit bereikt door de samenwerking van meerdere autonome modules in een zogenaamd 'zwermconcept', ter vervanging van gebruik van één grote machine. Deze configuratie kan een positieve impact hebben op energieverbruik, arbeid en efficiëntie van gewasbeheer.

Het resultaat van deze poging is een lichtgewicht robotvoertuig met een configureerbare gereedschapseenheid. De huidige configuratie is in staat om onkruid te beheren in de ontkiemingsfase. Het gerealiseerde platform bestaat uit een configuratie met vier wielen en beweegt zich voort door middel van een differentieelbesturing van twee drijvende wielen ondersteund door twee passieve zwenkwielen. Twee 200 W elektromotoren, aangedreven door een lithium-ion-mangaanoxide-batterij (LiMnO2) staan in voor de voortbeweging. De uitkomst van dit project wordt bereikt door aspecten vanuit het ingenieursdomein en industriële ontwerpmethodes te combineren volgens een gebruikersgericht ontwerpmodel, waarbij menselijke factoren verweven zijn met technisch probleemoplossend denken.

De onderstaande afbeeldingen tonen het verwezenlijkte prototype van het robotsysteem.

Design and Modelling of a Modular Robotic System to Improve Weed Management in Raised Bed Organic Farming

Rembrandt Perneel

Supervisors: prof. dr. ir. Francis Wyffels, prof. Jan Devos, dr. ir. Simon Cool

Abstract **The introduction of robotics in agriculture may be a radical step away from the current tendencies in farming of increasingly large machines designed to improve productivity. But unlike large, industrial monoculture farms, small-scale organic farming businesses, specifically within Community-supported Agriculture (CSA), also welcome robotic innovations since many different crops are grown and more manual labour is required to execute tasks such as weed control. This work presents the design process and the prototyping of a modular robotic system to improve weed management in raised bed organic farming. The outcome of this effort is a lightweight robotic vehicle with a configurable implement unit. The current configuration is capable of undertaking weed mitigation tasks at seedling stage. The realised platform has a four-wheel configuration, driving through the use of two differential steering wheels and two passive caster wheels.**

Keywords **Agriculture, Community Supported Agriculture, Robotics, Raised Bed Farming, Market Gardening, Integrated Weed Management, Precision Agriculture**

I. Introduction

By 2050, the UN predicts that global food production must increase by more than 70% in order to continue supporting higher populations, estimated at 9.1 billion people [1]. Current trends in farming methods will not enable farmers to meet the demand for future food production without causing serious environmental damage. In order to achieve production increases, farms need to significantly increase production efficiency per hectare [2]. The focus of this work is to investigate how a robotic system can help improve efficiency in weed management in small-scale raised bed organic farming. Specifically, this project focusses on a farming model which facilitates a direct exchange between producers and consumers. Community-supported agriculture, or community-shared agriculture (CSA) is a farming system where consumers buy a share in the farm's production at the beginning of the season, thus becoming a partner in the endeavour [3].

One of the main advantages of agricultural robotic platforms is the substitution of human workforce by mechanised systems that can handle the tasks more accurately and uniformly at a lower cost and higher efficiency [4]. Weed control is one of the most demanded applications for agricultural robots. While still not fully commercialised, various promising technologies for weeding robots have been introduced and implemented over the past ten years as the results of interdisciplinary collaborative projects between different international research groups and companies. When designing a robotic solution for a weed control program, the available time, labour, equipment, costs and types of weeds and the areas infested need to be considered. For such a robot to be efficient, it should be able to not only substitute the manual weed removal task, but also decrease the use of agrochemicals. Bakker et al. [5] designed an autonomous platform using a systematic design methods. The objective of designing the vehicle was to target mechanical weed removal from organic sugar beet fields. Jensen et al. [6] designed a mobile implement carrier which consisted of track modules mounted on the side of an exchangeable implement. The system allowed for the adjustment of height and width of the vehicle. For the design of agricultural robotic vehicles, technologies from many other industrial sectors, including car and motorcycle manufacturing, have been integrated. These industries have conducted significant research efforts into developing chassis incorporating stronger and lighter materials [7]. This enables the manufacturing of lightweight agricultural vehicles, which is an important aspect when designing for reduced soil compaction.

II. Materials and Method

A. Methodology

The outcome of this project is achieved by using aspects of the engineering field and industrial design practices together according to a user-centred design (UCD) model, where human factors are interwoven with technical problem-solving thinking [8]. The work carried out for this project was iteratively completed. Choices are created and made in each phase, so that the design process converges into one solution.

B. Design Indications

As part of the user-centred research for this project, farmers were asked to participate in contextual conversations and observations at six CSA farm locations in Belgium and The Netherlands. The purpose of the study was to better understand the farmer's perspective of agricultural robots in order to make substantiated design decisions in terms of technology and usability issues. The contextual conversations enabled, through discussion and demonstration by the farmers, the potential and challenges of incorporating agricultural robots. Observations by participating in agricultural tasks such as weed removal gave an understanding of the current weed control techniques, tactics and machinery used. Also, an understanding was developed of how labour-intensive weed control actually is.

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Figure 1: Observations during one of six farm visits.

A set of design indications extracted from the conversations, observations and participative work with farmers was extracted:

- Farmers believe small robotic platforms are suited for precision tasks in agriculture such as weed mitigation.
- The platform should allow for maintenance and adaptability.
- A simple, user level, access to the interface system providing adequate and easily understandable visual information about the state of the machine.
- The number of operators for the platform to be monitored and maintained should be minimised. Preferably the farmer could do those tasks.
- The weight should be minimised to prevent soil compaction.
- Energy efficiency should be higher than in traditional motorised agricultural machinery.

C. *Robot Configuration*

The aim of this project is to design and develop a small, lightweight robotic platform and implement for application in CSA farming businesses. The robot's main task will be weed mitigation at seedling stage.

The design of the platform began with defining general requirements regarding dimensions, mass, speed and configuration. Appraisal was more important than in-depth analysis since this project is about the development and design of a prototype vehicle. Each of the general requirements directly affects the outcome of the design. Figure 2 shows an exploration to vehicle configurations, suspension and implement systems. The purpose is to discuss and analyse each configuration.

Based on this analysis, a two-wheel drive, four-wheel configuration was selected. This configuration is able to steer through differential steering by the driving wheels and stability is maintained by making use of two passive caster wheels. Passive averaging suspension or rocker-bogie suspension was selected because it offers great ground compliance, averages out the main body when driving through rough terrain while keeping complexity and component costs low. Due to its high stiffness, good dynamic characteristics and precise positioning capabilities, a parallel manipulator was the selected implement.

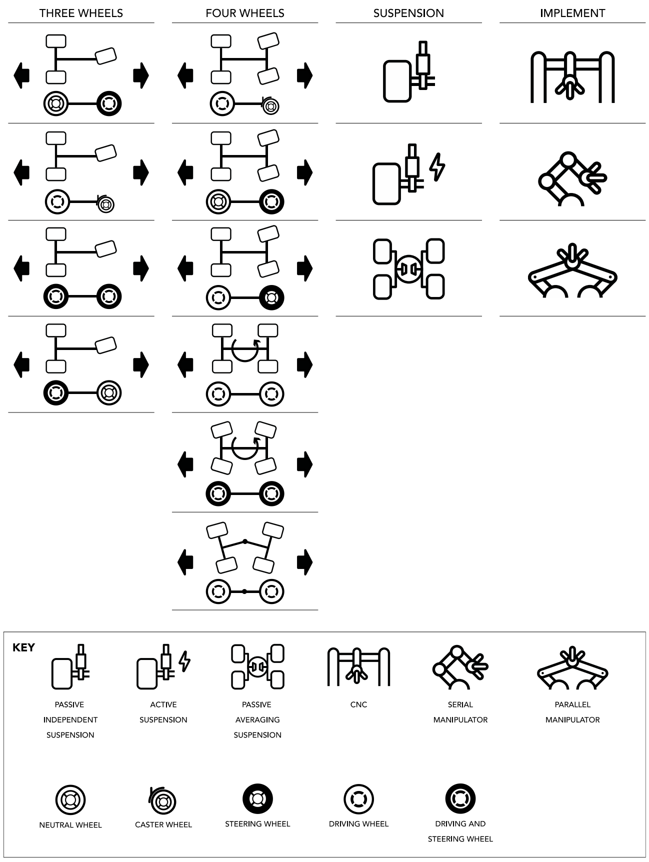

Figure 2: Robot configuration analysis.

D. *Platform and Implement Modelling*

1) *Differential Drive Inverse Kinematics*

A robot with differential drive steers in a direction by separately controlling the speeds ω_r and ω_l, left and right wheel speeds respectively. To keep the robot upright, passive wheels such as caster wheels, are added. These additional wheels follow the direction of the robot, induced by ω_r and ω_l.

In order to control the robot's movement, the only inputs to the system are ω_r and ω_l. The position and orientation of the robot are defined by (x, y, θ). In the kinematic model we typically want to connect the inputs, ω_r and ω_l, to the position and orientation (x, y, θ).

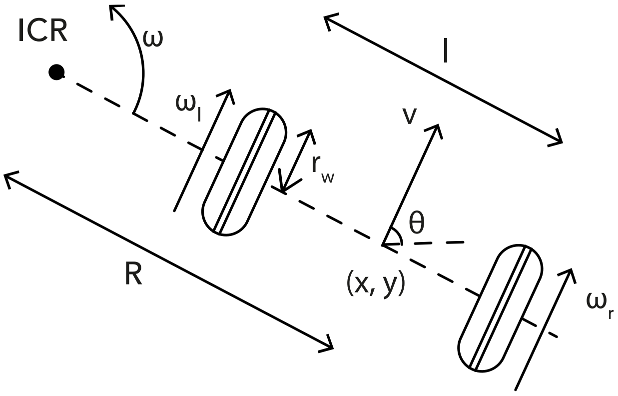

Figure 3: Differential Drive Inverse Kinematics Nomenclature.

The velocity kinematics of a differential drive mobile robot are given by [9]:

$$\begin{cases} \dot{x} = r_w \frac{(\omega_r+\omega_l)}{2} cos\theta \\ \dot{y} = r_w \frac{(\omega_r+\omega_l)}{2} sin\theta \\ \dot{\theta} = \frac{r_w}{l}(\omega_r - \omega_l) \end{cases} \quad (1)$$

The problem with this notation is that it is very unnatural to think in terms of wheel velocities. Instead of using [9] directly, the model proposed in [10] will be used to define ω_r and ω_l :

$$\begin{cases} \dot{x} = vcos\theta \\ \dot{y} = vsin\theta \\ \dot{\theta} = \omega \end{cases} \quad (2)$$

Mapping (2) and (1) together gives:

$$\begin{cases} \omega_r = \frac{2v+\omega l}{2r_w} \\ \omega_l = \frac{2v-\omega l}{2r_w} \end{cases} \quad (3)$$

Where the translational velocity v and the angular velocity ω are the design parameters for the inverse kinematic model. The wheel base l and wheel radius r_w are known parameters for the robot. ICR is the Instantaneous Centre of Rotation.

These design inputs are now mapped onto the actual inputs that will control the robot's movement.

2) Differential Suspension Kinematics

The primary role of a differential suspension, or rocker suspension, is to provide the mobile platform with a system that can adapt to unstructured terrain, such as ditches, soft soil and rocks, which is often the case in agricultural settings. By connecting a differential device in between two rocker suspensions, the four-wheeled robot can maintain ground contact with all wheels at any time. This way, the robot's suspension system is able to passively distribute the weight over the wheels and allows for constant traction by both motors at any point of time [10].

The differential mechanism of a rocker-type robot is a motion transfer mechanism with two degrees of freedom (DOF), which can transform the two rotating inputs into a rotating output. The output is the average linear value of the two inputs. If ω_1 and ω_2 are the two angular velocity inputs, ω the angular velocity output, φ_1 and φ_2 two rotational angle inputs and φ the rotational angle output, we define:

$$\omega = \frac{\omega_1+\omega_2}{2},\ \varphi = \frac{\varphi_1+\varphi_2}{2} \quad (4)$$

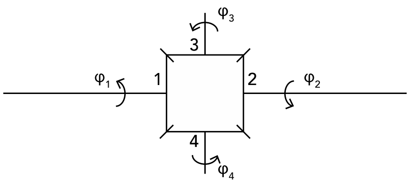

Figure 4: Schematic of the bevel gear differential mechanism.

Figure 4 shows a schematic of the bevel gear differential mechanism. Two bevel gears 1 and 2 mesh with the planetary bevel gears 3 and 4 orthogonally. The angular velocities of gears 1, 2, 3 and 4 are ω_1, ω_2, ω_3 and ω_4. The number of their teeth are Z_1, Z_2, Z_3 and Z_4. The rotational angles are φ_1, φ_2, φ_3 and φ_4. The relative velocity ratio of gear 1 and 2 with either gear 3 or 4 as carrier i_{12}^3, i_{12}^4 is then:

$$i_{12}^3 = \frac{\omega_1 - \omega_3}{\omega_2 - \omega_3} = -\frac{Z_3.Z_2}{Z_1.Z_3} = -1$$

$$i_{12}^4 = \frac{\omega_1 - \omega_4}{\omega_2 - \omega_4} = -\frac{Z_4.Z_2}{Z_1.Z_4} = -1$$

We obtain:

$$\omega_3 = \omega_4 = \frac{\omega_1+\omega_2}{2}\ and\ \varphi_3 = \varphi_4 = \frac{\varphi_1+\varphi_2}{2} \quad (5)$$

It can be seen that this bevel gear differential mechanism allows for the swing angles of the rocker suspensions to be averaged. The mean value, transformed into the swing angle of the main body, is then the output.

3) Parallel Manipulator Inverse Kinematics

Parallel manipulators are mechanisms which consist of one or more closed kinematic chains. The advantages of this type of manipulator are high stiffness, good dynamic characteristics and precise positioning capabilities [11]. A disadvantage of parallel mechanisms is that their orientation workspace is generally limited by mechanical interference[12] or type II singularities[13]. The presented arm in [14] is a 4 + 1 degree-of-freedom (DOF) parallel redundant manipulator. In this design, an extra redundant degree-of-freedom was added to make rotation of the end effector possible.

For the purposes of this project, application for weed mitigation, rotation of the end effector is not necessary. Therefore, the design in [14] will be simplified into a non-redundant 3 DOF robot manipulator. Figure 5 shows the simplified geometric model and nomenclature necessary for the derivation of the inverse kinematics.

Constraints

In Figure 5 the following constraints can be observed;

The position vector of points B_i, noted $\vec{b_i}$ expressed in the fixed reference frame O_{xyz} are defined as:

$$\vec{b_i} = \vec{p} + \vec{v_i}\ \ with\ i \in [1,3]\ ;\ \vec{v_i} = \begin{bmatrix} 0 \\ -v_i \\ 0 \end{bmatrix} \quad (6)$$

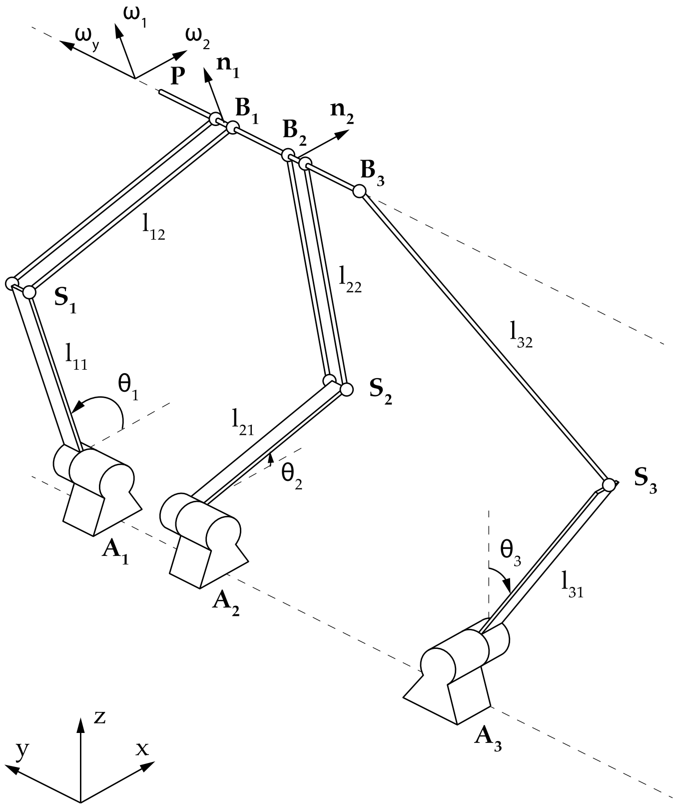

Figure 5: 3 DOF parallel manipulator simplified geometric model and nomenclature.

Scalar parameter v_i is defined as the distance in the direction of the y-axis between point P and points B_i with $i \in [1,3]$. The axis on which points P and B_i are located is always parallel with the XY plane.

The position vectors of points S_i are also defined in the fixed frame as:

$$\vec{s_i} = \vec{a_i} + \vec{f_i} \tag{7}$$

$$with\ i \in [1,2]\ ;\ \vec{f_i} = R_y(\theta_i).f_{i,0}\ where\ f_{i,0} = \begin{bmatrix} l_{i1} \\ 0 \\ 0 \end{bmatrix}$$

$$and\ with\ i \in [3]\ ;\ \vec{f_3} = R_x(\theta_3).f_{3,0}\ where\ f_{i,0} = \begin{bmatrix} 0 \\ 0 \\ l_{31} \end{bmatrix}$$

The distance between points B_i and S_i is also expressed. It is the Euclidean distance between those points:

$$\left(\vec{b_i} - \vec{s_i}\right)^T \left(\vec{b_i} - \vec{s_i}\right) = l_{i2}^2\ with\ i \in [1,3] \tag{8}$$

Inverse kinematics

The solution of the inverse kinematic problem consists in determining the input joint angles θ_i with $i \in [1,3]$of the three motors for given values of the Cartesian coordinates $\vec{p}$(x, y, z).

With $\vec{p}$ defined, with equation (1), it is possible to determine $\vec{b_i}$. Subsequently, (3) can be solved in order to obtain the values for θ_i with $i \in [1,3]$. The problem is similar to finding the intersection points between two circles, which generally has two solutions.

Substituting equation (1) and (2) in (3) and expanding the left member of equation (3) gives following form:

$$Q_i.\cos(\theta_i) + T_i.\sin(\theta_i) = R_i \quad for\ \ i \in [1,3] \tag{9}$$

To solve (9), tangent half-angle substitution is used:

$$Q_i.\left(1 - \tan^2\frac{\theta_i}{2}\right) + T_i.\left(2.\tan\frac{\theta_i}{2}\right) = R_i.\left(1 + \tan^2\frac{\theta_i}{2}\right) \tag{10}$$

Substituting $\tan\frac{\theta_i}{2}\ by\ t_i$ results in:

$$\theta_i = 2.\tan^{-1}(t_i) \tag{11}$$

The solution of the inverse kinematic problem can now be used for the trajectory planning of the parallel manipulator for weed mitigation.

E. Robot Design Development

1) Desired Platform Parameters

Table 1 summarises the desired platform parameters. These parameters will be used during the design and development phases of the robot to calculate the power requirements, select a drive unit and transmission and configure the suspension system.

2) Design Concept

The iterative nature of the concept design phase converged into a refined concept for the platform, according to the established vehicle configuration and key platform parameters. At the same time, standard mechanical components, motors, wheels and power sources were investigated to bring the design concept closer to the development phase.

The design developed is a four-wheeled platform, driven by two-wheel drive through brushless DC motors and a chain drive. Steering is made possible by a differential steering strategy of the driven wheels in combination with passive caster wheels. The side units or swing arms connect the driven and caster wheels and allow for driving along the raised growing beds. The main body of the robot contains the bevel gear transmission which averages the angle between both swingarms. The interchangeable implement unit is attached to the backside of the body and adjustable in height.

Table 1: Desired Platform Parameters

Specification	Dimension	Unit	Description
Vehicle mass	200	kg	Total vehicle mass
Nominal Speed	1	m/s	
Max. Speed	2	m/s	
Number of Wheels	4		
Drive/Steering Wheels	2		Differential steering
Caster wheels	2		
Wheel Width	0,3	m	
Platform Width	1,2	m	Wheel centre to centre
Platform Length	1,2	m	Wheel centre to centre
Height Clearance	0,35	m	
Operating Time	6	hrs	

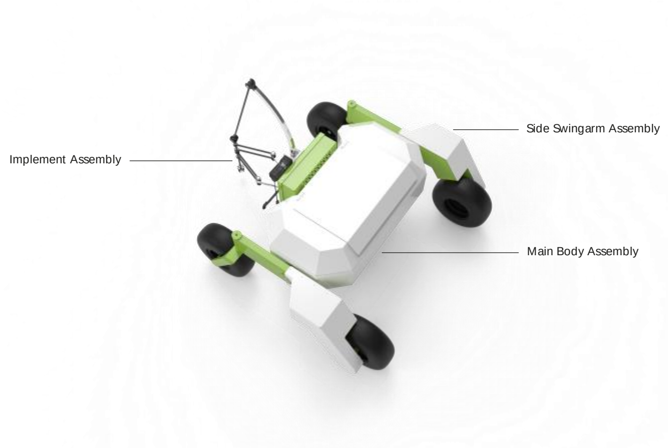

Figure 6: Concept visualisation.

3) Platform Development

Three main assemblies are distinctive: 1. Side swingarm assembly, 2. Main body assembly, 3. Implement assembly. Figure 6 depicts the main assemblies of the robot.

Side Swingarm Assembly

The side swingarm functions as the structure carrying the driving and caster wheels, the motor, transmission and the main body. The platform is designed to allow for over-bed driving.

The chassis of the Swingarm Assembly is fabricated from 3mm S235JR mild steel sheet and 120x40x3mm S235JRH mild steel rectangle tube. Shafts for the driving wheel, caster wheel and bushing house are fabricated from CK45 alloy steel. Individual parts are laser cut, CNC folded and cold rolled. Shafts are lathed for fixed and clearance fits. The chassis components are welded together using MIG welding and shafts are welded to the chassis using oxy acetylene and TIG welding techniques.

Main Body Assembly

The main body connects the two side swingarm assemblies. Its function is to fix the width of the vehicle, stabilise the side units, house the differential suspension system and carry the implement and electronics. The chassis of the main body is fabricated from 40x40x2 mm S235JRH mild steel square tubes. The body components are fabricated from 3 mm S235JR mild steel sheet and 3 mm $AlMg_3$ aluminium magnesium alloy sheet. Shafts for the suspension system are fabricated from CK45 alloy steel. Sheets and tubes are laser cut and CNC folded. Shafts are lathed for clearance fits. The chassis components are welded together using MIG welding technique.

In the design, laser cut panels and tubes interlock together with tabs and slots to create a ridged chassis. The advantages of this fabrication method are that contact surface area between the chassis components is greatly increased and no secondary alignment jigs are required during assembly. Figure 7 depicts the tab and slot assembly method used. This way of manufacturing and assembling takes away the issues of alignment of mutual parts, which is otherwise a time-consuming procedure. Using tab and slot features in the chassis components also makes it easier to differentiate parts and improves the speed and accuracy of assembly.

The main body chassis connects both the side swingarm assemblies through the differential system. The differential system is attached to the interior of the main body and supported by bearing units. Two extended shafts of the differential system are supported by flange bearings in the lateral walls of the main body and connected to the side swingarms, installed at both sides of the main body. The extended shafts connect to the side swingarms through keyless bushings, clamping the components together.

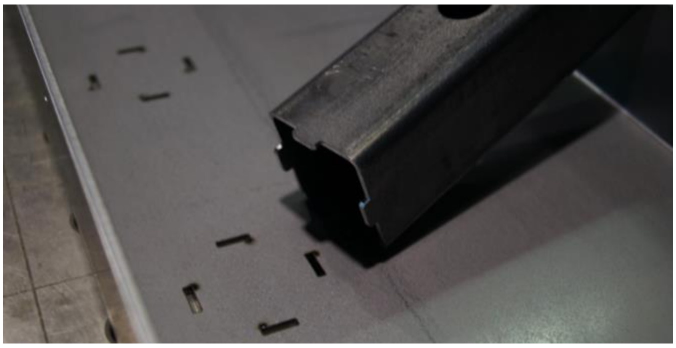

Figure 7: Tab and slot assembly method.

Implement Unit Assembly

The implement unit carries the parallel manipulator assembly, stepper motors and electronics for the robot arm. Its function is to drive the end effector to a desired location where weed mitigation is required.

In CSA, growing beds typically have a width of 750 mm [3]. This is also the work area the parallel manipulator must cover. Figure 8 shows the simulated workspace when couplers l_{11}, l_{21}, l_{12} and l_{22} are chosen 270 mm, l_{31} 500 mm and l_{32} 720 mm. At a working distance of 300 mm from the base it can be seen that a working width of 800 mm can be achieved. This working width allows for 50 mm extra space, which is desirable to not operate on the joint limits.

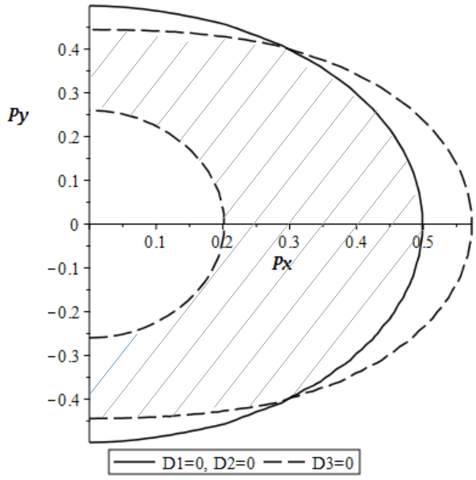

Figure 8: Parallel manipulator simulated workspace.

The chassis of the implement unit is fabricated from 3 mm S235JR mild steel sheet and 3, 4 and 8 mm $AlMg_3$ aluminium magnesium alloy sheet. The proximal couplers are made from 20 mm S235JR mild steel bars and the distal couplers are off-the-shelf double spherical joints made of an impact-resistant, long-fibre-reinforced polymer, connected by stainless steel links.

4) Drive Unit Design

A main factor in selecting a suitable drive unit is to determine the torque requirements to drive the wheels and set the vehicle in motion. When selecting a drive motor for an electric vehicle, a number of factors must be taken into account to determine the minimum torque requirements [15]: 1. Rolling resistance, 2. Grade resistance, 3. Acceleration force. The resulting force was calculated as 1067,2 N. The torque required to move the vehicle under worst case conditions was calculated as 219,9 Nm and the required power was calculated as 1067,2 W. Two 24 VDC 200 W electric motors with a rated torque between 38,3 and 55,3 Nm at 1 to 40 rpm, together with a 100:1 planetary flat gearbox were chosen to provide good locomotion at the desired speed range of 1-2 m/s. Emergency braking is provided by adding an electromagnetic brake.

III. Results

The result, shown in Figure 9, has led to the design and prototyping of a complete robotic system, addressing the defined user requirements.

The robot weighs less than anticipated at around 150 kg.

Figure 9: Agricultural robot prototype.

The differential suspension system was tested by elevating one wheel for about 30 cm up in the air. All four wheels maintained ground contact and the main body rotation was averaged (Figure 10).

Figure 10: Differential suspension testing.

In a next phase, when the motors are tested, dynamic behaviour of the suspension system will be observed.

Unfortunately, both caster wheels collide with the main body while rotating. This design flaw was not foreseen during the development phase. Either the length of the side swingarms has to be extended or the main body needs to be adapted. Because of this, bi-directional driving is not possible at the moment.

IV. Conclusion and Future work

This work presents the design and development of a lightweight, modular, low cost robotic system applicable in raised bed organic farming. The focus of this project was to develop a platform solution for raised bed organic farming, specifically within Community-supported Agriculture (CSA), aimed towards the end user, the farmer. A modular, lightweight and low-cost prototype has been realised using a variety of different manufacturing methods, materials and assembly techniques.

In a next phase, research will be conducted to design an end-effector suitable for weed mitigation at seedling stage. Testing of the differential drive kinematics will provide insights on how well this configuration performs on agricultural terrain. An emergency stop system, the use of a perimeter safety system and the integration of obstacle avoidance will later be included.

V. References

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List of Abbreviations

Abbreviation	Definition
ILVO	Instituut voor Landbouw-, Visserij- en Voedingsonderzoek
CSA	Community-supported Agriculture
UCD	User-centred Design
FEM	Finite Element Method
UN	United Nations
CTF	Control Traffic Farming
ATV	All-terrain Vehicle
4WD	Four-wheel Drive
RWD	Rear-wheel Drive
FWD	Front-wheel Drive
CNC	Computer Numerical Control
CAD	Computer Aided Design
DOF	Degree of Freedom
ICR	Instantaneous Centre of Rotation
MIG	Metal Inert Gas
TIG	Tungsten Inert Gas
GVW	Gross Vehicle Weight

Chapter 1: Introduction

1.1 Design Brief

1.1.1 Objectives

This project creates together with the target group and validates with them the paradigm change towards the use of small, modular semi-autonomous robotic platforms that can be used for various agricultural tasks. This is achieved by linking a task-specific tool to a (semi-)autonomous unit. The concept is scalable to medium-sized companies by deploying a swarm of these units. This proposal analyses how and which underlying innovative mechatronic techniques can meet existing needs from the agricultural sector and can be optimally implemented in economical, ecological and practical perspective.

This project conceptually develops alternatives based on a small semi-autonomous vehicle or unit. Each driving unit forms the basis of a module that combines traction and actuation with an application-specific tool for controlling weeds in crop fields. Upscaling for larger tasks can be realised by deploying a so-called 'swarm concept'. This concept consists of several similar modules working actively together rather than making use of one single, large machine.

The project develops technological solutions at a high conceptual level for agricultural tasks in all target sectors and always determines both the technical feasibility and the user requirements. The project implements, demonstrates and validates this concept on carefully selected operations from which generic conclusions are drawn. The project makes a prototype as a demonstrator that can primarily be used for mechanical weed control. The design could potentially also become a platform for the implementation of other implements for sowing, fertilization and harvesting of some labour-intensive crops. From a technological point of view, this project focuses strongly on raising the state-of-practice to a higher level by implementing mechatronics (multi-physical holistic, sensory, actuation). Recent developments in mechatronics (cost-effective sensors and computing power, lightweight structures, new algorithms for data use and control, interconnectability of systems) in other sectors ensure that machines and products become smarter and work more optimally.

This project aims to boost a new generation of small robotic platforms, of which different types are already commercially available, but are always focused on task-specific applications and cultivation of monoculture. The actual implementation of innovative technology on such a system platform will allow to strengthen organic cultivation and traditional agriculture in terms of sustainability, labour, ergonomics, performance and economy. The project places a strong focus on optimal selection, further development and flexible integration of one or more available system platforms into autonomous, efficient and powerful tools that can be widely used in the farm of tomorrow. Optimal flexibility is a must in order to be a workable alternative to current practice and mechanization.The impact of this technological innovation will be more noticeable where agricultural companies strive for (i) sustainability by including, among other things, the proven principles of organic cultivation and (ii) for zero emissions and lower energy consumption.

In summary, the specific objectives are: i. Investigate, specify and design a (semi-)autonomous, modular robot platform with associated task- specific tools that can be used for weed control and ii. Development and implementation of one platform and accompanying implement.

1.1.2 Scope

Research in agriculture and food production with a view to current and future problems. The focus is mainly on small-scale organic cultivation in CSA (Community Supported Agriculture) farming businesses.

- Research into weed management practices in organic farming.
- State-of-the-art study on weed control robot platforms. What has already been tried, what technologies and techniques have been used, what has become commercially available.
- Acquiring insights at various farm locations in Belgium and the Netherlands using observation studies and contextual interviews.
- Drawing up requirements for the design of an autonomous robot platform suitable for small-scale organic cultivation.
- Development of conceptual designs of an autonomous robotic system.

- Performing a kinematic analysis for the platform and tool configuration.
- Selection of a suitable platform and tool configuration to elaborate a detailed design and development.
- Carry out a detailed design and development of the selected concepts with the aim of building one prototype.
- Fabrication of a prototype.

1.1.3 Advantages

The introduction of robotics into agriculture is seen as a revolutionary step away from the current direction of improved productivity by using ever larger machines. Shifting the use of large machines to the use of fleets or "swarms" of smaller autonomous platforms is a paradigm shift in agriculture with the following advantages:

- Less impact on the environment with a reduction of soil compaction.
- Multi-purpose for weed control, crop detection, sowing, fertilising and harvesting.
- Better manoeuvrability which reduces the amount of unused land area.
- Scalability, which facilitates employability in small, medium and large farms.
- Reduction of errors and failed operations through multi-robot redundancy.
- Lower development costs due to reduced complexity of the platform and implement.
- Reduction of chemical pesticides.
- Smaller, more precise implements which enable to perform precise operations.

- Improvement of ergonomics for workers by reducing hand labour.
- Reduction of energy consumption per hectare - reduced energy cost.
- Better understanding of crop-soil requirements.

1.1.4 Stakeholders

The stakeholders are individuals, organizations and systems that are actively involved or whose interests are affected as a result of the implementation or termination of this project. They also influence the objectives and outcomes of the project[6].

- Small-scale organic growers
- Consumers and CSA communities (social)
- Machine manufacturers (platform / implement / development)
- Industrial organisations (ILVO)
- Research institutes (universities)
- Government (regulation / certification)
- (local) ecosystem (environment)

Figure 1: Project stakeholders.

1.1.5 Risks and Opportunities

The agricultural sector offers a challenging but potentially favourable opportunity for the development of semi-autonomous systems. The rewarding advantages of implementation in this sector are considerable: it allows longer working hours, it can offer a solution for frequently occurring repetitive tasks that are ergonomically stressful or cognitively less stimulating for humans. In addition, such systems offer greater adaptability to unpleasant working conditions. The use of agricultural robots can potentially reduce the impact on the environment. Small semi-autonomous systems, alone or deployed in swarms performing precision tasks, can be less damaging to the ecosystem than large, heavy agricultural machines. Demand for automated systems in agriculture is also driven by a shortage of workers in this sector.Facing these opportunities is a series of challenges and risks; the diversity between agricultural environments, set-up costs, and the need to adapt to new processes. In the agricultural sector, specifically organic farming, there is a much lesser presence of a structured, homogeneous environment and there is clearly more human interaction in contrast to implementations in, for example, factory environments. Implementation of semi-autonomous systems also means more complexity and risk for the worker and the environment. A wrong decision of the system can make a large financial impact in a small-scale agricultural business.

1.1.6 Methodology

The outcome of this project is achieved by using aspects of the engineering field and industrial design practices together according to a user-centred design (UCD) model, where human factors are interwoven with technical problem-solving thinking [1]. This approach to innovation reaches into the "tool box" of designers and engineers to integrate peoples' needs, technological capabilities and requirements for successful business. The role of the field of "industrial design" is to bring up the full experience of the product. In terms of content, this represents usage, attitudes, perception and emotions, ideological and social aspects.

User-centred design (UCD) is a multi-stage, iterative design process in which designers focus on the users and their needs. UCD engages end users throughout the design process through a range of research and design techniques, creating actionable, easy to use and accessible products.

The work carried out for this thesis was split into five phases, iteratively completed. Choices are created and made in each phase, so that the design process converges into one solution. Below is a description of each stage where the actual completed tasks are aligned. These five stages are:

1. Discover
2. Defining requirements and design specifications
3. Concept design
4. Concept development
5. Deploying and user testing

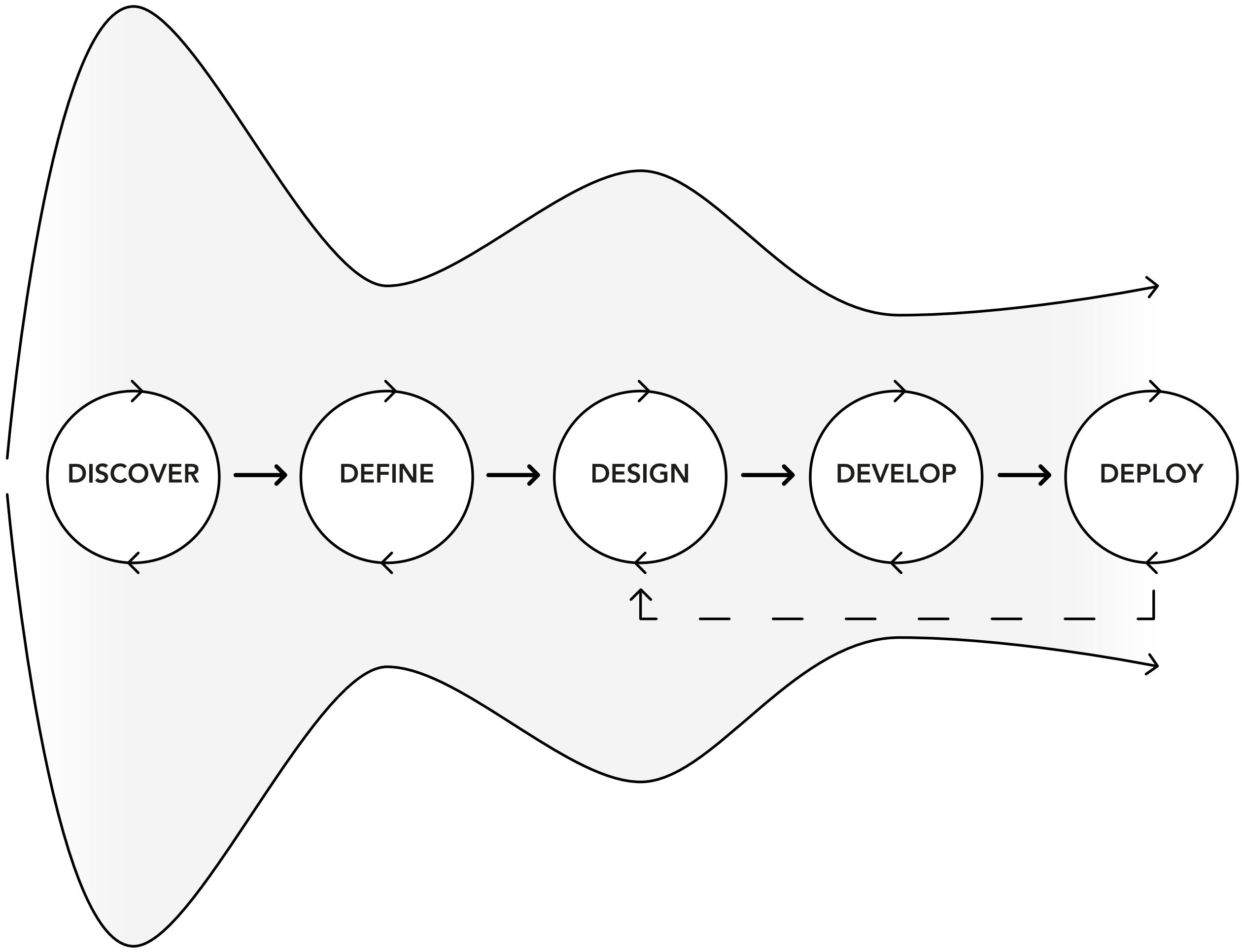

Figure 2: Methodology.

Discover phase

In the research phase, creativity is stimulated and information about new possibilities and ideas is gathered. Initial research looked at current farming methods, technologies and philosophies at Community-supported Agriculture (CSA) businesses. In addition, information was collected on weed management in organic agriculture. Detailed research was conducted on agricultural robots. Key stakeholders were defined.

Qualitative research methods provided insights into the specific requirements and wishes of farms and crops visited. Insights were acquired on CSA farms in Belgium and the Netherlands and included observations in combination with contextual interviews and conversations with the farmers. A good understanding of the various opportunities was largely made possible by mapping the experiences of the farmers. In this phase, project parameters were also set to explore during the concept design phase.

Defining requirements and design specifications

The information from the investigation phase is converged to specific system requirements: vehicle and implementation specifications. Here, observations are analysed and then synthesized in order to define important aspects and problems. In the next phase, this will give the opportunity to come up with good ideas about the functions and elements of the design.

Concept design

In the conceptual design phase, different concepts are diversified around the project parameters and design specifications. Merging and condensing information from the research phase created new perspectives and encouraged innovation. With an already solid background on the context, new solutions to the problem can be considered. The problem can also be viewed from different points of view during this phase. Here it is important to generate many ideas and solutions. Using a set of decision methods, the best solutions are then chosen.

Concept development

This phase includes a clear integration into the design; functionality, identity and purpose. Competitor Engineering or parallel development is used here in particular to reduce development time and to identify and solve problems during the design process as quickly as possible. The development of the platform compositions and sub-assemblies is iteratively followed by prototypes, and expert advice.

Deploying and testing

The final prototype is tested and validated in this last phase. Because this is an iterative process, the generated results can be used to redefine one or more problems. Insights are gained with regard to the users and usage conditions. Even in this phase, changes and improvements can take place to achieve the best possible final solution.

Chapter 2: Robot Design Goals

2.1 State-of-the-Art

2.1.1 Overview

By 2050, the UN predicts that global food production must increase by more than 70% in order to continue supporting higher populations, estimated at 9.1 billion people[1]. An increase in the demand for food of both new and traditional origin will put increasing pressure on agricultural resources. In addition, strong competition for land and water use will come from real estate, industry and the conservation of natural habitats to conserve biodiversity.

As the population increases, and so does the wealth of the people, the demand for more varied food will increase. Most notable is the still growing switch to high protein diets [10]. This shift will have an increasing impact on the environment. That is why the big challenge is also how to produce more food with less environmental impact. In order to continue to feed this increasing world population, we need to think of an agriculture developing in a direction where it does not significantly increase the production of greenhouse gases, but it does increase in its own production capacity [11].

Current trends in farming methods will not enable farmers to meet the demand for future food production without causing serious environmental damage. In order to achieve production increases, farms need to significantly increase production efficiency per hectare [12]. Whenever technology and nature come together, significant technical and non-technical challenges need to be resolved. When robots are deployed in complex environments such as fields, they end up in circumstances such as changing light conditions, wind, rain, temperature and dust. The challenge for the future will be the development of light, robust platforms that will meet the needs of the users.

2.1.2 Challenges for Flemish Agriculture

2.1.2.1 Current Situation

In 2017, Flanders counted 23,225 agricultural businesses. Compared to 2007, this number has been decreasing 3% per year on average. Smaller farms in particular stop their activities, which leads to a constant increase in scale[2].

88% of Flanders' agricultural businesses is specialised in one of three main subsectors; livestock farming (50%), arable farming (26%) and horticulture (12%).

Another form of specialisation is organic farming. Starting 2018, 468 organic farms were active, including those in conversion. The number of organic producers has grown by an average of 9% per year since 2013. The organic farming businesses in Flanders account for approximately 1.2% of the entire agricultural area.

A survey of the participants in the Flemish Farm Accountancy Data Network in 2017, showed that half of the agricultural and horticultural businesses carried out one or more innovation activities in the previous two years[3]. The survey showed that the business type is a determining factor in the adoption of innovation activities such as precision agriculture. Three specialised sectors stand out: arable farming (70%), livestock farming (69%) and dairy (68%).

Today, more than one in three farmers in crop production use differential GPS systems (41%), GPS surveying of land plots (39%), site-specific crop protection (37%) and field mapping (36%). More than one in five farmers make use of site-specific fertilisation (25%), variable sowing/planting (24%) and field irrigation (22%). Management information systems (18%) and satellite imaging (16%) are used as well. Other applications clearly fall behind: crop sensors (8%), drone imaging (6%), precision mechanical weeding (3%) and soil scanning (2%).

2.1.2.2 Challenges for Agriculture

All numbers in this section are referenced to [2].

Viable agricultural businesses

Agriculture should be economically sustainable. A farmer must be able to earn a living or a fair income from his business. Because of the dependence on natural factors such as climate, weather conditions, pests and diseases, a farmer's income has always fluctuated. Additionally, political stability and market mechanisms in the food supply chain also have a major impact on prices. Farmers are increasingly exposed to fluctuations in world market prices. The European Union has opened its markets to larger quantities of duty-free or duty-reduced products, which results in more competition for farmers. Also, while the price paid to European farmers for their products is barely increasing, the cost of inputs such as land, fertilizers, animal feed and crop protection products is rising sharply.

New farmers

New farmers encounter many hurdles, of which access to land is considered the most important. Taking over or starting up a farm business also requires significant financial resources. Young or starting farmers often do not have sufficient access to capital.

Interesting is the emergence of new farmers who did not grow up on a farm and do not have a previous link with agriculture. They can bring in new insights and often have a network from outside the sector.

Space for agriculture

From a spatial point of view, Flanders is highly urbanised. Every day, approximately six hectares of open space disappear. The remaining open space is also increasingly fragmented. In the countryside, agriculture is now more under threat than ever before, even within the space intended for agriculture on spatial plans. The status of agricultural area appears insufficient to protect agricultural land from transformation processes such as hardening, petrifaction and the use of vacant farm buildings for purposes other than agriculture. Currently, 11% of the agricultural land is not being used for agriculture. But 11% of the land used for agriculture is legally not intended for farming activities.

Increasing spatial efficiency in agriculture can be achieved through a combination of intensification, mixed land use (including shared use), re-use and the temporary use of space.

Circular agriculture

Over the past century, the agriculture and food system has evolved towards a very efficient, but linear system of extraction and exhaustion. There is a strong dependence on natural resources such as nutrients, fossil fuels, agro-chemicals, water and land. Negative consequences of the linear system are soil degradation, environment pollution, waste and spillage. A resource efficient food system reduces the environmental impact, takes advantage of renewable resources in a more sustainable way and uses all resources more efficiently. Preventing losses in the agri-food chain therefore is a priority. Solutions mainly focus on efficiency to prevent losses. A circular farm usually closes the resource loops as much as possible on its own farm or with a few neighbouring farmers. In this model, a farmer searches for viable outlets for certain residual flows from his or her farm without the valorisation of these residual flows being the goal. However, development of these systems requires coordination with many parties from different sectors.

Climate change

Agriculture has an impact on climate change. On a global scale, agriculture is responsible for 17% of greenhouse gas emissions, while in Flanders greenhouse gas emissions from agricultural practices amount for 10%. Agriculture mainly emits methane (CH_4) and nitrous oxide (N_2O), which come from digestion in ruminants, the production and storage of manure and soil use.

Due to its close connection with the rest of the ecosystem, agriculture is particularly sensitive to disturbances within the ecosystem. Not all effects of climate change are negative by definition. For example, the higher CO_2 concentration in the atmosphere is an additional fertiliser for plants. But in recent decades, the yield of agricultural crops has fluctuated more strongly, due to diseases and pests and extreme climatologic conditions such as heath waves, drought and storms.

Healthy diet

Healthy food provides us with the necessary energy and nutrients to function optimally. Despite the powerful ability that food can provide, this potential is not being fully used.

The average Belgian does not take in sufficient fruits and vegetables, cereal products and water. Consumption of cheese, meat and the residual group (rich in calories, poor in nutrients) is higher than recommended. Overweight and obesity are the cause of many health problems, such as the development of chronic diseases, muscle diseases and certain cancers. Scientists performing research on healthy diets agree that eating no more food than necessary reduces the environmental impact and the risk of developing health problems. Diets rich in animal products have a greater negative impact on the environment and health.

Protein transition

The worldwide increasing and unsustainable demand for animal proteins is challenging agriculture to shift towards more supply and valorisation of vegetable proteins. Protein transition refers to new ways to make high-quality proteins available in a more direct and sustainable way for humans. Shifting towards the consumption of vegetable protein clearly has consequences for livestock farming, but also offers new opportunities for the entire sector. It will stimulate the sector to accelerate innovation, develop new business models and focus more on alternatives in the coming decades.

Reconnecting with the consumer

By 2050, more than two-thirds of the world population will live in cities. To feed all these people, enough food must be produced[1]. All over the world, cities have taken up a more active role in food supply. Not only from a food security point of view, but also from the point of view of sustainability, social development and public health.

In Flanders, where the city and the countryside are close to each other, there is an increasing suspicion among people living in the city about farming methods and the way our food is produced. At the same time, there is a growing awareness and interest in food production and consumption. This trend is a trigger for the strengthening of the link between urban consumers and rural producers. Examples are farm sales or self-picking farming models, but also other diversification activities such as nature management, care farming and farm tourism. These short chain initiatives reduce the gap between farmer and citizen.

2.1.3 Community-supported Agriculture (CSA)

The focus of this project is to investigate how a robotic system can help improve efficiency in raised bed organic farming. Specifically, this project focusses on a farming model which facilitates a direct exchange between producers and consumers. Community-supported agriculture, or community-shared agriculture (CSA) is a farming system where consumers buy a share in the farm's production at the beginning of the season, thus becoming a partner in the endeavour. In exchange, the farm commits to providing quality produce, usually harvested the day before, or even the same day. In addition to the demand for quality produce, this model of food distribution addresses people's desire to have a relationship with the farmers who grow their food[4].

2.1.3.1 History

The CSA farming model originates from Japan. In the early 1960's, a group of Japanese mothers united after many children died from the excessive use of petrochemical pesticides used in agriculture. The movement was baptised Tei Kei and spread very quickly all over the world[5]. Inspired by the Japanese activists and Rudolf Steiner's biodynamic movement[6], the first community-supported agriculture farms were built in 1984 in America. The first farms based their operations on the idea that consumers and farmers are jointly responsible for building sustainable farms. This, among other things, translated into the joint purchase of land, so that it was no longer tradable and thus available for ecological production methods.

The movement was reinforced by the ideas of, among others, S. Witt[7] and R. van En[8] who wanted to develop an economy where producers and consumers are also geographically close to each other. Between 1986 and today, more than 17,000 CSA farms emerged worldwide. Unlike In the US, Europe took much longer for CSA to gain a foothold. In Belgium, the first CSA farm started In Leuven In 2007[5].

2.1.3.2 Advantages of the CSA model

Consumer motivation

According to literature[8]–[13] there are different reasons for consumers to join a CSA community. The reasons mentioned by [14] are:

- Freshness, taste and nutritional value of food
- Organic or other means of production that require little production resources
- Ecological sustainability
- Produce origins
- Personal connection with farmer
- Seasonal produce

- Support of small(er) companies
- Being part of a community
- Connecting with the local ecology
- Maintenance and preservation of the local environment and open spaces
- Reduction of the ecological footprint

Farmer motivation

Advantages of the CSA model for farmers are mentioned by [4]:

- Guaranteed sales: the main advantage of the CSA model is that production is prepaid at the start of the season, often before the first seed has been sown. This model allows the farmer to budget with greater precision.
- Simpler production plans: since members have already purchased the produce, the farmer can plan production based on the sales. Once the number of customers has been determined, the contents of each share can be planned out beforehand.
- Risk sharing: the idea behind CSA is that the risks inherent to agriculture are shared between the farmer and the members. When members sign up, they sign a contract inviting them to be tolerant in case of failed harvest due to, for instance, natural catastrophes. If the season is good, the members will receive more than planned, but if the season is bad, they will receive less.
- Customer loyalty: CSA allows farmers to build not just customer loyalty but tangible relationships between consumers and the farm.
- Networking: CSA is even more advantageous when a third organisation can play a coordinating role. In Belgium this is the case with CSA-netwerk vzw[15]. This organisation promotes CSA through publicity campaigns and finds members for the farms through its network.

2.1.4 Weed Management in Organic farming

Weeds are usually defined as any plants growing where they are not wanted. In an agricultural setting, weeds are traditionally taken to mean any non-crop plants in a field or raised growing bed, but could also include plants growing in field margins and in other locations where they are likely to spread or otherwise cause a nuisance. They are normally perceived to be doing some 'damage' or 'harm'; that is, they are having negative effects like reducing yields, lowering crop quality or causing difficulties with crop management operations[16]. Weed management is generally understood to be a process that manipulates the crop and cropping practices to the advantage of the crop and the disadvantage of the weeds. It is important to acknowledge that weeds compete with crops for water, nutrients, growing space and light. The aim of organic weed management is to maintain a low and tolerable level of weed infestation within crops and on the farm[4].

Because organic farming systems lack the equivalent of inexpensive and nearly complete chemical weed control available for conventional systems, effective weed management for organic farming requires the concerted use of multiple physical, biological, and cultural tactics[17], [18]. Liebman and Gallandt [18] characterised strategies composed of multiple weed suppression tactics that are Individually weak but cumulatively strong. Following is a review of developments in cultural and direct methods of non-chemical weed control, and aspects of weed biology and weed competition that are of particular relevance to weed management in organic farming systems.

2.1.4.1 Cultural Weed Control

In organic and other low-external-input farming practices, the approach to weed management involves the whole cropping system[19]. The aim is to balance crop plants and weeds, with the farmer adjusting the balance in favour of the crop whenever possible.

Pre-crop and post-harvest soil cultivation

The benefits of ploughing compared with reduced-tillage systems for weed management have been the subject of considerable research and debate[20]. In weed control, ploughing is used to bury freshly shed weed seeds below the depth from which they will germinate. This consumes a lot of energy and is often a short-term solution that can lead to long-term problems. The buried seeds may persist for many years in the soil seedbank until they are returned to the soil surface by new cultivations. Non-inversion tillage keeps fresh weed seeds near the soil surface where shallow cultivations can be used to reducing seed numbers[21]. Reduced-tillage systems typically have a more efficient use of fossil fuel, greater conservation of soil moisture and less risk of soil erosion[22]. The principle of flushing out weed seeds before cropping is known as stale or false seedbed technique, where soil cultivation may take place days or weeks before planting or transplanting a crop[23]. Using this technique, the seedbank in the surface layer of the soil is depleted and reduces weed emergence. For many buried weed seeds, it is the exposure to light during soil cultivation that stimulates germination. Taking away light during seedbed preparation has been shown to reduce weed emergence[24].

After crop harvest, the appropriate timing of cultural operations to clear the land can aid future weed management by reducing the persistence of freshly-shed seeds left on the soil surface. If post-harvest cultivations are delayed by about two weeks, the seeds will germinate and perish[25].

Crop rotation

The growth and reproduction of a troublesome weed species may be actively discouraged by introducing unfavourable practices into a rotation[26]. Within a rotation, crop choice will determine both the current and the potential future weed problems that a grower will face. For an organic farmer, crop choice is further complicated because of the need to consider soil fertility levels within the cropping sequence and to Include fertility building periods in the rotation. Variations in crop and weed responses to soil nutrient levels can also play an important role in weed management[19].

Crop establishment

Plants that emerge first have a competitive advantage, and for a crop this improves selectivity during weeding operations. In field vegetables, the choice of plant-raising systems can also provide an early advantage over the weeds through the use of primed or pre-germinated seed, and bare-rooted or module-raised transplants[27]. There are also opportunities to adjust crop spacing to improve weed suppression in field vegetables.

2.1.4.2 Direct Weed Control

Although the cultural methods described above provide the base for organic weed management, it is likely that direct action will, at one time or another, be needed against weeds to prevent crop losses. Direct action means that weeds will have to be physically killed in, or removed from, the crop or field[16]. Research on direct non-chemical weed control techniques has followed traditional directions, based largely on mechanical and thermal methods.

Mechanical weed control

Mechanical weeders include cultivating tools such as hoes, harrows, tines and brush weeders, and mowers and trimmers. The choice of implement and the timing and frequency of its use depends on the morphology of the crop and the weeds. Implements such as fixed harrows are more suitable for arable crops, whereas inter-row brush weeders are considered to be more effective for horticultural use[28]. The optimal timing for mechanical weed control depends on the competitive ability of the crop[29] and the growth stage of the weeds[30].

Thermal weed control

Flaming equipment to burn off weeds has been developed in several countries including Germany, Holland, Sweden and Denmark[31]. The main fuel used in the burners is liquefied petroleum gas (LPG), usually propane[32], but renewable alternatives such as hydrogen have also been evaluated[33]. Flame weeders can be used when the soil is too moist for mechanical weeding and there is no soil disturbance to stimulate further weed emergence[28]. In flame weeding, the plant cells are ruptured and only the exposed plant tissues may be disrupted initially. Flame weeders may be used for total vegetation control or for selective removal of unwanted plants, but are not suitable for crops with shallow or sensitive root systems[34].

2.1.5 State-of-the-Art Weed Control Robotic Platforms

One of the main advantages of agricultural robotic platforms is the substitution of human workforce by mechanised systems that can handle the tasks more accurately and uniformly at a lower cost and higher efficiency[36]. Weed control is one of the most demanded applications for agricultural robots. While still not fully commercialised, various promising technologies for weeding robots have been introduced and implemented over the past ten years as the results of interdisciplinary collaborative projects between different international research groups and companies. Actively involved in the research and development for various types of weed control robots are the Wageningen University (The Netherlands), Queensland University of Technology, the University of Sydney, Blue River Technologies (CA, USA), ecoRobotix (Switzerland), and Naio Technologies (France). When designing a robotic solution for a weed control program, the available time, labour, equipment, costs and types of weeds and the areas infested need to be considered. For such a robot to be efficient, it should be able to not only substitute the manual weed removal task, but also decrease the use of agrochemicals. Bakker et al.[37] designed an autonomous platform using a systematic design methods. The objective of designing the vehicle was to target mechanical weed removal from organic sugar beet fields. Jensen et al.[38] designed a mobile implement carrier which consisted of track modules mounted on the side of an exchangeable implement. The system allowed for the adjustment of height and width of the vehicle. The use of tracks as opposed to wheels was evaluated to reduce complexity while still allowing for flexible steering (turning the platform around its geometric centre).

For the design of agricultural robotic vehicles, technologies from many other industrial sectors, including car and motorcycle manufacturing, have been integrated. These industries have conducted significant research efforts into developing chassis incorporating stronger and lighter materials[39]. This enables the manufacturing of lightweight agricultural vehicles, which is an important aspect when designing for reduced soil compaction. Among the lightweight, solar powered vehicles, the ecoRobotix field robot[40], as seen in Figure 3, is a robotic platform for inter/intra row weeding using a delta-arm manipulator. This delta-arm consists of three rods connected to a universal joint at the base. Through the parallelogram configurations in the arm, the orientation of the end effector is maintained. The design was developed to manipulate small and light objects at high speeds. Implements such as rotating blades to dig out small weeds out of the ground or precision spraying booms were developed.

BoniRob[41] (Figure 3) is an integrated multipurpose farming robotic platform for row crops weed control, developed by interdisciplinary teams and recently licenced by Bosch (one of the project industry parnters). The platform is being developed for commercialisation as a research platform to universities and other organisations. The robot design includes individual wheel drives, adjustable ground clearance and track widths. Aside from its weeding capabilities, BoniRob is also capable of creating detailed field maps.

Figure 3: ecoRobotix and BoniRob.

AgBot II[42] (Figure 4) is an iwwnnovative field robot prototype developed by the Queensland University of Technology for autonomous fertiliser application, weed detection and classification, and mechanical or chemical weed control.

Weedy Robot[43] (Figure 4) is a robotic weeding platform effort developed by Osnabrück University of Applied Sciences.

Figure 4: AgBot II and Weedy Robot.

Tertill[44] (Figure 5) is a fully autonomous solar powered compact robot for weed cutting developed by FranklinRobotics.

Hortibot[45] (Figure 5) is a robot developed by the Faculty of Agricultural Sciences at the University of Aarhus. Hortibot is used for transporting and attaching a variety of weed detection and control tools such as cameras and spraying booms.

Figure 5: Tertill and Hortibot.

RIPPA[46] (Figure 6) is a solar-powered robot for Intelligent perception and precision applications developed be the Australian Centre for Field Robotics at Sydney University.

Ladybird[47] (Figure 6) is an omni-directional platform designed and developed for horticulture Implementation. It is a solar-powered platform capable of weed mitigation and plant phenotyping.

Figure 6: RIPPA and Ladybird.

The majority of robotic agricultural platforms developed until now have been four wheeled vehicles with either 2 or 4 wheel steering (examples above). An example of a tracked vehicle system is the Armadillo[38] (Figure 7). Tracks were chosen for manoeuvrability over soil disturbance and as a reliable solution. However, shielding the powertrain on the track system from dirt and mud was a noted Issue during development.

Figure 7: Armadillo.

2.2 Market Analysis

Robotics know many opportunities within agriculture and horticulture sectors. Figure 8 shows the four key stages of the farming cycle and associated activities that could be influenced by robotics in the near future.

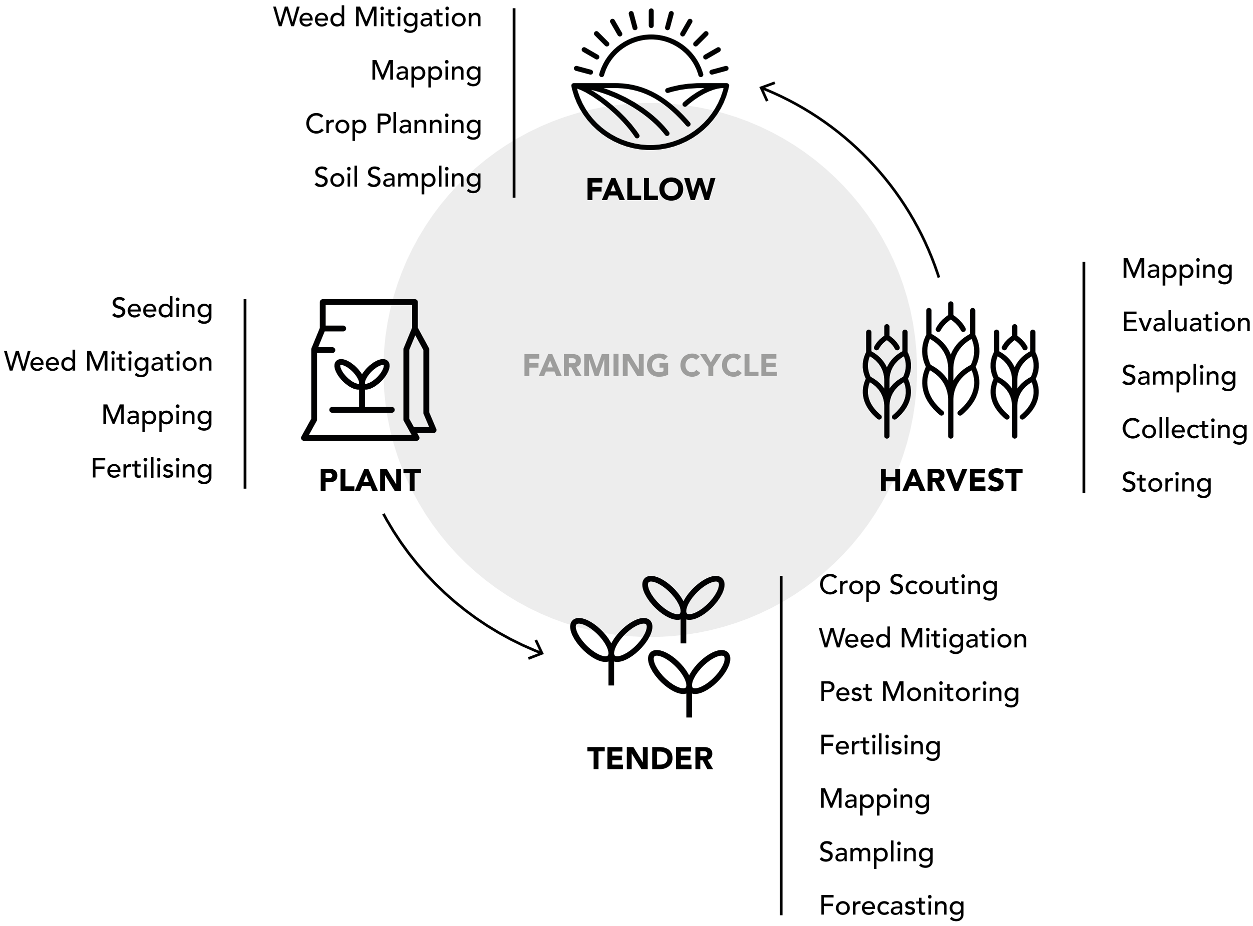

Figure 8: Opportunities for robotics in the farming cycle.

Weed mitigation has been selected as the first task for this agricultural robot because of the high cost, labour and environmental impact associated with it[16]. There are many products for the mechanical control of weeds, with the most common being tillage by a tractor pulling tines or disks through the soil, superficial cultivating with a hoe or wheel hoe or by using a flame weeder[4]. As shown previously, there are very few (semi-)autonomous robotic platforms for weed mitigation on the market. However, the opportunities in this sector are immense.

Introducing new, disruptive technologies can involve a substantial capital investment in upgrading to new specialised machinery and equipment. A farm's investment level in new machinery is driven by factors such as farm scale expansion, labour availability, lifestyle needs, the importance placed on machinery relative to other aspects of the business and the personal demands for capital[48]. According to [48], farm machinery costs, including the use of contractors are, on average, one third of the farm income. In general, farm machinery is financed over a period of 3 to 5 years and becomes a fixed overhead cost across all years, averaging 11% of the farm income.

Business models looking to implement robotics in agricultural operations will focus on different areas of ownership; direct to farmers, outsourced through contractors, hired, syndicated or shared with neighbours. Depending on the model, total lifecycle costs will include: capital costs, operating costs, labour costs and contracting costs.

As part of the user-centred research for this project, farmers were asked to participate in contextual conversations and observations at CSA farm locations in Belgium and The Netherlands. The purpose of the study was to better understand the farmer's perspective of agricultural robots in order to make substantiated design decisions in terms of technology and usability issues.

The objectives of the research were:

- To understand the critical drivers for CSA agriculture now.
- To understand the farmer's needs and issues regarding weed management.
- To investigate the current weed management practices used on the farms.
- To investigate the costs associated with current weed management practices.
- To establish the level of technology implementation currently on farms.
- To understand farmers perception of the development and implementation of small robotic platforms, incorporated in a fleet, for farm usage.
- To investigate what information farmers might find useful, if communicated by a robot. What level of detail? How should the interaction be with the information?
- To understand the required flexibility of the robot platform.

- To determine the level of autonomy robots should have.
- To understand the safety needs and expectations.
- To establish an idea of how CSA farming environments are structured.
- To understand the level of infrastructure farmers are willing to put into a new technology.
- To understand key drivers when buying equipment and machinery.

To outline the context at the start of each farm visit, the concept of fleets or swarms of small robots collaborating with farmers to execute agricultural tasks such as weed removal was presented.

2.2.1 Methods

Farm visits were undertaken at six CSA farms in Belgium and The Netherlands. Figure 9 shows the farms visited: Goedinge Boerderij (BE), 't Schaaphof (BE), Plukhof Beernem (BE), De Stadsgroenteboer (NL), Pluk! (NL) and Tuinen van Hartstocht (NL). The visits included contextual conversations, observations and collaborative work in an attempt to understand the above-mentioned research objectives.

The farm sizes ranged from 0.5ha to 3ha. All the farmers were the owners of the land. The farms visited were either family run or run as a collective business between different farmers. All farmers worked fulltime on the properties. The purpose of the visits was to develop an understanding of CSA farming practice, and to learn more about the farmer's opinion about incorporating agricultural robots in their farming practice.

Contextual conversations were held and a tour around the properties showed the fields, crops, buildings, machinery and equipment. The contextual conversations enabled, through discussion and demonstration by the farmers, the potential and challenges of incorporating agricultural robots. Observations by participating in agricultural tasks such as weed removal gave an understanding of the current weed control techniques, tactics and machinery used. Also, an understanding was developed of how labour-intensive weed control actually is.

Figure 9: Farms visited: A. Goedinge Boerderij (BE), B. 't Schaaphof (BE), C. Plukhof Beernem (BE), D. De Stadsgroenteboer (NL), E. Pluk! (NL) and F. Tuinen van Hartstocht (NL).

Photos of the farming infrastructure were taken and videos of the participative observations were made. Key insights were mapped and design indications from the contextual conversations, observations and participative work were identified.

Figure 10 shows how similar bed layouts are used on the different farms. The beds are 75 cm wide and the traffic paths are 45 cm wide on average. As can be seen on the images, there is not much space for manoeuvring around the growing beds.

A key insight from the farmers at Tuinen van Hartstocht (NL) was that they have seen major reductions in weed re-emergence from the moment they stopped hoeing a few years ago.

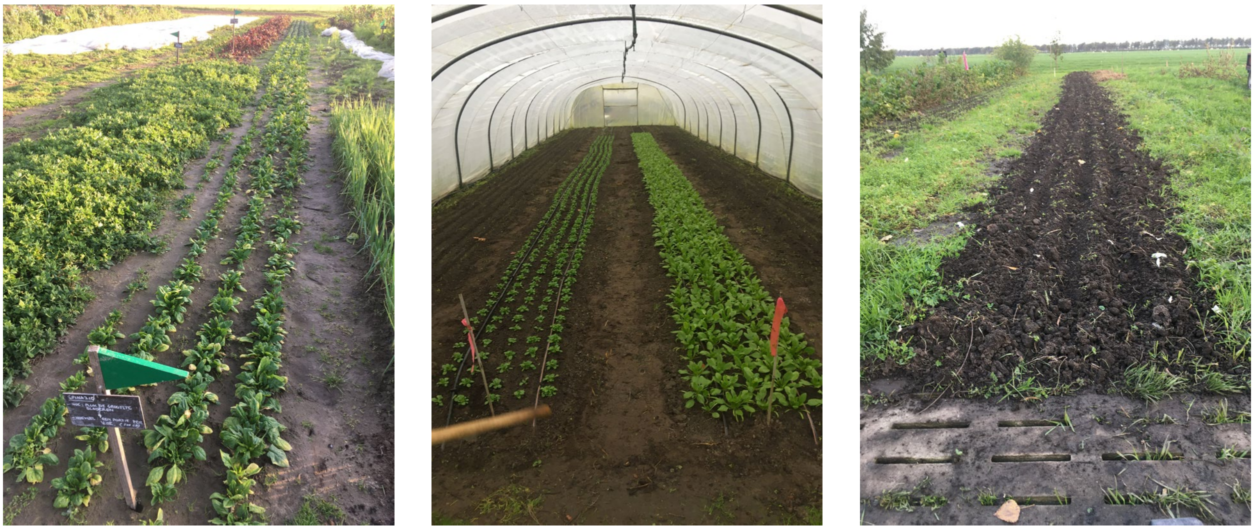

Figure 10: Similar bed layouts on the different farms.

They explained that hoeing brings seeds in the soil up to the surface, where they easily germinate. After thorough assessment, they decided that hand labour is more efficient in the long-term than using hoeing tools (Figure 11).

The farmers at De Stadsgroenteboer (NL) also used hand labour to remove weeds. As seen in Figure 11, they found that weeding from a standing position over the beds, moving backwards is an ergonomically pleasant way to do the labour.

Figure 11: Weeding at Tuinen van Hartstocht (NL) and De Stadsgroenteboer (NL).

At Plukhof Beernem (BE) and Pluk! (NL), some tools where used for working the soil superficially, such as a hand hoe and wheel hoe (Figure 12).

Figure 12: Hand tools used at Plukhof Beernem (BE) and Pluk! (NL).

2.2.2 Design Indications

Below is a list of design indications extracted from the conversations, observations and participative work with farmers.

- Farmers believe small robotic platforms are suited for precision tasks in agriculture such as weed mitigation.
- The platform should allow for maintenance and adaptability.
- A simple, user level, access to the interface system providing adequate and easily understandable visual information about the state of the machine.
- The number of operators for the platform to be monitored and maintained should be minimised. Preferably the farmer could do those tasks.
- Social position of the robot in the farm's ecosystem. Emotional aspects such as shape, colour, human interaction is important.
- The weight should be minimised to prevent soil compaction.
- Energy efficiency should be higher than in traditional motorised agricultural machinery.

2.3 Main Research Themes

Having looked into the challenges farmers face, the state-of-the-art in agricultural robotics, the existing market opportunities and the insights into farmers' perspective on the use of robotics in agriculture, key themes appear which will be addressed in this project.

2.3.1 Platform Application

Many opportunities can be found within CSA farming businesses for the application of robotic platforms to execute a variety of precision agricultural tasks, such as weed mitigation.

2.3.2 Cost of Development

An important aspect in the emergence of robotics in small-scale agriculture is the focus on keeping the costs down. It is the intention of this project to look at low cost manufacturing and assembly techniques.

2.3.3 Platform Configuration and Dimensions

Many of the existing robotic platforms come at a high cost and complexity due to the number of drive and steering motors in the design. This project will look at alternative platform configurations to reduce cost and complexity that still offer optimum traction and steering.

2.3.4 Usability

The aim of the project in terms of usability is to design a platform focused on the farmers' needs, specifically in small-scale CSA agriculture. Design and engineering skills will be used to address the needs of people with the possibilities of technology.

2.4 Design Criteria and Specifications

The aim of this project is to design and develop a small, lightweight robotic platform and implement for application in CSA farming businesses. The robot's main task will be weed mitigation at seedling stage. The goal for this platform is to deliver more productive farming outcomes in small-scale farming.

2.4.1 Platform

2.4.1.1 Overall Platform Requirements

- The robot's main function must be related to weed management. Specifically, mechanical weed mitigation at seedling stage.
- The robot must be lightweight in order to reduce soil compaction.
- The robot must be able to identify and locate weeds in order to apply a non-chemical weed treatment.
- The robot must be suited for driving autonomously over agricultural terrain.
- The robot should be reliable and easy to disassemble and maintain.
- The robot must operate safely.
- The robot should be low cost.
- The robot should be transportable on a standard trailer.
- The design must be scalable in order to cover use on different farm sizes in the form of a 'swarm'.

Considerations

The design of the platform began with defining general requirements regarding dimensions, mass, speed and configuration. Appraisal was more important than in-depth analysis since this project is about the development and design of a prototype vehicle. Each of the general requirements directly affects the outcome of the design.

2.4.1.2 Dimensions

The design of this platform is strongly related to its function. The overall dimensions are therefore defined based on the operating criteria. The actual width, height and length of the platform will be defined by a trade-off between aspects such as stability, working area, transportability and farming practices[49].

Control Traffic Farming

Control Traffic Farming (CTF) is a crop production system in which the crop rows and the paths are permanently separated. In reality it means that all tools and implements have set measurements and that the wheels tracks and paths are corresponding.

Many CSA farming businesses adopt the market gardening crop production system. Market gardening is a small-scale production system typically applied in farms of under 3ha[4]. In market gardening a wide range and steady supply of fresh produce is provided throughout the local growing season. Unlike large, industrial monoculture farms, which heavily depend on mechanisation and machinery, many different crop varieties are grown and more manual labour and gardening techniques are used. Managing the complexity of growing many different crops at once becomes easier when standardising the field layout. Standardising the field blocks to be of equal size, shape and length is a very effective way to manage different aspects of production, such as crop rotation, calculating soil amendments, and production planning. In the market gardening community, many hand tools are already sold to work specifically within those standards. Because of this, the CSA farming model could be ideal for integration, to a certain degree, of (collaborative) robotics operations. Raised beds in market gardening systems are generally 75 cm wide and paths are 45 cm wide[4]. Additionally, contextual conversations with farmers revealed similar parameters.

Based on this research, a platform width (wheel centre to wheel centre) of **1200 mm** was chosen for this prototype. Figure 13 depicts how this configuration would allow to take advantage of the CTF layout already in place on many farms following the market gardening principles.

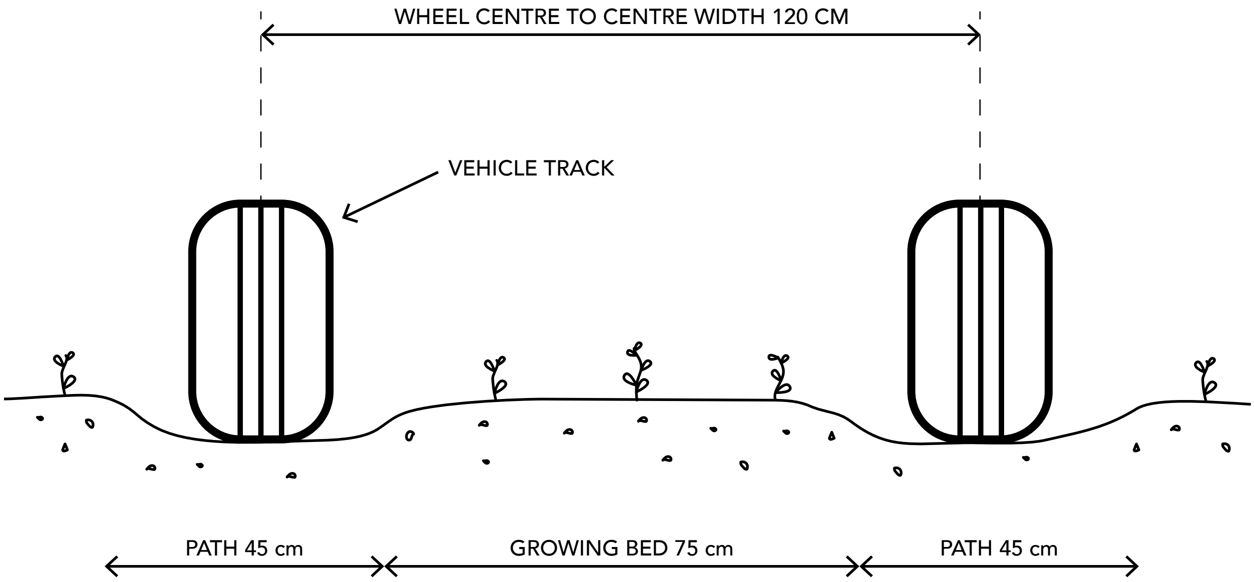

Figure 13: Vehicle wheel track in market gardening CTF layout.

Also, although the platform is not designed to drive on public roads, an important requirement is the ability to be transported on public roads to farms using a trailer. Article 46 of the Royal Decree containing general regulations on the police of road traffic and the use of public roads in Belgium[50] states that the width of a loaded vehicle or trailer must not exceed 2,55 metres.

Since many CSA farms use path widths of 45 cm, considering allowance for overhanging leaves and steering margin, a wheel width of approximately **300 mm** was considered a good guideline.

Crop height and operating gradients

This platform is designed to help control weed management at a seedling stage of the crops. Therefore, crop heights are not as much of importance to the clearance height of the vehicle. More important in this design are the operating gradients and specifically the clearance needed in order to drive the robot on a trailer. Trailer and ramp configurations were analysed and ground angles varied between 15 and 20 degrees. In order to avoid collision with the trailer, a clearance height of the vehicle was set at **350 mm**.

2.4.1.3 Mass

At a prototyping stage, mass estimation is a difficult parameter to specify. At this stage, the design still changes often which keeps the mass determination not specifiable.

Conversations with the farmers revealed that the mass target of the prototype should be similar to the mass of an All-Terrain Vehicle (ATV). According to the farmers, ATV's cause minimal soil disturbance compared with regular tractors. ATV's range in mass from 200 – 600 kg. Based on this, mass was estimated at **200 kg** maximum (platform and implement combined).

2.4.1.4 Speed

The platform operating speed is mainly constrained by the operational safety of the robot. For autonomous vehicles, a safe operating speed is considered to be the walking pace of a human[51]. The average walking speed for humans is approximately 5 km/h (1,38 m/s). The operating speed for the platform was chosen at **1 m/s**.

Other factors include weed removal application and obstacle detection.

The robot platform and the implement in this design are considered separate systems. The robot will not move when the implement is executing a task and vice versa. The reasons for this are to reduce complexity to control the system as well as safety precautions. This means that the speed of the platform is not constrained by the operation of the implement.

Current sensors used for obstacle detection have an optimal range of around 10m[52]. If the speed of the vehicle relates to the time of impact from detection, travelling at 1m/s, time to impact with the obstacle would be 10 seconds. This timeframe should be sufficient for sensor feedback and wheel motors to adjust rotational velocities.

2.4.1.5 Autonomy

Autonomy or operating time of the platform is affected by many factors such as the power supply and power requirements for operation. Operating time directly relates the speed of the platform to the required coverage of an area. Conversations with CSA farmers revealed that most farmers would like to be present when the robot is executing tasks. Most farmers require the platform to run for at least six hours continuously before refuelling or recharging. A continuous operating time of **six hours** at nominal speeds and loads was chosen.

2.4.1.6 Platform Configuration

Configuration analysis of the platform is at the foundation of good design development. The analysis consists of aspects about manoeuvrability, stability, locomotion and suspension, which are evaluated and finally a decision regarding which solutions to integrate in the full design development are made.

Manoeuvrability and steering strategy

CSA farms are quite similar in terms of field layout and size. Field research revealed that growing beds are mostly 30 metres long (maximum 50 metres) and are relatively straight. Headlands mainly consist of a two-metre stroke of fallow.

Potential use of a robotic vehicle in this environment would mean that a large portion of their operating time would be traversing in relatively straight lines along the growing beds. Manoeuvring around headlands would only take a small percentage of the operating time.

Differential steering

Differential steering works by applying more or less drive torque to a driving wheel on one side of the vehicle. This way, steering is enabled by the lateral displacement of the chassis. It is the primary means of steering in tracked vehicles, such as tanks and bulldozers, but it is also used in wheeled vehicles, known as skid-steering.

Depending on the differential steering type implemented, friction between the tires and ground, and available power, a vehicle with all-drive wheels may have a zero turning radius equal to half of the length of the vehicle by driving the wheels on each side at the same speed but in opposite directions. Due to the occurrence of slipping when turning, all-drive skid steering requires high power. Vehicles where only one drive wheel on each side is aligned with the chassis and all the others are free to caster, such as in wheelchairs, may have a larger turning radius but require the least power to turn.

Independent all-wheel steering

With independent steering each wheel is individually steered. Lateral movement in all directions is possible (holonomic movement) which means this system offers much flexibility for motion and is desirable in many mobile robots. However, there are issues regarding the complexity of the mechanism, the large number of motors required and the coordination needed to turn.

Articulated steering

In contrast with differential steering and independent all wheel steering, articulated steering is obtained by changing the angle between the front and rear axle of the vehicle. This system is allowed by splitting the vehicle into front and rear parts which are connected by a vertical hinge.

Locomotion

Stability

The way the platform is configured will directly affect its stability. One and two-wheeled vehicles suffer from instability at low speeds. Even with gyroscopic mechanisms, their payload capacity for this application is too limited. Four-wheeled configurations offer good stability due to the four points of contact with the ground, enabling a large payload capacity. Three wheels may also offer good stability, provided that the centre-of-mass is low and close in between the side-by-side wheels.

Wheels vs continuous tracks

Choosing between wheels and tracks in robotics is difficult because each system provides certain features and performances. Several factors are important; traction, ground pressure, suspension, and steering.

Tracked vehicles offer greater ground traction compared to wheeled vehicles due to their larger soil contact area. For the same reason, tracked vehicles induce lower ground pressure than wheels and are more suited to operate on soft terrains. But as a result of this larger contact area, rolling resistance and overall efficiency in tracked vehicles is reduced. Also, to obtain good traction, a good suspension system plays an important role. Building a suspension system for a tracked vehicle is much more complicated and expensive than for a wheeled vehicle. Tracked vehicles generally manoeuvre using differential steering which allows for tight turning, but increases soil disturbance compared with wheeled vehicles.

Having reviewed these factors it was decided that a **wheeled** platform configuration would be more suited for a small-scale CSA farming context.

Four-wheel drive, rear-wheel drive, front-wheel drive

Depending on the steering strategy and the traction requirements the choice of which wheels should be driving is made. Four-wheel drive (4WD) gives the best off-road performance, particularly on slopes and when overcoming obstacles. However, 4WD requires more energy to allow for locomotion. Rear-wheel drive (RWD) and Front-wheel drive (FWD) are more energy efficient on flat terrains. Traction difference between RWD and FWD on flat terrains is very small, especially at low speeds.

SUSPENSION

Suspension allows the platform to dampen road noise, vibration and bumps in the terrain and affects the handling characteristics. A good suspension system is also crucial for maintaining ground contact with the wheels at any time, especially when traversing larger bumps or uneven terrain. It allows the vehicle to not lose traction. Also, by smoothing out the ride, suspension can help to improve data collection from cameras and sensors. Different suspension systems have been incorporated in robotic vehicles design; passive independent suspension, passive averaging (rocker-bogie) and active suspension.

2.4.2 Implement

2.4.2.1 Overall Requirements

- The implement's main function must be related to weed management. Specifically, mechanical weed mitigation at seedling stage.
- The implement should minimise soil disturbance.
- The implement must cover the full width of a growing bed.

- The implement must operate safely.
- The implement should be low cost.
- The implement should be detachable, easy to maintain and easy to adapt.

2.4.2.2 Dimensions

The overall dimensions of the implement are defined based on the operating criteria. The actual size will mainly be defined by the working area it has to cover. As mentioned above, Control Traffic Farming (CTF) is a crop production system using fixed crop rows or growing beds and paths. The system used in CSA agriculture often follows the market gardening principle[4] where raised beds are generally 75 cm wide. Together with the interviewed farmers, it was decided that a working width for the implement should be around 75 cm. The implement should be adjustable in height for operation with different crops and crop growing stages. The implement should not obstruct the clearance height defined for the platform, especially not when transporting the robot.

2.4.2.3 Speed and Safety

The implement operating speed is mainly constrained by the safety requirements for collaborative mobile robots. Collaborative robots can operate autonomously when there is no human in their safeguarded workspace. When a human does enter their safeguarded space, a protective stop must be executed. The ISO 10218-1 standard for the Safety of Industrial Robots imposes four safety criteria for collaborative work. The four criteria are related to: 1. Monitored stops, 2. Controlled speeds, 3. Separation Distances, 4. Power and force limits. Whenever a collaborative mobile robot is performing an operation at high speed, or speeds exceeding 250 mm/s, a manual clearance of 450 mm is always required regardless of the location of the tasks.

2.4.2.4 Implement Configuration

Configuration analysis of the implement consist of a comparison between three manipulator systems; parallel manipulator, serial manipulator and a classic CNC system. All systems are evaluated and a final decision is made, which will be materialised in the development stage.

Parallel manipulator vs serial manipulator

A parallel manipulator is a mechanism which consists of one or more closed kinematic chains to support an end effector[53]. A parallel manipulator is designed so that each chain is usually short, simple and robust and thus rigid against unwanted movement. Errors in the position of a chain are averaged together with the other chains, rather than being cumulative as with serial manipulators. The closed-loop nature of a parallel manipulator makes the system relatively stiff relative to its components, unlike in a serial chain which becomes continuously less rigid with more components. The mutual stiffening of the system also permits for simple construction and lower cost parts. Another advantage of the parallel manipulator is that the actuators are often mounted on a single base platform, where the movement of the arm takes place through joints in the kinematic chains. This reduction in mass along the arm allows for a lighter construction, meaning lighter actuators can be used and faster movements can be achieved. The consolidation of mass also reduces the arm's overall moment of inertia, which is an advantage for a mobile robot.

A shortcoming of parallel manipulators, compared to serial manipulators, is their limited workspace. Serial manipulators are limited by the geometrical and mechanical limits of the design (collisions between legs and leg lengths)[54]. Parallel manipulators are also limited by the existence of singularities[55]. Singularities are positions where, for certain trajectories, the variation of the lengths of the legs is infinitely smaller than the variation of the position. At a singularity point a force applied on the end-effector induces, theoretically, infinitely large constraints on the legs, which may result in unstable conditions of the system and in worst case rupture of the manipulator.

Another disadvantage of parallel manipulators is their nonlinear behaviour. Having the end-effector perform a linear or circular movement heavily depends on the location in the workspace and does not vary linearly during the movement. Modelling for parallel manipulators is therefore more challenging than modelling for serial manipulators.

Classic CNC machine

A Computer Numerical Control (CNC) machine is a motorised, manoeuvrable tool or platform in which actuators control multiple axes. Usually at least two laterally (X and Y), and one end-effector moving in the Z direction. Due to its simple and robust construction, a CNC machine is more rigid than robot arms. High rigidity strongly influences the output accuracy. A disadvantage of using a CNC setup is that it is inherent to its workspace. Robotic arms often allow for more workspace while maintaining a smaller physical footprint within their environment.

2.4.3 Configuration Analysis

Figure 14 shows an exploration to vehicle configurations, suspension and implement systems. The purpose is to discuss and analyse each configuration. A final configuration suitable for CSA agriculture purposes was ultimately selected.

2.4.4 Resulting Configuration

Based on the above analysis, a two-wheel drive, four-wheel configuration was selected. This configuration is able to steer through differential steering by the driving wheels and stability is maintained by making use of two passive caster wheels. Passive averaging suspension or rocker-bogie suspension was selected because it offers great ground compliance, averages out the main body when driving through rough terrain while keeping complexity and component costs low. Due to its high stiffness, good dynamic characteristics and precise positioning capabilities, a parallel manipulator was the selected implement choice.

All of the robot's aspects have been selected by keeping in mind a suitable balance between functionality, vehicle complexity and cost.

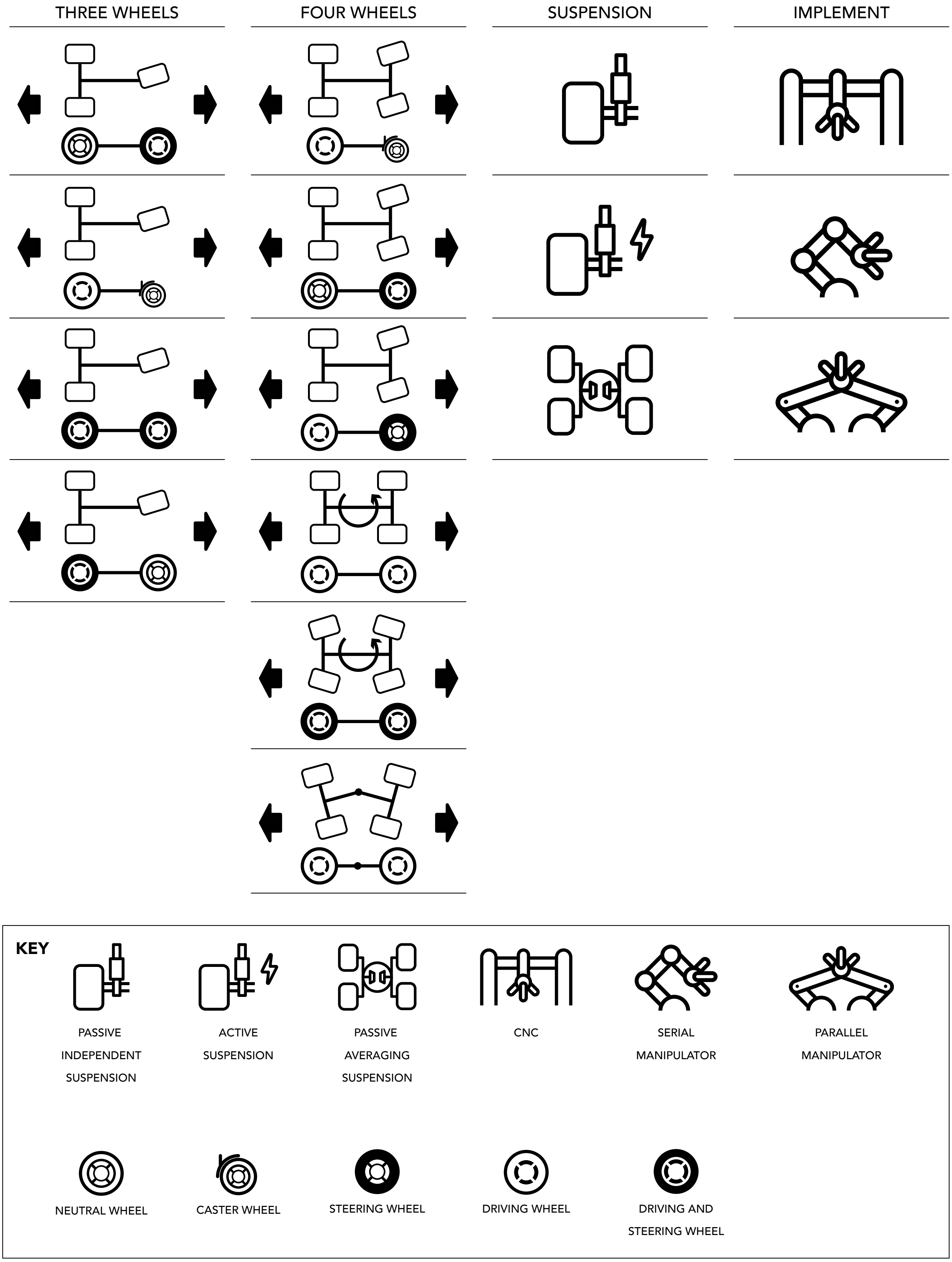

Figure 14: Configuration analysis.

2.4.5 Desired Platform Parameters

Table 1 summarises the desired platform parameters. These parameters will be used during the design and development phases of the robot to calculate the power requirements, select a drive unit and transmission and configure the suspension system. With a set platform configuration and main parameters, the process continues by modelling the steering kinematics, suspension kinematics and manipulator kinematics. Concept sketching, CAD modelling and building a first prototype are the final steps of this design process.

Not treated in depth is a detailed analysis of the operating forces acting on the vehicle. Further research and analysis need to be initiated to determine what these forces are going to be and where they will be acting in the environment in which the robot will operate. During the detailed design phase, educated estimates concerning these forces will be made so that the realisation of the prototype can be achieved in the small timeframe.

Table 1: Desired platform parameters.

Specification	Dimension	Unit	Description
Vehicle mass	200	kg	Total vehicle mass
Nominal Speed	1	m/s	
Max. Speed	2	m/s	
Number of Wheels	4		
Drive/Steering Wheels	2		Differential steering
Caster wheels	2		
Wheel Width	0,3	m	
Platform Width	1,2	m	Wheel centre to centre
Platform Length	1,2	m	Wheel centre to centre
Height Clearance	0,35	m	
Operating Time	6	hrs	

Chapter 3: Platform and Implement Modelling

3.1 Platform

3.1.1 Differential Drive Kinematics

3.1.1.1 Overview

A mobile robot or vehicle has 6 degrees of freedom (DOF), and its behaviour consists of two parts: 1. the position (x, y, z) and 2. the stance (roll, pitch, orientation). Roll is defined as the sidewise rotation and pitch as the rotation forward or backwards. Orientation refers to the direction in which the robot moves (x-y plane). The motion for a robot on a two-dimensional plane is described by its 2D behaviour (x, y, θ), where θ points the forward direction of the robot. Figure 15 illustrates the robot in a global coordinate system.

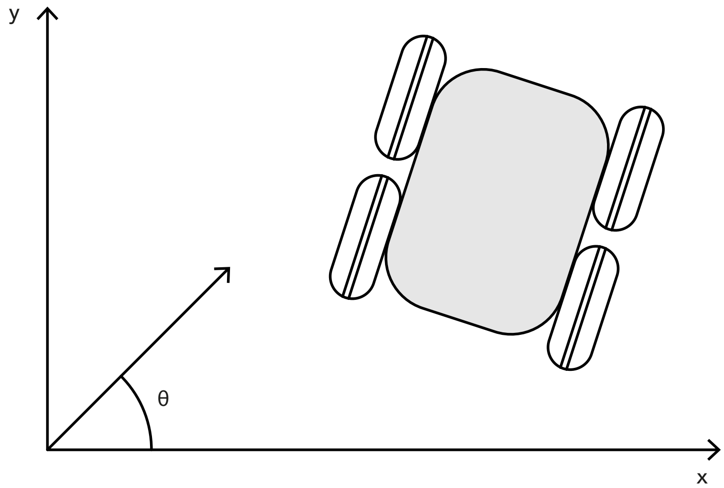

Figure 15: The robot's 2D behaviour (x, y, θ), given in a global coordinate system.

A robot with differential drive steers in a direction by separately controlling the speeds v_l and v_r, left and right wheel speeds respectively. To keep the robot upright, passive wheel(s) such as caster wheels, are added. These additional wheels follow the direction of the robot, induced by v_l and v_r.

3.1.1.2 Forward Kinematics Equations

Forward kinematics equations for a differential drive robot are used to solve the following problem:

At time t, in (x_t, y_t, θ_t), determine ($x_{t+\Delta t}$, $y_{t+\Delta t}$, $\theta_{t+\Delta t}$) at time t + Δt with given parameters v_l and v_r.

In Figure 16 a single rotating wheel (top view) can be observed. Motion along the y-axis is defined as roll. Any motion occurring along the x-axis is defined as slip.

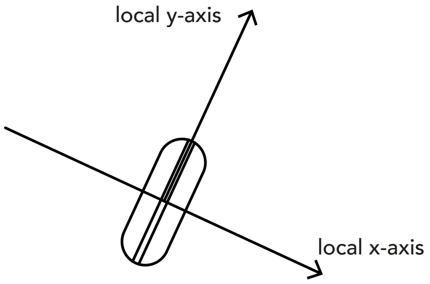

Figure 16: A single rotating wheel rolls along the local y-axis.

For one full rotation of the wheel, the centre moves a distance $2\pi r_w$ where r_w is the radius of the wheel. This is only true if based on the assumption that no slip occurs and that the motion is truly 2-dimensional.

A robot system with more driving wheels, such as in this project, must have a common centre point for rotation because each wheel must roll along its own y-axis (Figure 17). This point is called Instantaneous Centre of Rotation (ICR). The wheels do not move relative to each other; each wheel has to be coherent with the rigid rotation of the robot.

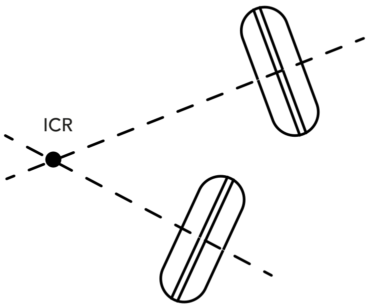

Figure 17: Two rotating wheels must share a common point of rotation.

A robot with a differential drive contains a pair of driving wheels on a common axis as shown in Figure 18. If the wheels are rotating on a plane, then a point ICR exists, around which both wheels rotate (with $v_l \neq v_r$). Changing v_l and v_r will force ICR to move and different trajectories for the robot are chosen. Given the fact that both driving wheels share a common axis, angular velocities ω of both wheels will be equal. The angular velocity of a wheel rotating around ICR is defined as its speed on a circular trajectory with radius r.

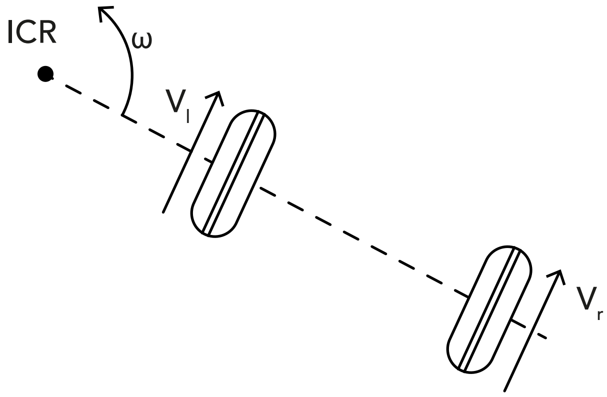

Figure 18: Wheel configuration for a robot with differential drive.

Wheel speed $v = 2\pi r/T$ (m/s) where T is the time to complete one full rotation around the ICR. Angular velocity $\omega = 2\pi/T$ (rad/s). Combining the equations for v and ω gives:

$$\omega r = v \qquad (1)$$

r and v for both left and right wheel result in the same ω (wheels move on a common axis around ICR), hence

$$\omega \left[R + \left(\frac{l}{2}\right)\right] = v_r \qquad (2)$$

$$\omega \left[R - \left(\frac{l}{2}\right)\right] = v_l \qquad (3)$$

where R is the distance between ICR and the midpoint between both wheels on the same axis, and l is the distance between both wheels (Figure 19).

Solving for ω and R gives

$$R = \frac{{}^{l}/_{2}(v_l+v_r)}{v_r-v_l} \qquad (4)$$

$$\omega = \frac{(v_r-v_l)}{l} \qquad (5)$$

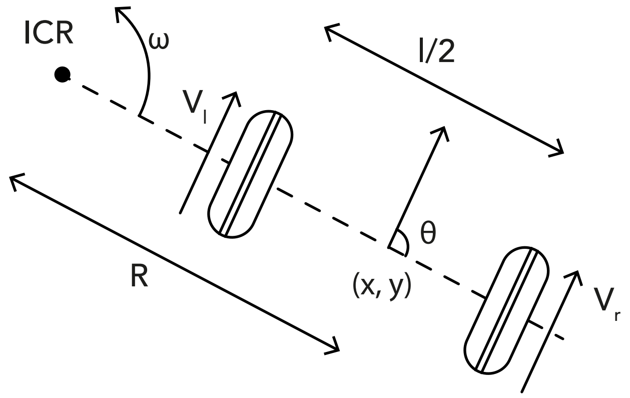

Figure 19: Wheel configuration for a robot with differential drive.

Assuming that the robot rotates around ICR with angular velocity ω for **Δ**t seconds (Figure 20), the orientation will change according to:

$$\theta_{t+\Delta t} = \omega\Delta t + \theta_t \qquad (6)$$

where ICR is given by trigonometry:

$$ICR = [ICR_x, ICR_y] = [x - Rsin\theta_t, y + Rcos\theta_t] \qquad (7)$$

Given a starting position (x_t, y_t), the new position ($x_{t+\Delta t}$, $y_{t+\Delta t}$) at time t+ **Δt** is defined by rotation around ICR with angular velocity ω for **Δ**t seconds:

$$\begin{bmatrix} x_{t+\Delta t} \\ y_{t+\Delta t} \end{bmatrix} = \begin{bmatrix} \cos(\omega\Delta t) & -\sin(\omega\Delta t) \\ \sin(\omega\Delta t) & \cos(\omega\Delta t) \end{bmatrix} \begin{bmatrix} x - ICR_x \\ y - ICR_y \end{bmatrix} + \begin{bmatrix} ICR_x \\ ICR_y \end{bmatrix} \qquad (8)$$

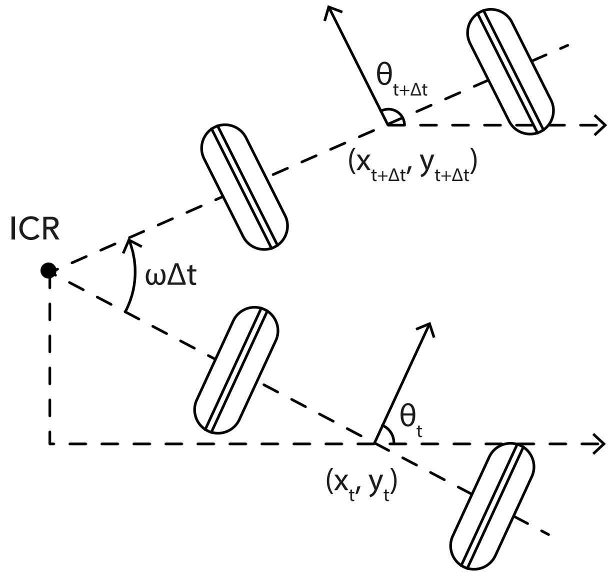

Figure 20: Rotating the robot $\omega\Delta t$ degrees around ICR.

The new position ($x_{t+\Delta t}$, $y_{t+\Delta t}$,$\theta_{t+\Delta t}$) can be calculated from equations (6) and (8) given ω (5), Δt and R:

$$\begin{bmatrix} x_{t+\Delta t} \\ y_{t+\Delta t} \\ \theta_{t+\Delta t} \end{bmatrix} = \begin{bmatrix} \cos(\omega\Delta t) & -\sin(\omega\Delta t) & 0 \\ \sin(\omega\Delta t) & \cos(\omega\Delta t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x - ICR_x \\ y - ICR_y \\ \theta \end{bmatrix} + \begin{bmatrix} ICR_x \\ ICR_y \\ \omega\Delta t \end{bmatrix} \tag{9}$$

3.1.1.3 Inverse Kinematics

While the forward kinematics equations provide an updated position given certain wheel speeds, the inverse problem can be formulated:

At time t, in (x_t, y_t, θ_t), determine the control parameters v_l and v_r in order to reach a position ($x_{t+\Delta t}$, $y_{t+\Delta t}$, $\theta_{t+\Delta t}$) at time t + Δt.

In order to control the robot's movement, the only inputs to the system are ω_r and ω_l. The position and orientation of the robot are defined by (x_t, y_t, θ_t). In the kinematic model we typically want to connect the inputs, ω_r and ω_l, to the position and orientation (x_t, y_t, θ_t).

The velocity kinematics of a differential drive mobile robot are given by [56]:

$$\begin{cases} \dot{x} = r_w \frac{(\omega_r+\omega_l)}{2} cos\theta \\ \dot{y} = r_w \frac{(\omega_r+\omega_l)}{2} sin\theta \\ \dot{\theta} = \frac{r_w}{l}(\omega_r - \omega_l) \end{cases} \quad (1)$$

Where $\dot{x}$ and $\dot{y}$ are the robot velocities, $\dot{\theta}$ is the angular velocity of the robot, r_w is the radius of the wheels, and l is the distance between the two drive wheels (wheel base).

This model gives us what we need in terms of mapping control inputs onto position and orientation states. The problem with this notation is that it is very unnatural to think in terms of wheel velocities. Instead of using [56] directly, the model proposed in [57] will be used to define ω_r and ω_l:

$$\begin{cases} \dot{x} = vcos\theta \\ \dot{y} = vsin\theta \\ \dot{\theta} = \omega \end{cases} \quad (2)$$

In this model, the speed v (translational velocity) and orientation ω (angular velocity) are controlled directly. These inputs are very 'natural', meaning we can feel what they are doing. However, the model in (2) is not the differential drive model, but rather the model used to design the control inputs for the robot. ω_r and ω_l are the actual control parameters at our disposal. Mapping (2) and (1) together gives:

$$\begin{cases} v = r_w \frac{(\omega_r+\omega_l)}{2} \\ \omega = \frac{r_w}{l}(\omega_r - \omega_l) \end{cases} \quad (3)$$

Thus

$$\begin{cases} \frac{2v}{r_w} = \omega_r + \omega_l \\ \frac{\omega l}{r_w} = \omega_r - \omega_l \end{cases} \quad (4)$$

In (4) the translational velocity v and the angular velocity ω is connected to the wheel velocities ω_r and ω_l. Solving these linear equations for ω_r and ω_l gives:

$$\begin{cases} \omega_r = \frac{2v+\omega l}{2r_w} \\ \omega_l = \frac{2v-\omega l}{2r_w} \end{cases} \qquad (5)$$

Where the translational velocity v and the angular velocity ω are the design parameters for the inverse kinematic model. The wheel base l and wheel radius r_w are known parameters for the robot.

These design inputs are now mapped onto the actual inputs that will control the robot's movement.

3.1.2 Differential Suspension Kinematics

3.1.2.1 Function

The primary role of a differential suspension, or rocker suspension, is to provide the mobile platform with a system that can adapt to unstructured terrain, such as ditches, soft soil and rocks, which is often the case in agricultural settings. By connecting a differential device in between two rocker suspensions, the four wheeled robot can maintain ground contact with all wheels at any time. This way, the robot's suspension system is able to passively distribute the weight over the wheels[58] and allows for constant traction by both motors at any point of time.

3.1.2.2 Structure

As shown in Figure 21, the suspension system is composed of a main body, a bevel gear-type differential device, two rocker suspensions and four wheels. The differential device is attached to the interior of the main body. Two extended shafts of the differential device are supported by flange bearings in the lateral walls of the main body and connected to the rocker suspensions, installed at both sides of the main body. Each rocker suspension includes two wheels, a caster wheel in the back and a driving wheel in the front, and a DC Motor with transmission to the driving wheel.

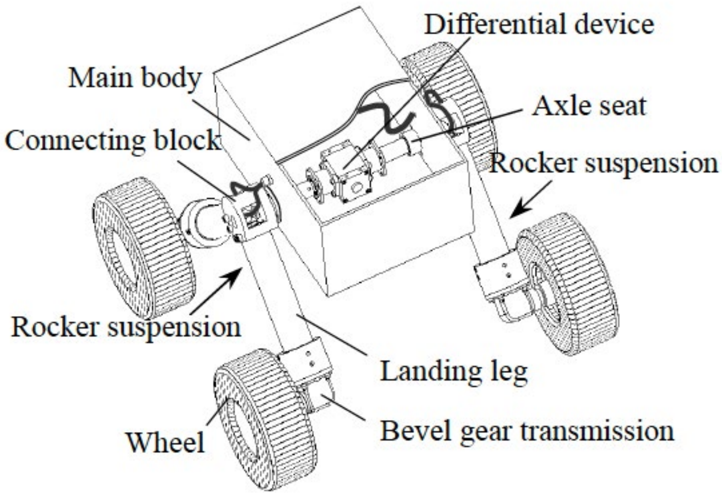

Figure 21: Rocker-type four-wheel mobile platform[58].

3.1.2.3 Differential Mechanism

The differential mechanism of a rocker-type robot is a motion transfer mechanism with two degrees of freedom (DOF), which can transform the two rotating inputs into a rotating output. The output is the average linear value of the two inputs. If ω_1 and ω_2 are the two angular velocity inputs, ω the angular velocity output, ϕ_1 and ϕ_2 two rotational angle inputs and ϕ the rotational angle output, we define:

$$\omega = \frac{\omega_1+\omega_2}{2},\ \varphi = \frac{\varphi_1+\varphi_2}{2} \qquad (1)$$

Two rotational input components connect to both rocker suspensions and the output component connects to the main body of the robot. This system allows for the swing angles of the rocker suspensions to be averaged by the differential mechanism. The mean value, transformed into the swing angle of the main body, is then the output. This mechanism is effective in the way that it decreases the swing of the main body and thus reduces the terrain effect.

If we consider the main swing angle of the main body as input and the swing angles of both rocker suspensions as outputs, the rotational input is decomposed into two different rotational outputs. If the output is the average value of two inputs, the average weight of the body is allocated to each wheel which can adjust its position passively and independently in the terrain.

Given the above characteristics and operating requirements of differential mechanisms, the working principle of a bevel gear type differential mechanism is analysed.

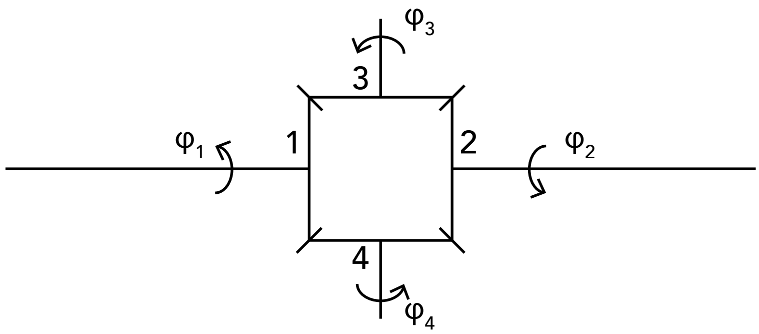

Figure 22: Schematic of the bevel gear differential mechanism.

Figure 22 shows a schematic of the bevel gear differential mechanism. Two bevel gears 1 and 2 mesh with the planetary bevel gears 3 and 4 orthogonally. The angular velocities of gears 1, 2, 3 and 4 are ω_1, ω_2, ω_3 and ω_4. The number of their teeth are Z_1, Z_2, Z_3 and Z_4. The rotational angles are ϕ_1, ϕ_2, ϕ_3 and ϕ_4. The relative velocity ratio of gear 1 and 2 with either gear 3 or 4 as carrier i_{12}^3, i_{12}^4 is then:

$$i_{12}^{3} = \frac{\omega_1 - \omega_3}{\omega_2 - \omega_3} = -\frac{Z_3.Z_2}{Z_1.Z_3} = -1$$

$$i_{12}^{4} = \frac{\omega_1 - \omega_4}{\omega_2 - \omega_4} = -\frac{Z_4.Z_2}{Z_1.Z_4} = -1$$

We obtain:

$$\omega_3 = \omega_4 = \frac{\omega_1 + \omega_2}{2} \; and \; \varphi_3 = \varphi_4 = \frac{\varphi_1 + \varphi_2}{2} \qquad \textbf{(2)}$$

It can be seen that this bevel gear differential mechanism allows for the swing angles of the rocker suspensions to be averaged. The mean value, transformed into the swing angle of the main body, is then the output.

3.2 Parallel Manipulator Inverse Kinematics

Parallel manipulators are mechanisms which consist of one or more closed kinematic chains. The advantages of this type of manipulator are high stiffness, good dynamic characteristics and precise positioning capabilities[53]. A disadvantage of parallel mechanisms is that their orientation workspace is generally limited by mechanical interference[54] or type II singularities[55]. On the intention of producing high-performance robots for Schönflies motion (translational motion in three dimensional space plus one rotation around an axis with fixed direction, popularised by SCARA-type serial robots[59]), new parallel robots have been proposed such as for instance in[60]–[64]. In [65] a robot arm was developed with the same orientation workspace of a serial robot arm but with parallel mechanism performances. The presented arm in [65] is a 4 + 1 Degree-Of-Freedom (DOF) parallel redundant manipulator. In this design, an extra redundant Degree-Of-Freedom was added to make rotation of the end effector possible.

For the purposes of this project, application for weed mitigation, rotation of the end effector is not necessary. Therefore, the design in [65] will be simplified into a non-redundant robot manipulator. The simplified design will consist of three DOF's (XYZ) which means only three motors (the original design had five) will be required to position the end effector in space. To steer the end effector through the motors, the kinematics of the system are required.

Figure 23 shows the simplified geometric model and nomenclature necessary for the derivation of the inverse kinematics. Five revolute joints are located at points A_i with $i \in [1,3]$. The orientation of the links attached to these revolute joints, relative to the fixed x-axis (fixed z-axis in the case of A_3), are the joint coordinates θ_i. These coordinates define the positions of points S_i, which are located at the end of a rigid link of length l_{i1}. This rigid link is the proximal coupler of the two parallelograms with rods of length l_{i2}, connecting points S_i to points B_i with $i \in [1,2]$. Four spherical joints connect the two rigid bars with the distal (end-effector) and proximal couplers. The parallelogram configuration constraints the angular velocity of the end-effector in the direction of n_i (the vector normal to the plane containing the parallelogram) and thus two directions of angular velocities are constrained (ω_i=0, i=1,2). This is true as long as n_1 and n_2 are linearly independent. The angular velocity in the y direction (ω_y) is unconstrained by the parallelograms. Therefore, the axis passing through points P and B_i with $i \in [1,3]$ is kept parallel to the y-axis at all times.

The spherical joint at point B_3 connects the end-effector to the revolute joint at point A_3 with legs l_{31} and l_{32}.

Note that every point A_i, B_i, S_i with $i \in [1,3]$ and P have a corresponding position vector $\vec{a_i}, \vec{s_i}, \vec{b_i}$ *and* $\vec{p}$. These vectors are only defined in XYZ dimensions.

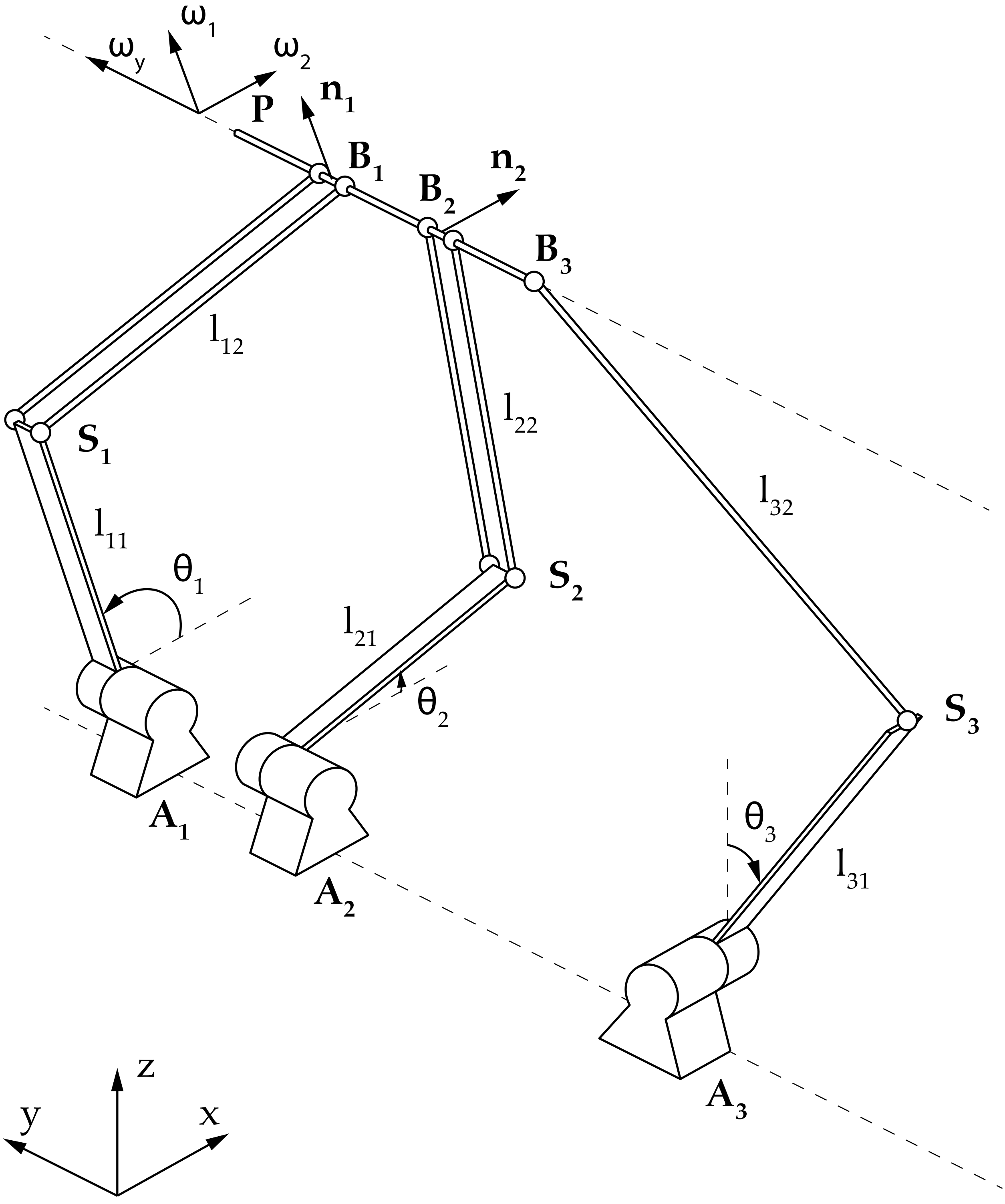

Figure 23: Simplified geometric model and nomenclature of a 3 DOF parallel manipulator.

The kinematic model for the proposed design is the relation between the vectors $\vec{\theta}(\theta_1, \theta_2, \theta_3)$ and the vector $\vec{p}(x, y, z)$. Also, to be able to control the speed of the end-effector, an additional relation between the vector $\frac{d\vec{\theta}}{dt}\left(\frac{d\vec{\theta_1}}{dt}, \frac{d\vec{\theta_2}}{dt}, \frac{d\vec{\theta_3}}{dt}\right)$ and the vector $\frac{d\vec{p}}{dt}\left(\frac{d\vec{x}}{dt}, \frac{d\vec{y}}{dt}, \frac{d\vec{z}}{dt}\right)$ has to be found.

Following is the derivation of the inverse kinematic model and the velocity equations for controlling the three motors of the parallel robot arm designed for this project. The rotation matrices below will be used in the derivation:

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

$$R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

3.2.1 Constraints

In Figure 23 the following constraints can be observed;

The position vector of points B_i, noted $\vec{b_i}$ expressed in the fixed reference frame O_{xyz} are defined as:

$$\vec{b_i} = \vec{p} + \vec{v_i} \quad with\ i \in [1,3]\ ;\ \vec{v_i} = \begin{bmatrix} 0 \\ -v_i \\ 0 \end{bmatrix} \qquad (1)$$

Scalar parameter v_i is defined as the distance in the direction of the y-axis between point P and points B_i with i ∈ [1,3]. The axis on which points P and B_i are located is always parallel with the XY plane.

The position vectors of points S_i are also defined in the fixed frame as:

$$\vec{s_i} = \vec{a_i} + \vec{f_i} \quad with\ i \in [1,2]\ ;\ \vec{f_i} = R_y(\theta_i).f_{i,0}\ where\ f_{i,0} = \begin{bmatrix} l_{i1} \\ 0 \\ 0 \end{bmatrix}$$

$$and\ with\ i \in [3]\ ;\ \vec{f_3} = R_x(\theta_3).f_{3,0}\ where\ f_{i,0} = \begin{bmatrix} 0 \\ 0 \\ l_{31} \end{bmatrix} \qquad (2)$$

The distance between points B_i and S_i is also expressed. It is the Euclidean distance between those points:

$$\left(\vec{b_i} - \vec{s_i}\right)^T \left(\vec{b_i} - \vec{s_i}\right) = l_{i2}^2\ with\ i \in [1,3] \qquad (3)$$

3.2.2 Velocities

To steer the end-effector, the angular velocity vector $\frac{d\vec{\theta}}{dt}\left(\frac{d\vec{\theta_1}}{dt}, \frac{d\vec{\theta_2}}{dt}, \frac{d\vec{\theta_3}}{dt}\right)$ representing the angular velocities of the three motors, needs to be obtained. The velocity vector of point P $\frac{d\vec{p}}{dt}\left(\frac{d\vec{x}}{dt}, \frac{d\vec{y}}{dt}, \frac{d\vec{z}}{dt}\right)$ is known. The velocity equations are composed.

Differentiating (3) with respect to time gives:

$$\frac{d\left[\left(\vec{b_i} - \vec{s_i}\right)^T \left(\vec{b_i} - \vec{s_i}\right)\right]}{dt} = \frac{dl_{i2}^2}{dt}\ (l_{i2} = cnst)$$

$$\Leftrightarrow \frac{d\left[(B_{ix} - S_{ix})^2.\vec{1_x} + \left(B_{iy} - S_{iy}\right)^2.\vec{1_y} + (B_{iz} - S_{iz})^2.\vec{1_z}\right]}{dt} = 0$$

$$\Leftrightarrow 2.(B_{ix} - S_{ix}).\left[\frac{dB_{ix}}{dt} - \frac{dS_{ix}}{dt}\right].\vec{1_x} + 2.\left(B_{iy} - S_{iy}\right).\left[\frac{dB_{iy}}{dt} - \frac{dS_{iy}}{dt}\right].\vec{1_y} + 2.(B_{iz} - S_{iz}).\left[\frac{dB_{iz}}{dt} - \frac{dS_{iz}}{dt}\right].\vec{1_z} = 0$$

$$\Leftrightarrow \left[\left(B_{ix}.\overrightarrow{1_x} + B_{iy}.\overrightarrow{1_y} + B_{iz}.\overrightarrow{1_z}\right) - \left(S_{ix}.\overrightarrow{1_x} + S_{iy}.\overrightarrow{1_y} + S_{iz}.\overrightarrow{1_z}\right)\right].\left(\frac{d\left(B_{ix}.1_x + B_{iy}.1_y + B_{iz}.1_z\right)}{dt} - \frac{d\left(S_{ix}.\overrightarrow{1_x} + S_{iy}.\overrightarrow{1_y} + S_{iz}.\overrightarrow{1_z}\right)}{dt}\right) = 0$$

$$\Leftrightarrow \left(\vec{b_i} - \vec{s_i}\right)^T.\frac{d\vec{b_i}}{dt} = \left(\vec{b_i} - \vec{s_i}\right)^T.\frac{d\vec{s_i}}{dt} \qquad \textbf{(4)}$$

Also, the differentiation of (1) with respect to time gives:

$$\frac{d\vec{b_i}}{dt} = \frac{d(\vec{p}+\vec{v_i})}{dt} = \frac{d\vec{p}}{dt}\ (v_i = const) \qquad \textbf{(5)}$$

The velocity of points S_i can be expressed from the joint coordinates. Differentiating (2) gives:

$$\frac{d\vec{s_i}}{dt} = \frac{d\left(\vec{a_i} + \vec{f_i}\right)}{dt} = \frac{d\vec{f_i}}{dt}\ (a_i = const)$$

$$\Rightarrow for\ \ i \in [1,2]:$$

$$\frac{d\vec{s_i}}{dt} = \frac{d\vec{f_i}}{dt} = \frac{d\left(R_y(\theta_i).f_{i,0}\right)}{dt} = f_{i,0}.\frac{dR_y(\theta_i)}{dt} = f_{i,0}.R_y\left(\frac{\pi}{2}\right).R_y(\theta_i).\frac{d\theta_i}{dt}$$

$$\Rightarrow for\ i = 3:$$

$$\frac{d\vec{s_3}}{dt} = \frac{d\vec{f_3}}{dt} = \frac{d\left(R_x(\theta_3).f_{3,0}\right)}{dt} = f_{3,0}.\frac{dR_x(\theta_3)}{dt} = f_{3,0}.R_x\left(\frac{\pi}{2}\right).R_x(\theta_3).\frac{d\theta_3}{dt} \qquad \textbf{(6)}$$

It can be shown that $\frac{dR_y(\theta_i)}{dt} = R_y\left(\frac{\pi}{2}\right).R_y(\theta_i)$

$$LM: \frac{dR_y(\theta_i)}{dt} = \frac{d}{dt}\begin{bmatrix} \cos(\theta_i) & 0 & \sin(\theta_i) \\ 0 & 1 & 0 \\ -\sin(\theta_i) & 0 & \cos(\theta_i) \end{bmatrix} = \begin{bmatrix} -\sin(\theta_i) & 0 & \cos(\theta_i) \\ 0 & 0 & 0 \\ -\cos(\theta_i) & 0 & -\sin(\theta_i) \end{bmatrix}$$

$$RM: R_y\left(\frac{\pi}{2}\right).R_y(\theta_i) = \frac{d}{dt}\begin{bmatrix} \cos\left(\frac{\pi}{2}\right) & 0 & \sin\left(\frac{\pi}{2}\right) \\ 0 & 1 & 0 \\ -\sin\left(\frac{\pi}{2}\right) & 0 & \cos\left(\frac{\pi}{2}\right) \end{bmatrix}.\begin{bmatrix} \cos(\theta_i) & 0 & \sin(\theta_i) \\ 0 & 1 & 0 \\ -\sin(\theta_i) & 0 & \cos(\theta_i) \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix}.\begin{bmatrix} \cos(\theta_i) & 0 & \sin(\theta_i) \\ 0 & 1 & 0 \\ -\sin(\theta_i) & 0 & \cos(\theta_i) \end{bmatrix} = LM$$

In a same fashion the equality $\frac{dR_x(\theta_3)}{dt} = R_x\left(\frac{\pi}{2}\right).R_x(\theta_3)$ can be proven.

Substituting (5) and (6) in equation (4) gives:

$$\left(\vec{b_i} - \vec{s_i}\right)^T.\frac{d\vec{p}}{dt} = \left(\vec{b_i} - \vec{s_i}\right)^T.f_{i,0}.R_y\left(\frac{\pi}{2}\right).R_y(\theta_i).\frac{d\theta_i}{dt} \; for \;\; i \in [1,2]$$

$$\left(\vec{b_i} - \vec{s_i}\right)^T.\frac{d\vec{p}}{dt} = \left(\vec{b_i} - \vec{s_i}\right)^T.f_{i,0}.R_x\left(\frac{\pi}{2}\right).R_x(\theta_i).\frac{d\theta_i}{dt} \; for \;\; i = 3 \qquad (7)$$

The relation between the motor joint velocities (defined by $\frac{d\theta_i}{dt}$) and the Cartesian velocities $(\frac{d\vec{p}}{dt})$ of the end-effector is shown in the Jacobian matrices.

Consider the function $\vec{g_i}(t)^T = \left(\vec{b_i} - \vec{s_i}\right)^T$, then equation (7) in matrix representation is shown as:

$$J\frac{d\vec{p}}{dt} = K\frac{d\vec{\theta}}{dt}$$

With:

$$J = \begin{bmatrix} \overrightarrow{g_1}^T \\ \overrightarrow{g_2}^T \\ \overrightarrow{g_3}^T \end{bmatrix} = \begin{bmatrix} (B_{1x} - S_{1x}) & (B_{1y} - S_{1y}) & (B_{1z} - S_{1z}) \\ (B_{2x} - S_{2x}) & (B_{2y} - S_{2y}) & (B_{2z} - S_{2z}) \\ (B_{3x} - S_{3x}) & (B_{3y} - S_{3y}) & (B_{3z} - S_{3z}) \end{bmatrix}$$

$$K = \begin{bmatrix} \overrightarrow{g_1}^T . R_y\left(\frac{\pi}{2}\right) . R_y(\theta_1) & 0 & 0 \\ 0 & \overrightarrow{g_2}^T . R_y\left(\frac{\pi}{2}\right) . R_y(\theta_2) & 0 \\ 0 & 0 & \overrightarrow{g_3}^T . R_x\left(\frac{\pi}{2}\right) . R_x(\theta_3) \end{bmatrix}$$

The angular velocities of the three motors are now:

$$\frac{d\vec{\theta}}{dt} = K^{-1} J \frac{d\vec{p}}{dt} \qquad (8)$$

3.2.3 Inverse kinematics

The solution of the inverse kinematic problem consists in determining the input joint angles θ_i with $i \in [1,3]$of the three motors for given values of the Cartesian coordinates $\vec{p}(x, y, z)$.

With $\vec{p}$ defined, with equation (1), it is possible to determine $\overrightarrow{b_i}$. Subsequently, (3) can be solved in order to obtain the values for θ_i with $i \in [1,3]$. The problem is similar to finding the intersection points between two circles, which generally has two solutions.

Substituting equation (1) and (2) in (3) and expanding the left member of equation (3):

$$\begin{aligned} l_{12}^2 = {} & (\cos(\theta_1)^2 + \sin(\theta_1)^2) . l_{11}^2 + (A_{1x}^2 - 2. A_{1x} . P_x + P_x^2) + (A_{1z}^2 - 2. A_{1z} . P_z + P_z^2) \\ & + \left(A_{1y}^2 + P_y^2 + v_1^2 - 2. A_{1y} . P_y + 2. A_{1y} . v_1 - 2. P_y . v_1\right) \\ & + 2. \cos(\theta_1) . l_{11} . (A_{1x} - P_x) - 2. \sin(\theta_1) . l_{11} . (A_{1z} - P_z) \end{aligned}$$

$$\Leftrightarrow l_{12}^2 = l_{11}^2 + (A_{1x}^2 - P_x)^2 + (A_{1z} - P_z)^2 + \left(A_{1y} + (P_y - v_1)\right)^2$$
$$+ 2.\cos(\theta_1).l_{11}.(A_{1x} - P_x) - 2.\sin(\theta_1).l_{11}.(A_{1z} - P_z)$$

$$\Leftrightarrow 2.\cos(\theta_1).(A_{1x} - P_x) - 2.\sin(\theta_1).(A_{1z} - P_z)$$
$$= \frac{l_{12}^2 - l_{11}^2 - (A_{1x}^2 - P_x)^2 - (A_{1z} - P_z)^2 - \left(A_{1y} + (P_y - v_1)\right)^2}{l_{11}}$$

The calculation for l_{22} is exactly the same as for l_{12}.

$$l_{32}^2 = (\cos(\theta_3)^2 + \sin(\theta_3)^2).l_{31}^2 + (A_{3x}^2 - 2.A_{3x}.P_x + P_x^2) + (A_{3z}^2 - 2.A_{3z}.P_z + P_z^2)$$
$$+ \left(A_{3y}^2 + P_y^2 + v_3^2 - 2.A_{3y}.P_y + 2.A_{3y}.v_3 - 2.P_y.v_3\right)$$
$$- 2.\sin(\theta_3).l_{31}.\left(A_{3y} - (P_y - v_3)\right) + 2.\cos(\theta_3).l_{31}.(A_{3z} - P_z)$$

$$\Leftrightarrow l_{32}^2 = l_{31}^2 + (A_{3x} - P_x)^2 + (A_{3z} - P_z)^2 + \left(A_{3y} - (P_y - v_3)\right)^2$$
$$- 2.\sin(\theta_3).l_{31}.\left(A_{3y} - (P_y - v_3)\right) + 2.\cos(\theta_3).l_{31}.(A_{3z} - P_z)$$

$$\Leftrightarrow 2.\cos(\theta_3).(A_{3x} - P_z) - 2.\sin(\theta_3).\left(A_{3y} - (P_y - v_3)\right)$$
$$= \frac{l_{32}^2 - l_{31}^2 - (A_{3x} - P_x)^2 - (A_{3z} - P_z)^2 - \left(A_{3y} - (P_y - v_3)\right)^2}{l_{31}}$$

The following form can be noticed in the expansion of equation (3):

$$Q_i.\cos(\theta_i) + T_i.\sin(\theta_i) = R_i \quad for \ \ i \in [1,3] \qquad \textbf{(9)}$$

for i ∈ [1,2]

$$Q_i = 2.(A_{ix} - P_x)\ and\ T_i = -2.(A_{iz} - P_z)\ and$$

$$R_i = \frac{l_{i2}^2 - l_{i1}^2 - (A_{ix}^2 - P_x)^2 - (A_{iz} - P_z)^2 - \left(A_{iy} + (P_y - v_i)\right)^2}{l_{i1}}$$

and for i=3

$$Q_3 = 2.(A_{3z} - P_z)\ and\ T_3 = -2.\left(A_{3y} - (P_y - v_3)\right)\ and$$

$$R_3 = \frac{l_{32}^2 - l_{31}^2 - (A_{3x} - P_x)^2 - (A_{3z} - P_z)^2 - \left(A_{3y} - (P_y - v_3)\right)^2}{l_{31}}$$

In general we can write for all i ∈ [1,3]:

$$R_i = \frac{l_{i2}^2 - l_{i1}^2 - \left(\overrightarrow{a_i} - \overrightarrow{b_i}\right)^T \left(\overrightarrow{a_i} - \overrightarrow{b_i}\right)}{l_{i1}}$$

To solve (9), tangent half-angle substitution is used.

In trigonometry, tangent half-angle formulas, among others, are:

$$\sin\alpha = \frac{2.\tan\frac{\alpha}{2}}{1+\tan^2\frac{\alpha}{2}} \quad \cos\alpha = \frac{1-\tan^2\frac{\alpha}{2}}{1+\tan^2\frac{\alpha}{2}} \quad \tan\alpha = \frac{2.\tan^2\frac{\alpha}{2}}{1-\tan^2\frac{\alpha}{2}} \qquad (10)$$

Substitution of the half-tangent formulas (10) in equation (9) gives:

$$Q_i.\frac{1-\tan^2\frac{\theta_i}{2}}{1+\tan^2\frac{\theta_i}{2}} + T_i.\frac{2.\tan\frac{\theta_i}{2}}{1+\tan^2\frac{\theta_i}{2}} = R_i$$

$$\Leftrightarrow Q_i.\left(1-\tan^2\frac{\theta_i}{2}\right) + T_i.\left(2.\tan\frac{\theta_i}{2}\right) = R_i.\left(1+\tan^2\frac{\theta_i}{2}\right)$$

Substituting $\tan\frac{\theta_i}{2}$ by t_i:

$$0 = (R_i + Q_i).t_i^2 - 2.T_i.t_i + (R_i - Q_i)$$

The discriminant is:

$$D = (2.T_i)^2 - 4.(R_i + Q_i).(R_i - Q_i) = 4.T_i^2 - 4.(R_i^2 - Q_i^2)$$

Thus:

$$t_i = \frac{T_i \pm \sqrt{T_i^2 - (R_i^2 - Q_i^2)}}{(R_i + Q_i)}$$

And finally:

$$\theta_i = 2.\tan^{-1}(t_i)$$

The solution of the inverse kinematic problem can now be used for the trajectory planning of the parallel manipulator for weed mitigation.

Chapter 4: Robot Design Development

4.1 Design Concept – Sketching

At the start of the design concept phase sketches were made to quickly visualise and communicate concepts concerning the platform and implement configurations and form. Figure 24 depicts some of those sketches. More sketching can be found in the appendix.

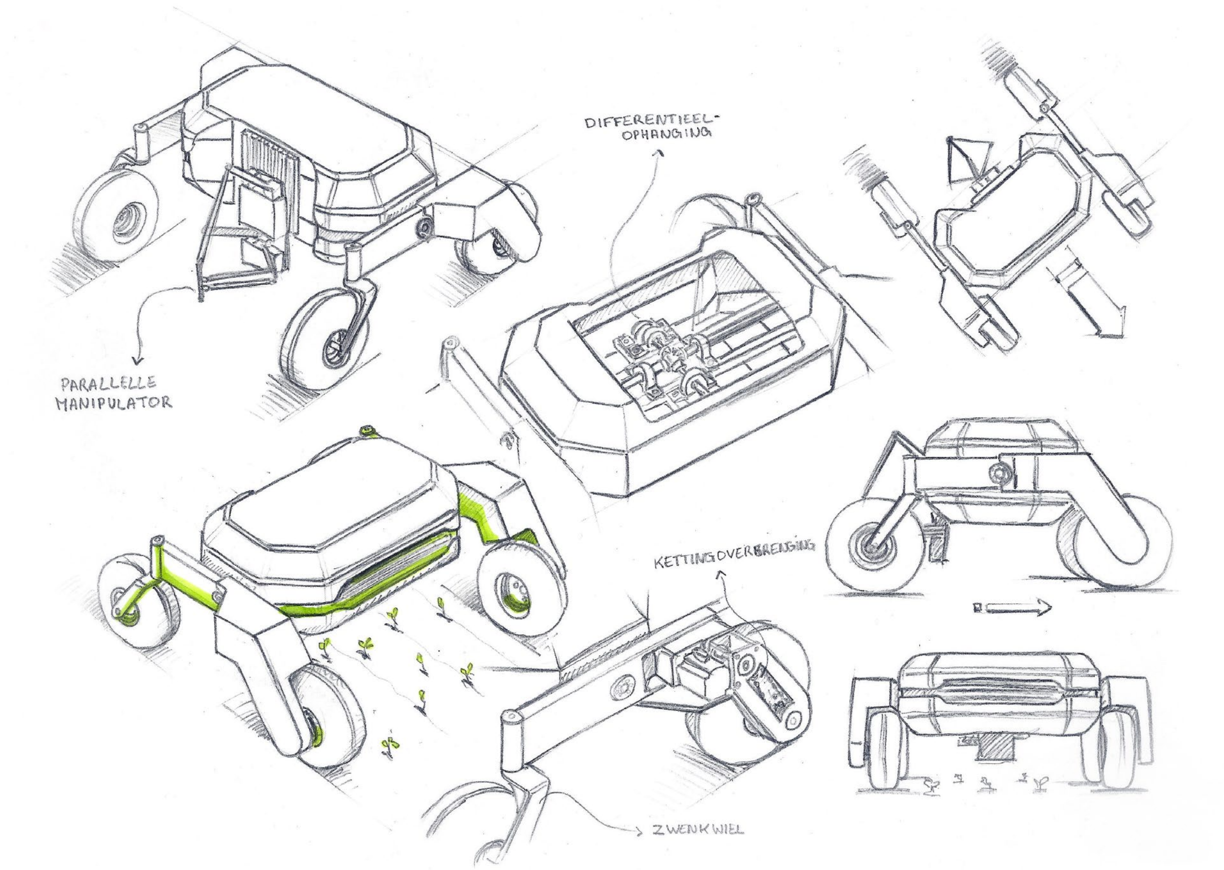

Figure 24: Conceptual sketches of the agricultural robot.

4.2 Design Concept - Renderings

The next step of the concept design phase was to model the vehicle in CAD software. Renderings of those models were made and used to assess the geometry of the platform and the possibility to assemble standard components. Renderings were also valuable to communicate the desired end result with the project stakeholders.

Figure 25: Renderings of the agricultural robot.

4.3 Robot Concept

The iterative nature of the concept design phase converged into a refined concept for the platform, according the established vehicle configuration and key platform parameters. At the same time, standard mechanical components, motors, wheels and power sources were investigated to bring the design concept closer to the development phase.

The design developed is a four-wheeled platform, driven by two-wheel drive through brushless DC motors and a chain drive. Steering is made possible by a differential steering strategy of the driven wheels in combination with passive caster wheels. The side units or swing arms connect the driven and caster wheels and allow for driving along the raised growing beds. The main body of the robot contains the bevel gear transmission which averages the angle between both swingarms. The interchangeable implement unit is attached to the backside of the body and adjustable in height.

4.4 Robot Development

In this section the materialisation of the prototype platform is described. Three main assemblies are distinctive: 1. Side Swingarm Assembly, 2. Main Body Assembly, 3. Implement Assembly. Figure 26 depicts the main assemblies of the vehicle.

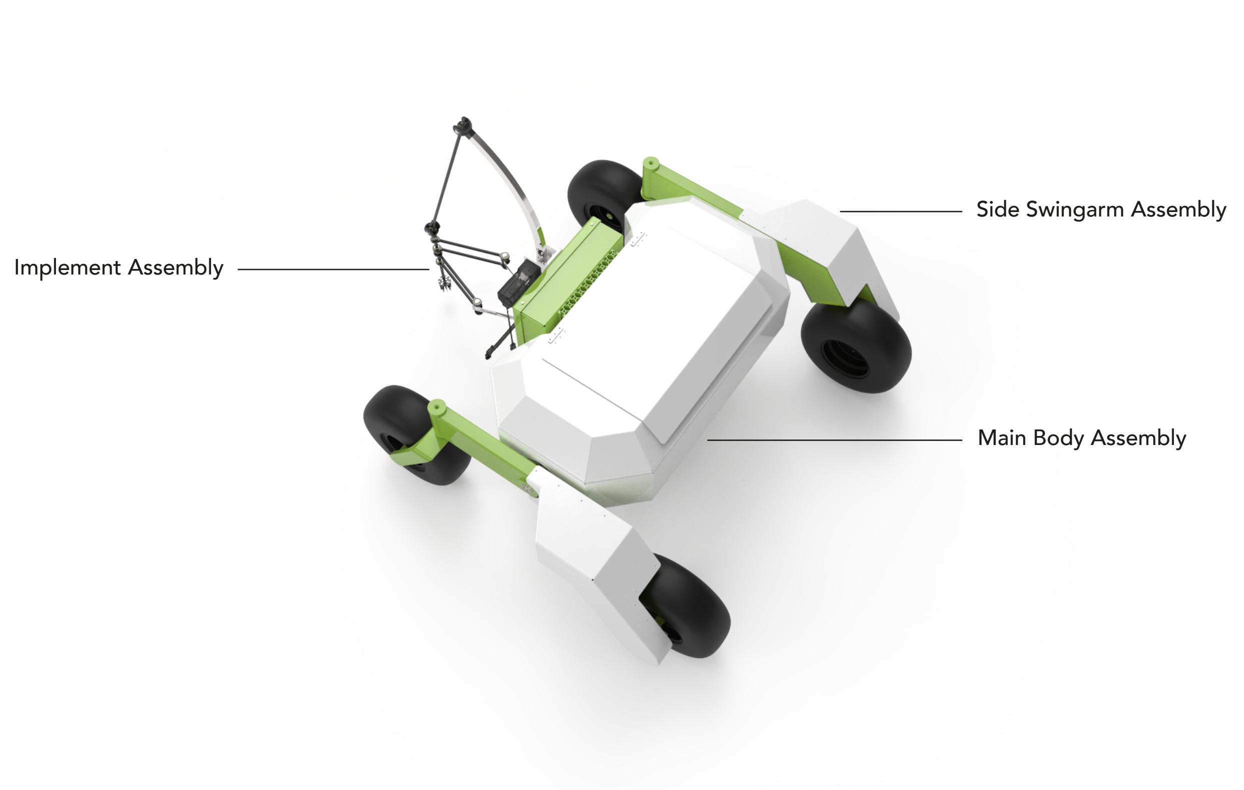

Figure 26: Main assemblies.

4.4.1 Overall Dimensions

Figure 27 indicates the overall dimensions (mm) of the prototype:

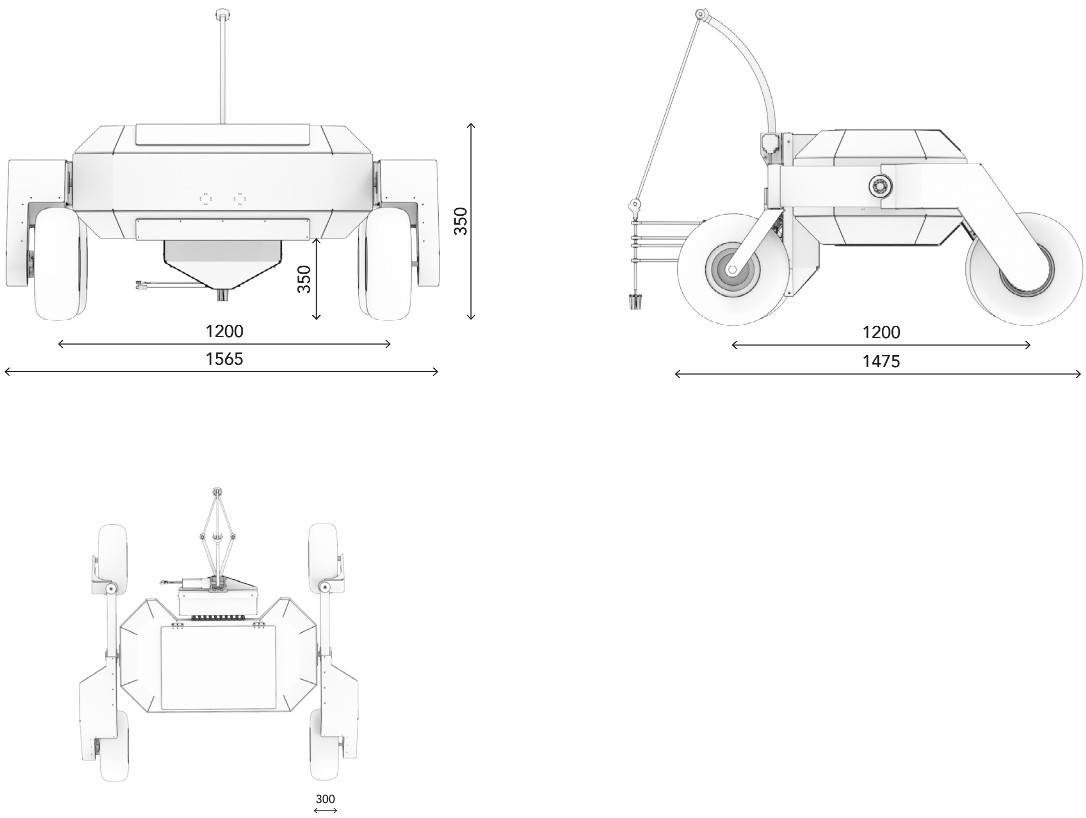

Figure 27: Overall Dimensions

4.4.2 Platform Chassis

Designing the platform chassis was heavily dependent on manufacturability, assembly, strength and weight requirements. The chassis needed to fulfil structural demands in certain areas where in other areas the focus was on reducing the weight of the components. Also, the chassis needed to be constructed in a simple way to facilitate easy maintenance and disassembly.

The chassis consists of two main assemblies:

1. Side Swingarm Assembly (mirrored on both sides of the platform)

2. Main Body Assembly

4.4.3 Side Swingarm Assembly

4.4.3.1 Function

The side swingarm functions as the structure carrying the driving and caster wheels, the motor, transmission and the main body. The unibody structure supports the loads through the external shell, allows for the motor to be tightly embedded and functions as an enclosure for the built-in components.

4.4.3.2 Dimensions

The side swingarm assembly measures 1475 x 580 x 360 mm.

The platform is designed to allow for over-bed driving. Literature and contextual conversations revealed that most CSA farms adopt a CTF farming model popularised by the market gardening principles[5]. In this model, raised growing beds and traffic paths are permanently embedded in the farm's layout. Typically, traffic paths have a width of 450 mm. The swingarm assembly is therefore attuned to a wheel width of 300 mm, leaving about 75 mm space allowance on either side.

The length of the side swingarm assembly was decided considering stability concerns and ease of steering. A wheel centre to wheel centre length of 1200 mm was established.

4.4.3.3 Materials

The chassis of the Swingarm Assembly is fabricated from 3 mm S235JR mild steel sheet and 120 x 40 x 3 mm S235JRH mild steel rectangle tube. Shafts for the driving wheel, caster wheel and bushing house are fabricated from CK45 alloy steel.

4.4.3.4 Fabrication and Design Details

Individual parts are laser cut, CNC folded and cold rolled. Shafts are lathed for fixed and clearance fits. The chassis components are welded together using MIG welding and shafts are welded to the chassis using oxy acetylene and TIG welding techniques.

Laser cutting steel sheet and CNC folding directly from 3D CAD files minimises setup time and cost common in other production methods such as hand cutting or CNC machining. Laser cutting is also relatively inexpensive compared to CNC machining. Tube laser cutting allows for the fabrication of high stiffness chassis components where complicated jigs are possible to realise.

Chassis components were welded together using a MIG welding setup. First, tack-welds were applied to lock all the components in place. This was the most labour and time intensive stage in the fabrication process. Once in place, all components were welded up and welds were grinded away. Shafts were lathed to size and welded onto the chassis. Welding higher carbon alloy steel requires preheating. Preheating the steel to be welded slows the cooling rate in the weld area. This may be necessary to avoid cracking of the weld metal or heat affected zone. Here, preheating was locally applied by using an oxy acetylene torch. Then, precise welds were made using DC TIG welding technique.

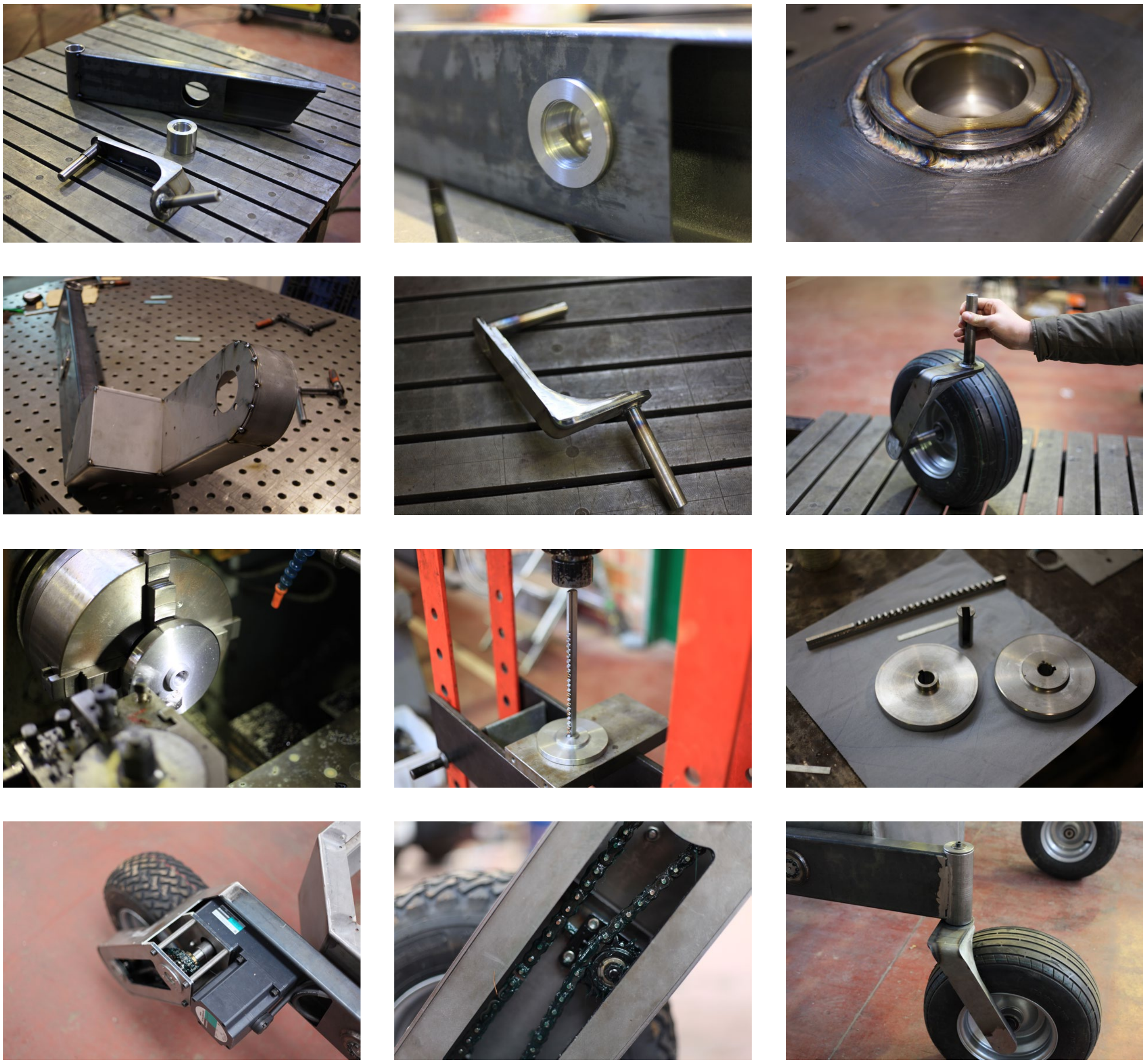

Figure 28: Side swingarm assembly fabrication

4.4.4 Main Body Assembly

4.4.4.1 Function

The main body connects the two side swingarm assemblies. Its function is to fix the width of the vehicle, stabilise the side units, house the differential suspension system and carry the implement and electronics.

4.4.4.2 Dimensions

The dimensions of the main body are 1110 x 640 x 430 mm

4.4.4.3 Materials

The chassis of the main body is fabricated from 40 x 40 x 2 mm S235JRH mild steel square tubes. The body components are fabricated from 3 mm S235JR mild steel sheet and 3 mm AlMg3 aluminium magnesium alloy sheet. Shafts for the suspension system are fabricated from CK45 alloy steel.

4.4.4.4 Fabrication and Design Details

Sheets and tubes are laser cut and CNC folded. Shafts are lathed for clearance fits. The chassis components are welded together using MIG welding technique.

In the design, laser cut panels and tubes interlock together with tabs and slots to create a ridged chassis. The advantages of this fabrication method are that contact surface area between the chassis components is greatly increased and no secondary alignment jigs are required during assembly. Figure 29 depicts the tab and slot assembly method used. This way of manufacturing and assembling takes away the issues of alignment of mutual parts, which is otherwise a time-consuming procedure. Using tab and slot features in the chassis components also makes it easier to differentiate parts and improves the speed and accuracy of assembly. After assembly, tabs and slots were welded together.

The design for the main body is constrained by the main platform parameters. The width of the main body was determined by the overall vehicle width required to drive over 75 cm wide raised growing beds.

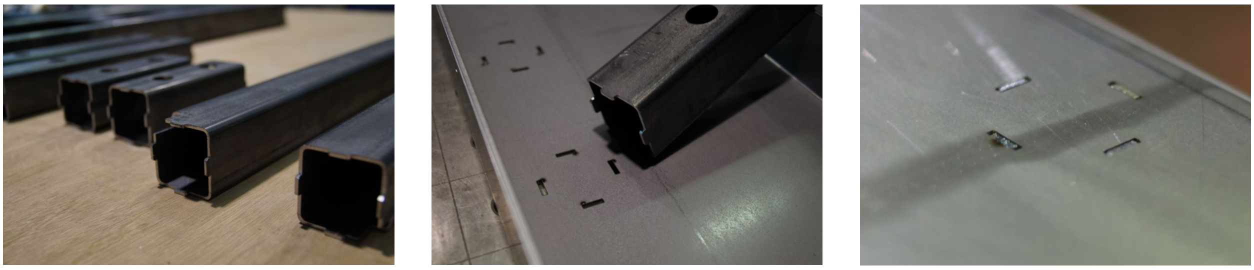

Figure 29: Tab and slot assembly.

The main body chassis connects both the side swingarm assemblies through the differential system. The differential system is attached to the interior of the main body and supported by bearing units. Two extended shafts of the differential system are supported by flange bearings in the lateral walls of the main body and connected to the side swingarms, installed at both sides of the main body. The extended shafts connect to the side swingarms through keyless bushings, clamping the components together.

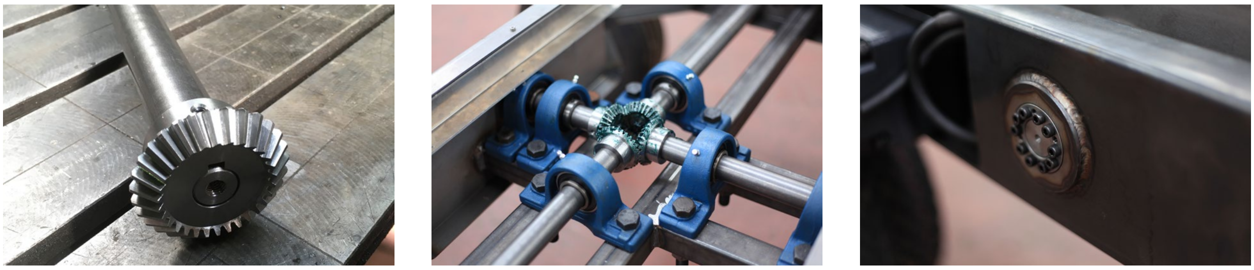

Figure 30: Differential suspension components.

One of the main requirements of the main body chassis was to carry the implement unit. An indent was included on one side of the main body where the implement can be mounted and adjusted in height. The reason for including the indent in the design was to keep the centre of mass of the vehicle as close as possible to its geometrical centre.

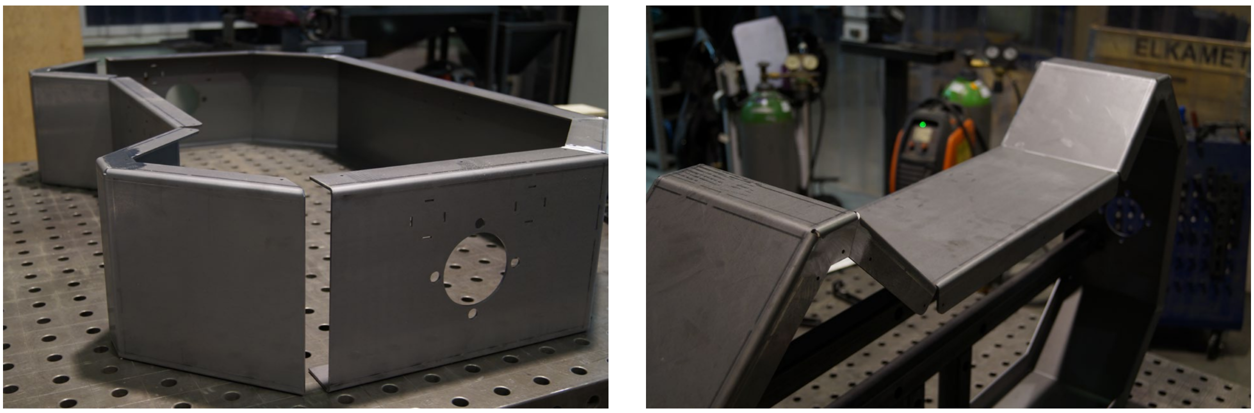

Figure 31: Implement indent.

Designing the main body to be lightweight was an important requirement. Inclusion of aluminium parts drastically lowers the vehicle's weight. The main body's top and bottom parts were fabricated in aluminium; laser cut, CNC folded and AC TIG welded. Because of structural stiffness concerns, the mid-section was fabricated in mild steel. All parts were bolted together.

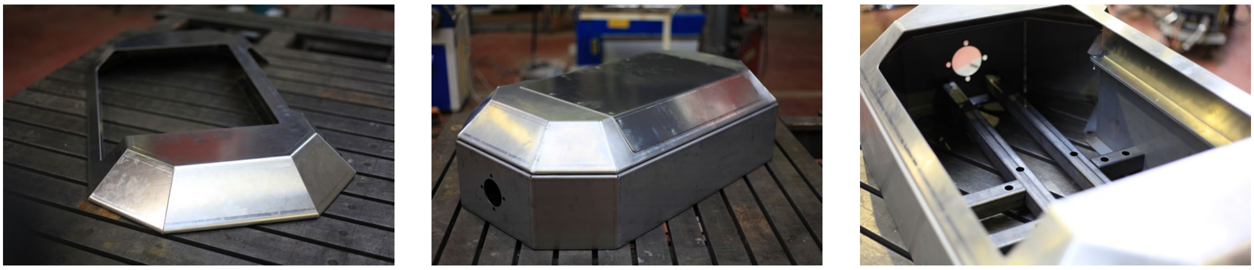

Figure 32: Lightweight body.

4.4.5 Implement Unit Assembly

4.4.5.1 Function

The implement unit carries the parallel manipulator assembly, stepper motors and electronics for the robot arm. Its function is to drive the end effector to a desired location where weed mitigation is required.

4.4.5.2 Dimensions

As mentioned above, CSA farms typically adopt a CTF farming model popularised by the market gardening principles. Typically, growing beds have a width of 750 mm. This is also the work area the parallel manipulator must cover. Figure 33 shows the simulated workspace when couplers l_{11}, l_{21}, l_{12} and l_{22} are chosen 270 mm, l_{31} 550 mm and l_{32} 750 mm. At a working distance of 300 mm from the base it can be seen that a working width of 800 mm can be achieved. This working width allows for 50 mm extra space, which is desirable to not operate on the joint limits.

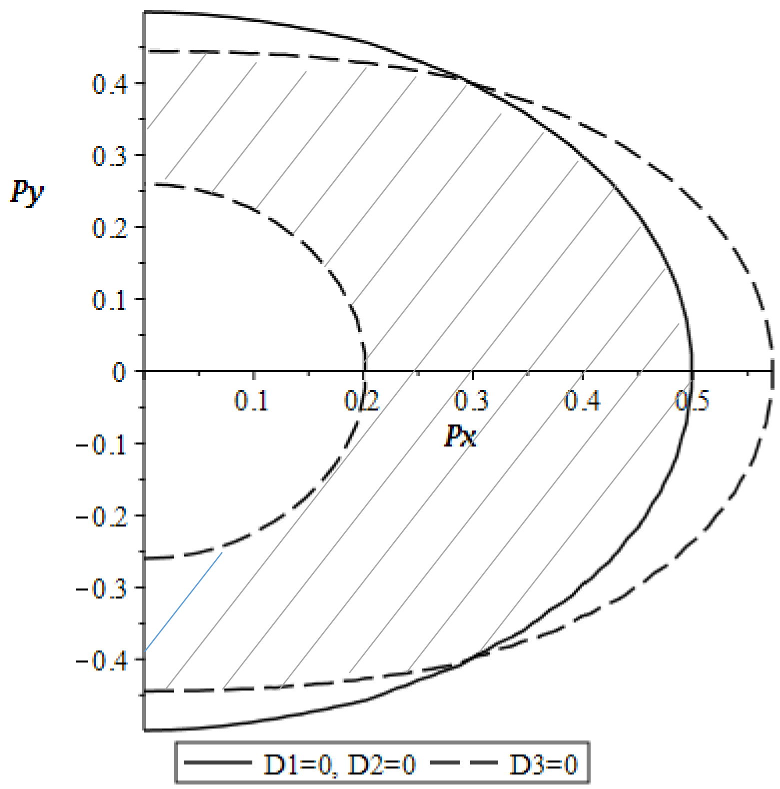

Figure 33: Simulated workspace.

4.4.5.3 Materials

The chassis of the implement unit is fabricated from 3 mm S235JR mild steel sheet and 3, 4 and 8 mm AlMg3 aluminium magnesium alloy sheet. The proximal couplers are made from 20 mm S235JR mild steel bars and the distal couplers are off the shelf double spherical joints made of an impact-resistant, long-fibre-reinforced polymer and stainless steel links. Extended motor shafts, coupler shafts and the end effector shaft are fabricated from CK45 alloy steel. The joints connecting the end effector shaft and the vertical arm are 3D printed out of polyamide.

4.4.5.4 Fabrication and Design Details

The Implement is mounted on its electronics box. Aluminium and steel sheets are laser cut, CNC folded and MIG/TIG welded. The chassis components are laser cut 4 mm and 8 mm aluminium sheet. The parts interlock together with tabs and slots and are welded together on the backside using AC TIG welding.

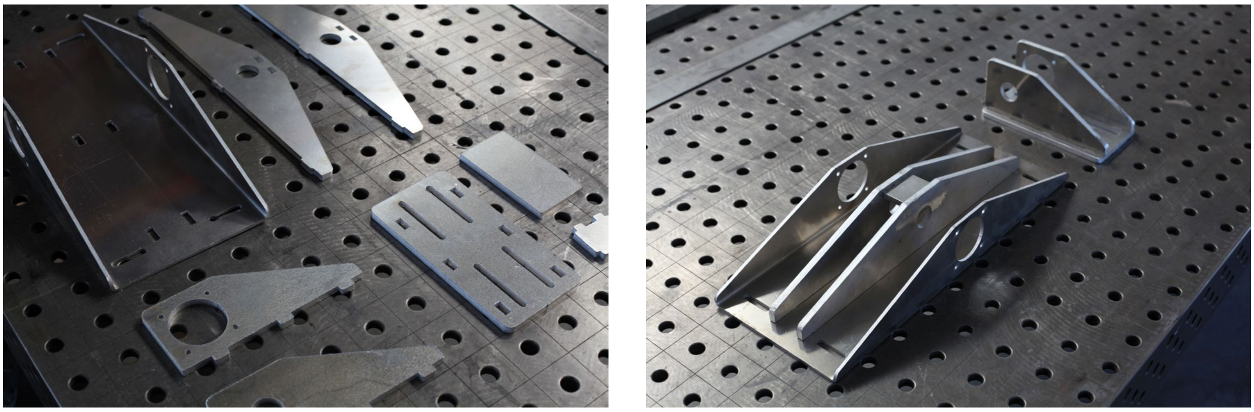

Figure 34: Interlocking parts with tabs and slots.

In order to clamp the proximal couplers on the motor shafts, extended shafts had to be lathed (Figure 35). Motors are bolted to the chassis and the extended shafts are mounted in the chassis with roller bearings.

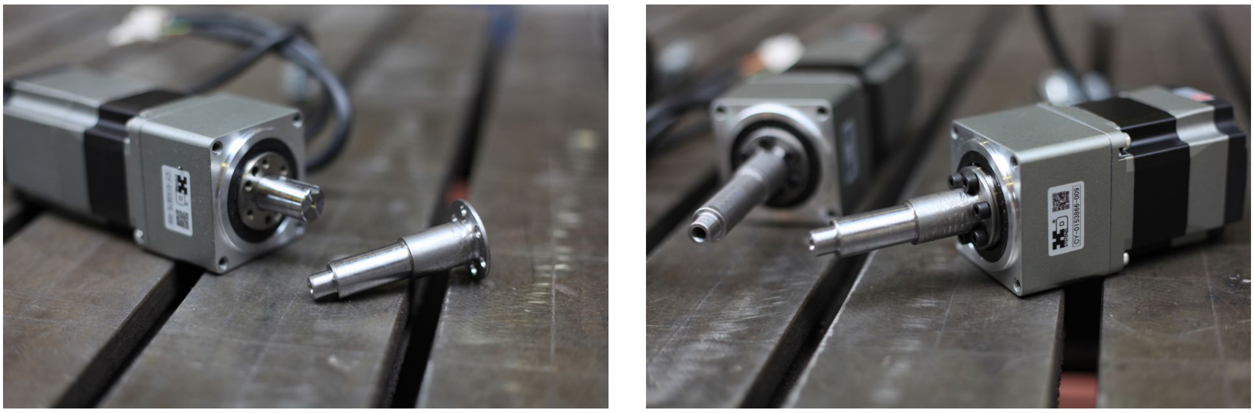

Figure 35: Extended motor shafts.

Custom joints are bolted onto the end effector shaft and the proximal coupler of the vertical arm. The joints are 3D printed in polyamide through Selective Laser Sintering (SLS) printing technique. The material is versatile, strong and impact resistant.

Figure 36: Custom designed joints.

The proximal couplers are laser cut and milled, clamping around the motor shafts. The double spherical joints connect the proximal couplers with the end effector shaft. Parallel constraints are secured by using retaining rings. The bottom of the end effector shaft is threaded (M8) to allow for the mounting of an end effector.

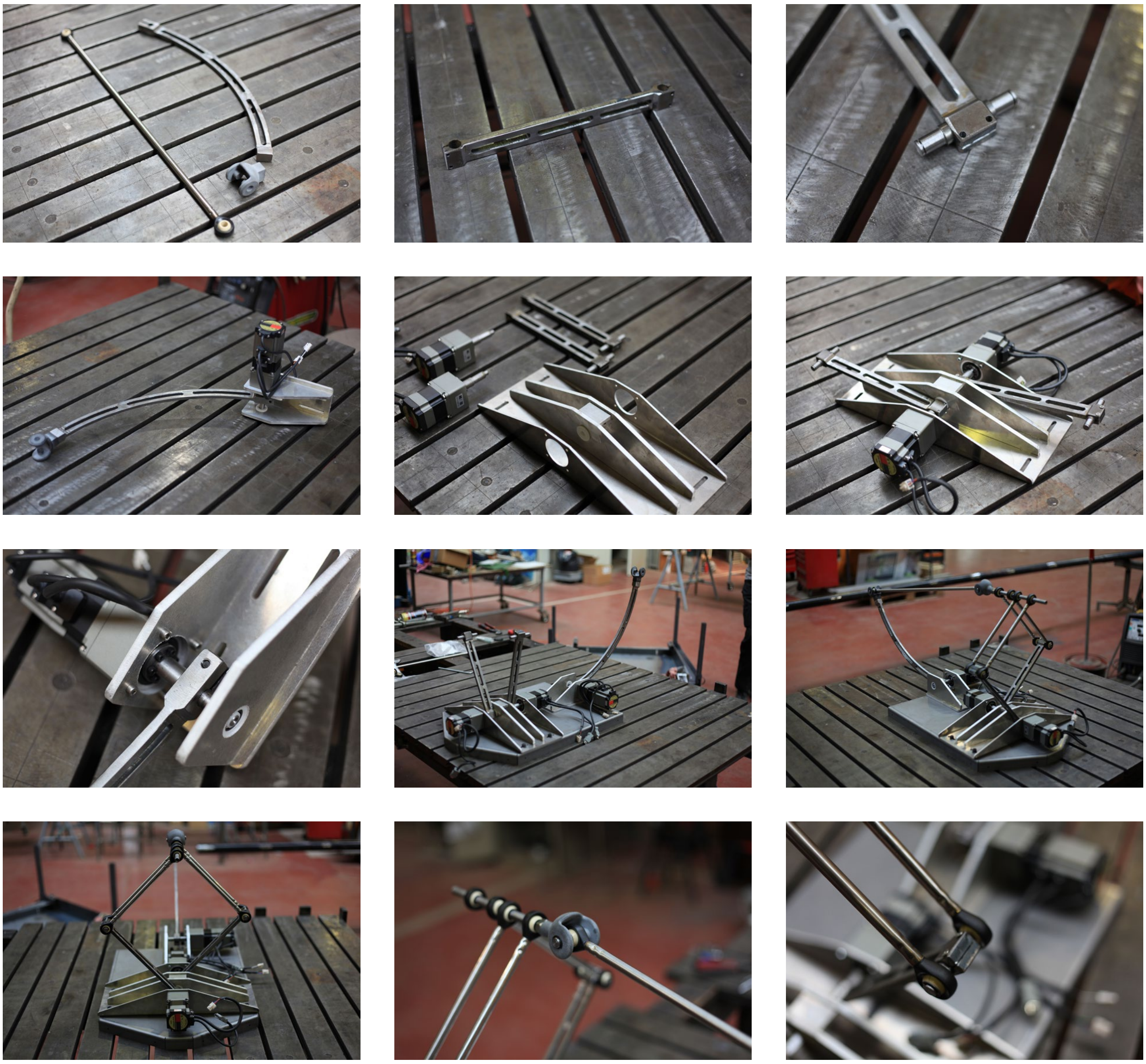

Figure 37: Implement assembly fabrication.

4.5 Drive Unit Design

4.5.1 Drive System Selection

In order to specify the drive motor requirements for the platform, considerations in table 2 were made.

Table 2: Drive system considerations.

Considerations	Answers
What is the nominal speed of the vehicle?	1 m/s
What is the maximum speed of the vehicle?	2 m/s
What should the acceleration of the vehicle be?	1 m/s^2
What will the mass of the vehicle be including payload?	200 kg
How will the vehicle be driven?	External motor with chain drive
How many wheels are to be powered?	2
Will the powered wheels also be equipped with a brake?	Yes
What slope angle should the vehicle be able to climb?	20 degrees

An electric motor solution was preferred as it is a drive system which can be precisely controlled, offers high efficiency and produces no (direct) emissions. Disadvantages of using electric motors include the current cost of batteries and relative low operating times compared to recharge times.

Power required to cross agricultural terrain was analysed; loose soil, compacted soil, wet soil and roads. Additionally, ramps to a trailer for transporting need to be handled.

A main factor in selecting a suitable drive unit is to determine the torque requirements to drive the wheels and set the vehicle in motion. When selecting a drive motor for an electric vehicle, a number of factors must be taken into account to determine the minimum torque requirements[67]:

1. Rolling resistance

2. Grade resistance

3. Acceleration force

4.5.1.1 Rolling Resistance

Rolling resistance is the opposing force that the vehicle has to overcome due to the rolling motion between the wheels and a surface. This resistant force is a combination of the deformation of both the soil and tire and the slippage between the two surfaces. It is difficult to theoretically calculate or set up a model for the rolling resistance because it is affected by many factors. Mainly, rolling resistance depends on tire inflation pressure, applied torque, applied load and the soil structure[68].

Tire inflation pressure has an inverse relation to the rolling resistance. A higher tire pressure results in reduced contact pressure of the tire. Applied torque affects the rolling resistance of a driven wheel strongly and may be substantially higher compared to the rolling resistance of a free wheel in the same environment[68].

Table 3 shows the coefficients of friction for various types of terrain.

Table 3: Rolling resistance coefficients C_{rr} [69].

Surface	Rolling resistance coefficient C_{rr}
Smooth concrete	0,01
Packed soil, dirt road	0,02
Grassy field - Dry crop	0,08
Loose soil, gravel	0,1
Fresh deep snow	0,15
Wet soil, mud	0,2
Sand	0,2 - 0,3

The rolling resistance can be calculated as:

$$F_r = GVW . C_{rr}$$

Where:

F_r = Rolling Resistance (N)

GVW = mg = Gross Vehicle Weight (N)

m = vehicle mass (kg)

g = gravitational force (m/s^2)

C_{rr} = Rolling resistance coefficient

4.5.1.2 Grade Resistance

Grade resistance is the additional force to move the vehicle up an incline or slope. This force is directly related to the gravitational force working on the vehicle. The gradeability of a vehicle is defined as the maximum grade the vehicle can climb. The grade resistance on the vehicle can be calculated as:

$$F_g = GVW.\sin\theta$$

Where:

F_g = Grade Resistance (N)

$GVW = mg$ = Gross Vehicle Weight (N)

m = vehicle mass (kg)

g = gravitational force (m/s^2)

θ = Grade or inclination angle

4.5.1.3 Acceleration Force

Acceleration force is the force required to accelerate a vehicle from an initial speed v_1 (m/s) to a speed v_2 (m/s) in t seconds. If the acceleration is from rest, v_1 is zero. The acceleration force is a function of the vehicle mass and can be calculated by Newton's second law of motion:

$$F_a = ma$$

Where:

F_a = Acceleration force (N)

m = vehicle mass (kg)

a = required acceleration (m/s^2)

Drive Unit Calculation

4.5.1.4 Drive Unit Calculation

Table 4 adds to the vehicle specifications the aspects needed to calculate power requirements of the drive motors.

Table 4: Complemented vehicle specifications.

Specification	Dimension	Unit	Description
Vehicle mass	200	kg	Total vehicle mass
Nominal Speed	1	m/s	
Max. Speed	2	m/s	
Acceleration	1	m/s^2	
Number of Wheels	4		
Drive/Steering Wheels	2		Differential steering
Caster wheels	2		
Wheel Width	0,3	m	
Drive Wheel radius	0,206	m	
Platform Width	1,2	m	Wheel centre to centre
Platform Length	1,2	m	Wheel centre to centre
Height Clearance	0,35	m	
Operating Time	6	hrs	
Operating Gradients	20	degrees	
Rolling Resistance Coefficient	0,1		Loose soil

Two important power requirements need to be calculated:

- The power and torque required under normal operating conditions, specifying the total required energy storage.
- The peak power and torque required under worst operating conditions, used to specify the drive motor.

First, the nominal power and torque are calculated.

The rolling resistance F_r to overcome the rolling resistance coefficient is given by:

$$F_r = GVW.C_{rr}$$

This was calculated as **196,2 N**.

The torque required to move the vehicle under normal conditions is given by:

$$T = F_r.r_{wheel}$$

Where:

F_r = Rolling Resistance (N)

r_{wheel} = the radius of a drive wheel (m)

This was calculated as **40,42 Nm**.

The power required to move the vehicle under normal conditions is given by:

$$P = F_r.v$$

Where:

Fr = Rolling Resistance (N)

v = the vehicle's nominal speed (m/s)

This was calculated as **196,2W**. At 75% system efficiency, a resulting average power of **261,6 W** is required.

The peak force F_p when accelerating up on an incline is given by:

$$F_p = F_r + F_a + F_g$$

Where:

F_r = Rolling Resistance (N)

F_a = Acceleration force (N)

F_g = Grade Resistance (N)

This was calculated as **1067,2 N**. The torque required to move the vehicle under worst case conditions is then calculated as **219,9 Nm** and the required power is calculated as **1067,2 W**.

At 75% system efficiency, a resulting peak power of **1422,9 W** is required.

4.5.2 Drive Unit

Based on the required power and torque requirements calculated in the previous section, a suitable commercially available drive unit was selected.

Two 24 VDC 200 W electric motors with a rated torque between 38,3 and 55,3 Nm at 1 to 40 rpm, together with a 100:1 planetary flat gearbox were chosen to provide good locomotion at the desired speed range of 1-2 m/s. Emergency braking is provided by adding an electromagnetic brake. The choice of this slightly underpowered motor was a trade-off between cost, frequency of occurance of peak requirements and the fact that the robot at the time of choice actually weighed half of the proposed weight of 200 kg (which is good because one of the aims is to reduce soil compaction). Table 5, table 6 and table 7 show the motor, gearbox and electromagnetic brake details. A full data sheet is included in the appendix.

Table 5: Motor details.

Motor	Description
Type	Brushless DC
Brand	Orientalmotor
Model	BLV Series
Voltage	24 VDC
Power	200 W
Speed	80 - 4000 min^{-1}
Rated input current	13 A
Rated torque	0,65 Nm
Starting torque	1,15 Nm
Motor shaft	Hollow shaft, keyed
Communication protocol	Modbus protocol

Table 6: Gearbox details.

Type	Hollow shaft flat gearhead
Gearbox	Description
Ratio	100:1
Output speed	1 - 40 min^{-1}
Output torque	38,3 - 55,3 Nm

Table 7: Electromagnetic brake details.

Electromagnetic brake	Description
Brake type	Power off activated type, automatically controlled by the driver
Static friction torque	0,65 Nm

4.5.3 Battery

The battery is located in the lower compartment of the main body assembly to keep the robot's centre of mass low. Analysis of the capacity and resistance was conducted before selecting the type and size of the battery pack to be used to power the platform. The operating currents for the motors and motor drivers where looked into, as well as voltage losses within the batteries, cabling and control electronics. As a result of this analysis, a custom-built battery was designed to house in the platform.

Many different battery technologies suitable for a farming robot exist. The different technologies considered were Lead-acid, Nickel-metal hydride and Lithium-ion. The considerations selecting a suitable battery technology were safety, weight and dimensions (energy density), cost and charging time. Lithium ion manganese oxide battery technology ($LiMnO_2$) was selected as power source. It is a consumer-grade lithium battery which uses inexpensive materials. The technology is suitable for low-drain, long-life and low-cost applications which is, relative to other lithium types, safe when failure occurs. Lithium batteries provide for a higher energy density per both mass and volume (250 – 693 Wh/L) compared to lead-acid (80 – 90 Wh/L) and nickel-metal hydride (140 – 300 Wh/L) batteries. It can also deliver high pulse currents which is an important feature when peak currents are required by the motors.

To make the vehicle safe for operators, a voltage of 24 VDC was selected. In the previous section, power requirements under normal conditions were calculated as 261,6 W and during peak conditions as 1422,9 W. The corresponding current requirements are thus 10,9 A and 59,3 A respectively. If the platform is required to operate for 6 hours on a single charge, a battery capacity of around 1,5 kWh is required. Table 8 shows the properties of the custom-built battery.

Table 8: Battery properties.

Battery	Description
Brand	Samsung
Type	INR 18650-35E
Cell technology	$LiMnO_2$
Amount of cells	70
Cell voltage	3,6 V
Cell rated current	10,5 A
Cell capacity	3450 mAh
Total output voltage	25,9 V
Charging voltage	29,4 V

4.6 Robot Prototype

Figure 38 depicts the current state of the prototype development of the agricultural robot system.

Figure 38: Current state of the prototype agricultural robot system.

Chapter 5: Conclusion and Future Work

This thesis presents the design and development of a lightweight, modular, low cost robotic system applicable in raised bed organic farming. In this thesis, opportunities in raised bed organic farming are investigated to potentially implement robotic systems in 'swarms' and undertake precision agricultural tasks, such as weed control. The focus of this project was to develop a platform solution for raised bed organic farming, specifically within Community-supported Agriculture (CSA), aimed towards the end user, the farmer. A modular, lightweight and low-cost prototype has been realised using a variety of different manufacturing methods, materials and assembly techniques. The work carried out for this thesis was split into distinct phases, iteratively completed. Choices were created and made in each phase, enabling the design process to converge into one solution. At the start, research and contextual investigation with farmers was conducted to define the system's requirements. Next, a platform and implement were designed, modelled, engineered and prototyped. In the last phase, testing started, field trials are set up and design refinements are made for further improvement of the system.

Research into CSA agriculture, present and future challenges for agriculture in Flanders, weed management in organic farming practises as well as a thorough market analysis including farm visits were conducted. These actions helped establish overall requirements for the design of the robotic system. How well these criteria were met is demonstrated in the fabricated prototype. Detailed testing of the design is essential to determine the poor but also the good design decisions. This period of testing will help evaluate and consequently improve the design of the robot.

The overall requirements for the design were established at the beginning of this thesis. Following is a brief summary of how each requirement was incorporated in the robot design.

The robot's main function must be related to weed management. Specifically, mechanical weed mitigation at seedling stage.

Design and integration of a parallel manipulator in an implement unit for weed mitigation addressed this requirement. The modular nature of the system allows for the implement to be adjusted in work area and ground clearance to conform to specific farming environments. In a next phase, research has to be conducted to design an end-effector suitable for weed mitigation at seedling stage. Initial exploration sketches have been made and can be found in the Appendix. Due to time constraints, this aspect of the system has not been elaborated in the thesis.

The robot must be lightweight in order to reduce soil compaction.

The combination of using strong, heavier materials (mild steel) for components requiring a certain structural strength, lightweight materials (aluminium alloy) for components fulfilling an enclosing purpose along with weight saving construction techniques (unibody) helped to achieve the weight targets for the vehicle.

The robot must be able to identify and locate weeds in order to apply a non-chemical weed treatment.

This requirement forms part of the sensor and software integration tasks which are currently being worked on as part of the ongoing development of the system.

The robot must be suited for driving autonomously over agricultural terrain.

Vehicle configuration analysis let to the development of a two-wheel drive, four-wheel configuration with differential steering. Testing of the differential drive kinematics, reviewed in Chapter 3, will provide insights on how well this configuration performs on agricultural terrain. At the time of writing this thesis, the sensor and software integration that will enable autonomous driving of the robot had not yet been integrated. This part of the development is done in a next phase and is outside the scope of this thesis.

The differential suspension system was tested by elevating one wheel for about 30 cm up in the air. All four wheels maintained ground contact and the main body rotation was averaged. In a next phase, when the motors are tested, dynamic behaviour of the suspension system will be observed.

The robot should be reliable and easy to disassemble and maintain.

Maintenance and disassembly considerations were included in the design. Specifically, the design takes into account the possibility for the end user, the farmer, to perform maintenance tasks themselves. This was achieved by designing components for easy disassembly, including hatches, leaving enough space and openings for access to all areas of the system and using standard components. Mechanical reliability of the system will be tested once operational testing starts.

The robot must operate safely.

Safety was considered by minimising pinch points in the design of the robot. The operational safety constrained the platform operating speed to be less than the walking pace of a human, chosen at 1 m/s.

An emergency stop system, the use of a perimeter safety system and the integration of obstacle avoidance will be included in a next phase. Also, future work includes vehicle signage and colour to inform users about the presence but also the dangers of the robotic system.

The robot should be low cost.

At this stage it is too early to determine the final cost of the working platform. By designing the chassis components to be fabricated using laser cutting and CNC bending techniques, assembly can be done relatively quickly. This design-for-assembly methodology minimises production and labour costs. Requiring they have the right tools at hand, farmers could potentially assemble their own robot and reduce cost even more. The use of standard components such as motors, wheels, bearings, bushings, etc. also helped to lower the cost of the robot.

The robot should be transportable on a standard trailer.

Based on the Control Traffic Farming system (CTF) widely used in CSA farms, a vehicle width of 1,2 metres wheel centre to wheel centre was chosen. Article 46 of the Royal Decree containing general regulations on the police of road traffic and the use of public roads in Belgium[51] states that the width of a loaded vehicle or trailer must not exceed 2,55 metres. Different trailer ramps with a ground angle varying from 15 to 20 degrees where tested which led to set a clearance height of 35 centimetres to drive up a standard trailer without colliding.

The design must be scalable in order to cover use on different farm sizes in the form of a 'swarm'.

A system of scalability for use of platforms on different farm sizes will allow single units to execute tasks on small farms and multi-unit configurations to take on larger operations, replacing the need for use of traditional heavy machinery. Multi-agent systems or self-organised systems will be implemented to enable cooperation of platforms. Implementation of such a system will take place in a next phase of the platform development.

The outcome of this project is achieved by using aspects of the engineering field and industrial design practices together according to a user-centred design model, where human factors are interwoven with technical problem-solving thinking. The result has led to the design and prototyping of a complete robotic system, addressing the defined user requirements.

Sustainable reflection

Agricultural robots are a component of precision agriculture, which hold the promise to improve farming practices in terms of sustainability. Advancements in precision agriculture are enabling farmers to use less pesticide, less water, produce less waste and improve the environmental sustainability of agriculture. While most (large-scale) farming businesses are focusing on cost savings as a rationale for using robotic systems in agriculture, robots can bring environmental benefits to the fields. Shifting the use of large machines to the use of fleets or "swarms" of smaller autonomous platforms, such as the robotic system presented in this thesis, is a paradigm shift in agriculture with the following advantages:

- Lightweight platforms reduce soil compaction.
- Multi-purpose for weed control but also crop detection, sowing, fertilizing and harvesting.
- Better manoeuvrability which reduces the amount of unused land area.
- Scalability, which facilitates employability in small, medium and large farms.
- Lower development costs due to reduced complexity of the platform and implement.
- Reduction of chemical herbicides and pesticides.
- Improvement of ergonomics for workers by reducing hand labour.
- Reduction of energy consumption per hectare - reduced energy cost.

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Appendices

Scoring matrix farm visits

	De Stadsgroenteboer	Pluk!	Tuinen van Hartstocht	Goedinge Boerderij	t Schaaphof	Plukhof Beernem	Totaalscore
Vervangen van handmatig wieden in bioteelt	2	2	3	3	3	3	16
Combineerbaar met andere onkruidbestrijdingsmethodes	3	3	3	3	3	3	18
(semi-)autonoom wieden van een akker	2	2	3	3	3	3	16
Mogelijkheid om dag en nacht te opereren	1	1	2	3	3	2	12
Intra-rij wieden	3	3	3	3	3	3	18
Inter-rij wieden	3	3	3	3	3	3	18
Platform mag de areaalgrenzen niet kunnen overschrijden	3	3	3	3	3	3	18
Areaaloppervlakte 0-1 ha	3	3	3	0	0	0	9
Areaaloppervlakte 1-2 ha	0	0	0	0	0	3	3
Areaaloppervlakte 2-3 ha	0	0	0	3	3	0	6
Manuele controle platform voor verplaatsing over korte afstanden	3	3	3	3	3	3	18
Platform moet zelf-herstartend zijn na een noodstop	2	2	2	3	3	2	14
Platform laat gebruiker weten wanneer permanent gestopt (vb. risicosituatie of taak volbracht)	3	3	3	3	3	3	18
Platform zendt operationele status op verzoek van gebruiker	3	3	3	3	3	3	18
Gewicht minimaal mbt. bodemverdichting door druk van de wielen	3	3	3	3	3	3	18
Flexibiliteit platform - modulariteit gereedschap	3	3	3	3	3	3	18
Flexibiliteit plantbedbezetting (vb. verschillende gewassen met verschillende tussenafstanden)	3	3	3	3	2	2	16
Energie-efficiëntie lager dan bij traditionele gemotoriseerde landbouwwerktuigen	3	3	3	3	3	3	18
Geluidsvervuiling lager dan bij traditionele gemotoriseerde landbouwwerktuigen	3	3	3	3	3	3	18
Groeibed lengte 0-25 m	0	0	0	0	0	3	3
Groeibed lengte 25-50 m	3	3	3	3	3	0	15
Groeibed breedte 0-0,75 m	3	3	3	3	0	3	15
Groeibed breedte 0-1,5 m	0	0	0	0	3	0	3
Verwijderen van tenminste 90% van het onkruid in en tussen de rijen	3	3	3	3	3	3	18
De kost per hectare moet kleiner of gelijk zijn aan de kost voor handmatig wieden	3	3	3	3	3	3	18
Schade aan de gewassen is lager of gelijk aan handmatig wieden	3	3	3	3	3	3	18
Veilig voor mens, dier, onderneming en ecosysteem	3	3	3	3	3	3	18
Toezichtsvereiste minstens lager dan bij handwieden	2	2	3	3	3	3	16
Betrouwbaarheid systeem	3	3	3	3	3	3	18

Farmers' wishes and demands

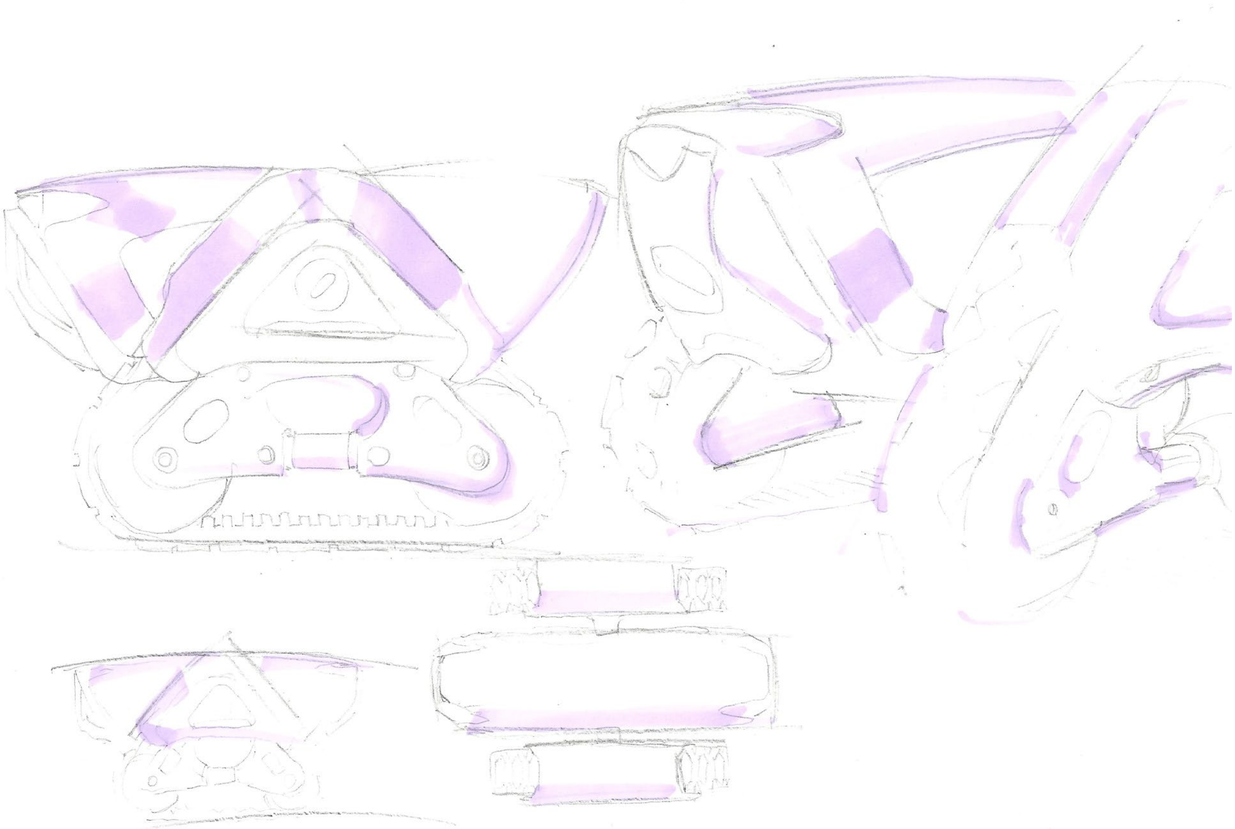
Eisen

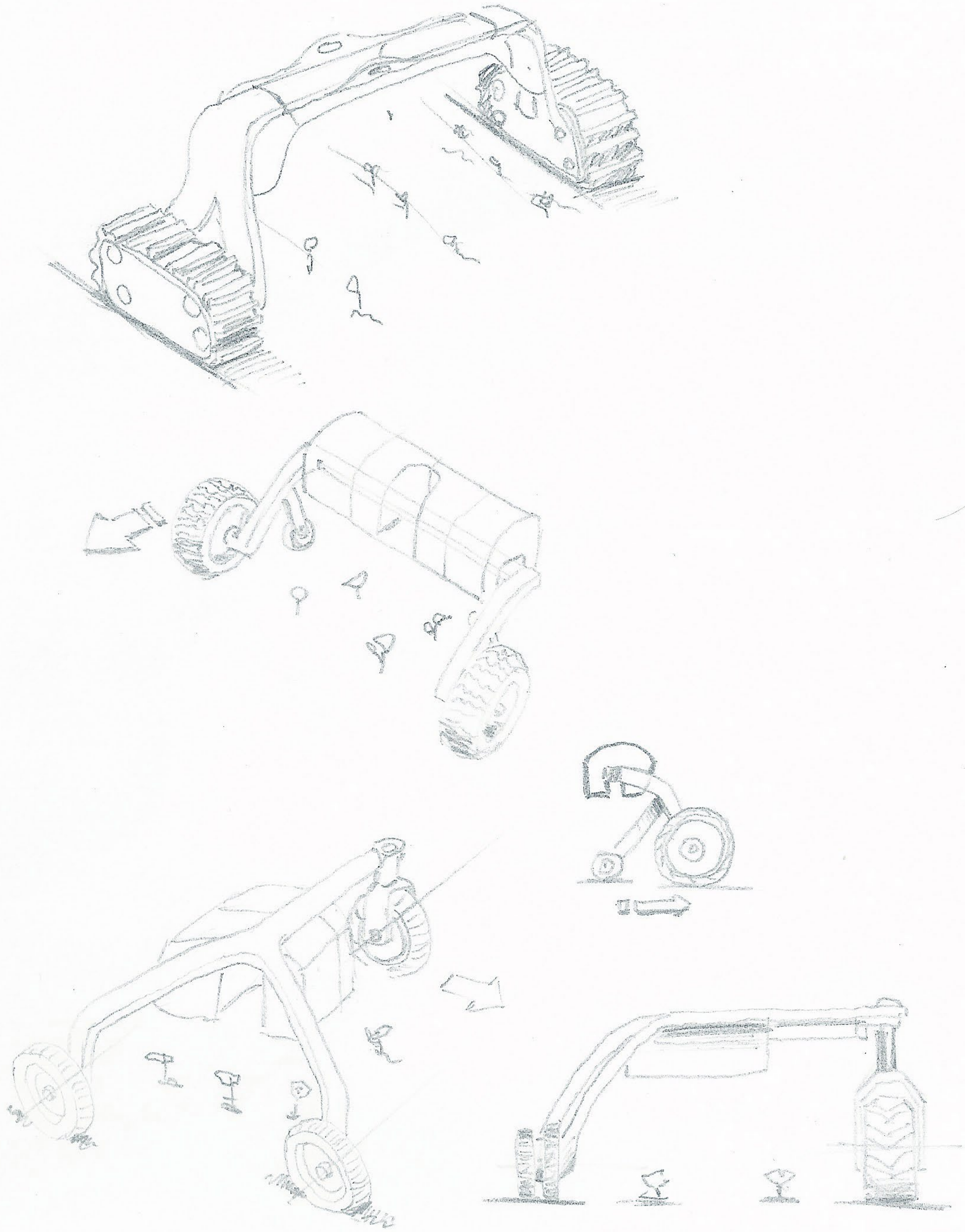
Vervangen van handmatig wieden in bioteelt
Het platform moet functioneren voor rode biet
(semi-) autonoom wieden van een akker
24/24 operatie
Intra- en interrij wieden
Platform mag areaalgrenzen niet overschrijden
Areaaloppervlakte tot 3 ha
Manuele controle platform voor verplaatsing over korte afstanden
Platform moet zelf-herstartend zijn na een noodstop
Platform laat gebruiker weten wanneer permanent gestopt wordt (vb. risicosituatie of taak volbracht)
Platform zendt operationele status op verzoek van gebruiker
Groeibed breedte 0,75 m

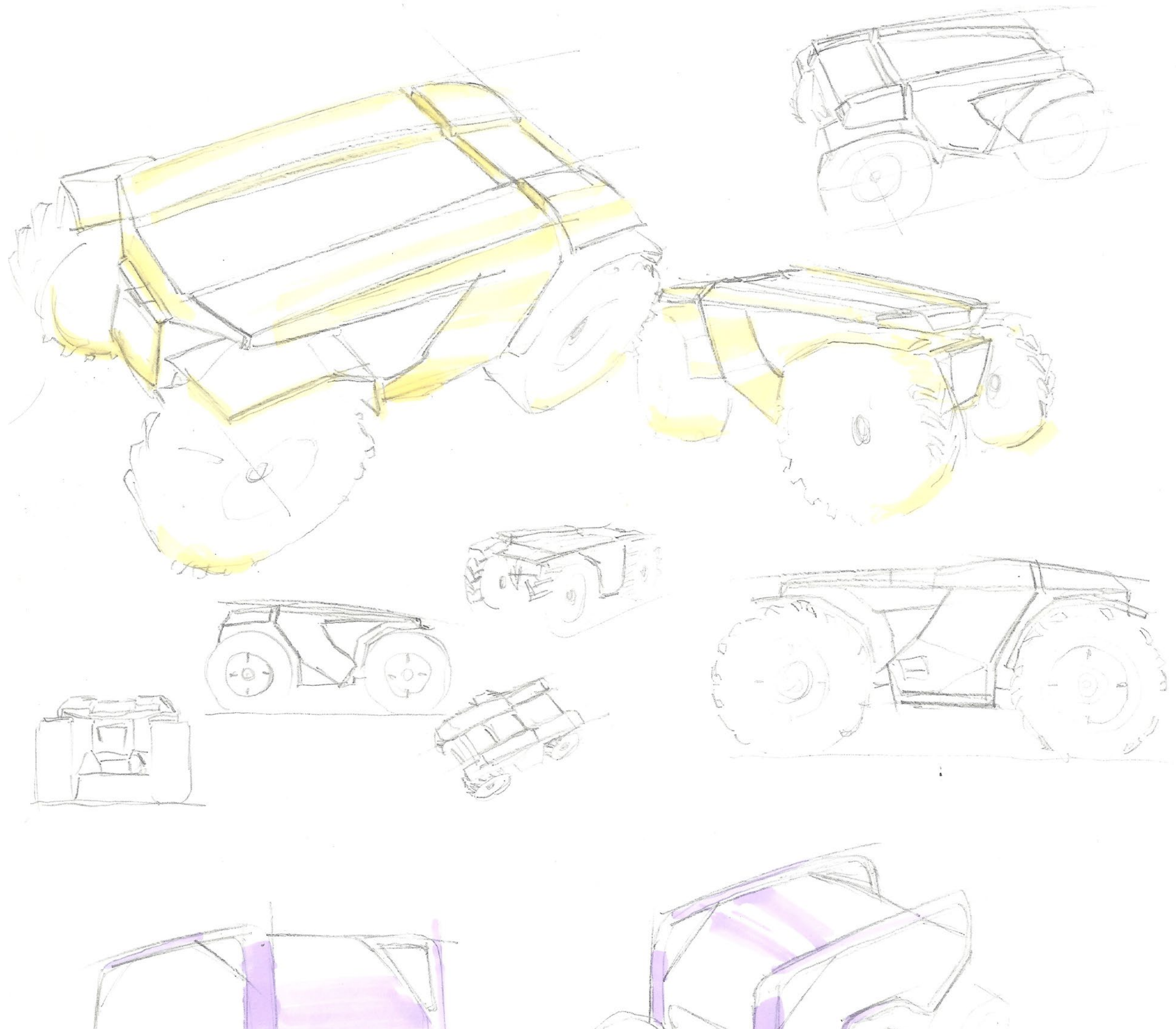
Wensen

Gewicht minimaal mbt. bodemverdichting door druk van wielen op bodem
Modulariteit gereedschap
Flexibiliteit plantbezetting (vb. verschillende gewassen/verschillende tussenafstanden in één groeibed)
Energie-efficiëntie hoger dan bij traditionele gemotoriseerde landbouwwerktuigen
Geluidsvervuiling lager dan bij traditionele gemotoriseerde landbouwwerktuigen
Groeibed lengte tot 50 m
Verwijderen van tenminste 90% van het onkruid in en tussen de rijen
De kost per hectare moet kleiner of gelijk zijn aan de kost voor handmatig wieden
Schade aan de gewassen is lager of gelijk aan handmatig wieden
Veilig voor mens, dier, onderneming en ecosysteem
Toezichtsvereiste minstens lager dan bij handwieden
Betrouwbaarheid systeem

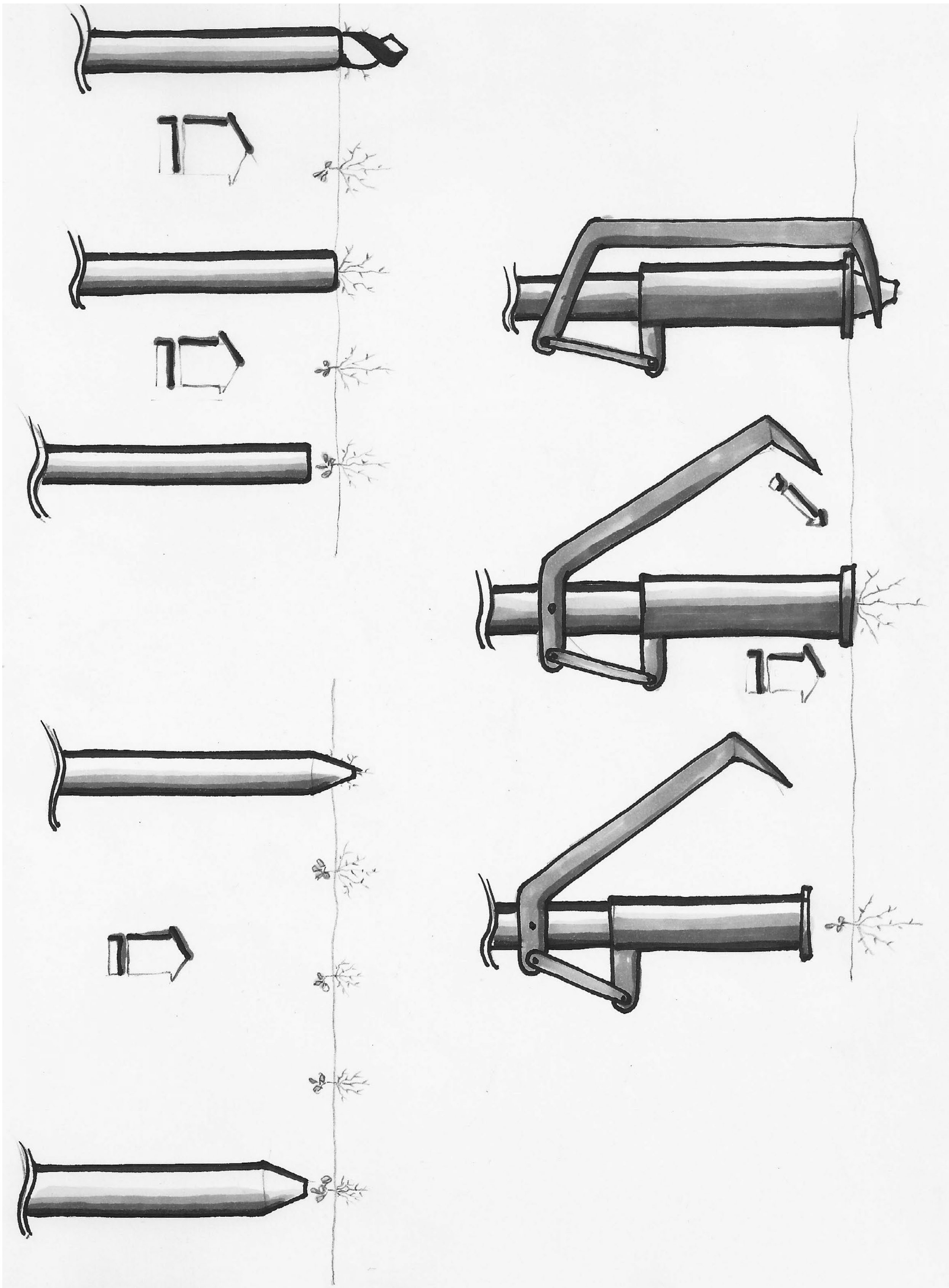
Concept Sketches Robot







Concept Sketches End Effector



Cost Components Robot Prototype

Onderdeel	Component	Leverancier	Referentie	Prijs/stuk (€ excl. BTW)	Aantal	Totaal (€ excl. BTW)	Levertijd (dagen)	Besteld
Platform	Aandrijfwiel	Starco	FR4165650860100	70,23	2	140,46	20	OK
	Zwenkwiel	Starco	FR11665082590	88,01	2	176,02	20	OK
	DC motor + Driver Oriental Mo	Act in Time BVBA	BLV620KM100F-2	849,6	2	1699,2		OK
	Batterij	Battery Supplies	1519300501	580,03	1	580,03		OK
	Klembus wielbrug	Misumi	MLM28	35,04	2	70,08	1	OK
	Conisch tandwiel	Misumi	KGEASK2.0-3030-18	41,73	4	166,92	5	OK
	Flenslager rond differentieel	Misumi	HDMC30	16,61	2	33,22	1	OK
	Steunlager differentieel	Misumi	CPDR30	7,69	6	46,14	1	OK
	Steunlager wielas	Misumi	HDMC20	11,65	2	23,3	1	OK
	Kogellager motoras	Misumi	B6003ZZ	3,88	2	7,76	1	OK
	Kogellager wielas	Misumi	B6003ZZ	3,88	2	7,76	1	OK
	Kettingwiel wielas	Misumi	LFSP40B15-20-B	29,67	2	59,34	7	OK
	Kettingwiel motoras	Misumi	LFSP40B15-20-B	29,67	2	59,34	7	OK
	Ketting	Misumi	CHEM40-66	20,76	2	41,52	3	OK
	Ketting sluitschakel	Misumi	JMTC40	0,83	8	6,64	1	OK
	Kettingspanner	Misumi	TSUB40-13-30	49,59	2	99,18	10	OK
	Hoekcontactlager zwenkwiel	Misumi	B7205	7,27	4	29,08	1	OK
	Spie tandwielen	Misumi	KES6-22	1,98	4	7,92	1	OK
	Sluitring balhoofd	Misumi	STWS25	1,36	8	10,88	1	OK
	Spie gedreven as	Misumi	KES6-22	1,98	2	3,96	1	OK
	Spie motoras	Misumi	KES8-80	2,15	2	4,3	1	OK
	Scharnier deksel	Misumi	SHHPS5-3	8,1	2	16,2	3	OK
	Eindkap zwenkas	Misumi	EDCM20	3,39	2	6,78	1	OK
	Eindkap Drijfas	Misumi	EDCM20	3,39	2	6,78	1	OK
	Polycarbonaat 455 x 580 x 6 m	Kunststofplatenshop	Helder polycarbonaat 6mm	69,25	0,264	18,282		OK
	Plaatwerk	STAAV		250	1	250	16	OK
	Plaatwerk	STAAV		1200	1	1200	16	OK
Implement	Stepper motor onder Oriental M	Act in Time BVBA	AZM66AK-HS50	850,5	2	1701	3	OK
	Stepper motor boven Oriental	Act in Time BVBA	AZM66MK-HS100	991,8	1	991,8		OK
	Stepper Driver Oriental Motor	Act in Time BVBA	AZD-KD	324	3	972		OK
	Gaffelkop eindeffector	Shapeways		25,13	1	25,13	14	OK
	Gaffelkop L3	Shapeways		26,06	1	26,06	6	OK
	Variabel dubbel gewricht	IGUS	KDGM-12-A-ER (700 mm)		1	0		OK
	Variabel dubbel gewricht	IGUS	KDGM-12-A-ER (270 mm)		4	0		OK
	Xirox radiale diepgroefkogellag	IGUS	BB-6000F3538-B180-10-ES	8,95	3	26,85	2	OK
	Plaatwerk	STAAV		400	1	400	14	OK
						0		
						0		
						0		
						0		
						0		
						0		
					Totaal	8913,932		

Orientalmotor

Brushless Motor and Driver Package DC Power Supply Input, High Power

BLV Series

Standard Type/Electromagnetic Brake Type

Introducing the new high power, DC input **BLV** Series brushless motor and driver with output options of 200 W to 400 W.
Communication control through I/O or RS-485 is available to support a wide variety of applications.

Features

DC Power Supply Input, High Power Output Options of 200 W to 400 W , Compact Motor

The **BLV** Series are compact, DC input brushless motors and drivers with output options of 200 W to 400 W.
An extensive variety of motors lets you select the model that best suits your specific application.

Output Power		200 W	400 W
Frame Size		□104 mm	□104 mm
Power Supply Voltage		24 VDC	48 VDC
Motor Type	Standard Type	●	●
	Electromagnetic Brake Type	●	●

Three Types Available (Shown below are standard type models):

Combination Type – Parallel Shaft Gearhead

Round Shaft Type

Combination Type – Hollow Shaft Flat Gearhead

*For gear ratios 5 to 20.

Features of the Hollow Shaft Flat Gearhead

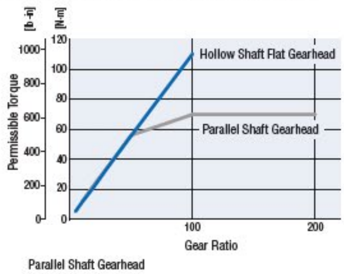
□104 mm, space-saving, hollow shaft flat gearhead has been added to the lineup.

Combination Motor Output	Gear Ratio	Rated Life
200 W, 400 W	5*, 10, 15, 20, 30, 50, 100	5000 hrs.

*Only compatible with the 400 W type.

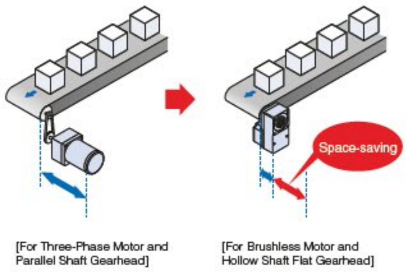
◇Permissible Torque without Saturation

The hollow shaft flat gearhead enables permissible torque without saturation so the motor torque can be fully utilized.



◇Space-saving

The output shaft can be coupled directly to a driven shaft without using a coupling, which allows you to reduce the size and installation space of your equipment.



Product Number Code

BLV 6 20 K M 200 S - 1

① ② ③ ④ ⑤ ⑥ ⑦ ⑧

①	Series	**BLV** : **BLV** Series
②	Motor Frame Size	**6**: 104 mm [Gearhead Frame Size: 110 mm]
③	Output Power (W)	**20**: 200 W **40**: 400 W
④	Power Supply Voltage	**K**: 24 VDC **N**: 48 VDC
⑤	**M**: Electromagnetic Brake Type Blank: Standard Type	
⑥	Gear Ratio/Shaft Type	Number: Parallel shaft gearhead type Gear ratio **5**~**200** Hollow shaft flat gearhead Gear ratio **5**~**100** **A**: Round Shaft Type
⑦	Gearhead Type (Combination type only)	**S**: Parallel Shaft Gearhead **F**: Hollow Shaft Flat Gearhead
⑧	Cable Length (Included)	**1**: 1 m **2**: 2 m **3**: 3 m

Product Line

Combination Type The combination type comes with the motor and its dedicated gearhead pre-assembled simplifying installation in equipment. Motors and gearheads are also available separately to facilitate changes or repairs.

●Standard Type

◇Combination Type – Parallel Shaft Gearhead

Output Power	Power Supply Voltage	Model	Gear Ratio
200 W	24 VDC	**BLV620K□S-◇**	**5, 10, 15, 20, 30, 50, 100, 200**
400 W	48 VDC	**BLV640N□S-◇**	**5, 10, 15, 20, 30, 50, 100, 200**

The following items are included in each product.
Motor, Driver, Gearhead, Connection Cable*, Power Connector, Mounting Screws, Parallel Key, Operating Manual
*A cable of 1 m, 2 m or 3 m long is included.

◇Combination Type – Hollow Shaft Flat Gearhead

Output Power	Power Supply Voltage	Model	Gear Ratio
200 W	24 VDC	**BLV620K□F-◇**	**10, 15, 20, 30, 50, 100**
400 W	48 VDC	**BLV640N□F-◇**	**5, 10, 15, 20, 30, 50, 100**

The following items are included in each product.
Motor, Driver, Gearhead, Connection Cable*, Power Connector, Mounting Screws, Parallel Key, Safety Cover (with screws), Operating Manual
*A cable of 1 m, 2 m or 3 m long is included.

◇Round Shaft Type

Output Power	Power Supply Voltage	Model
200 W	24 VDC	**BLV620KA-◇**
400 W	48 VDC	**BLV640NA-◇**

The following items are included in each product.
Motor, Driver, Connection Cable*, Power Connector, Operating Manual
*A cable of 1 m, 2 m or 3 m long is included.

●Electromagnetic Brake Type

◇Combination Type – Parallel Shaft Gearhead

Output Power	Power Supply Voltage	Model	Gear Ratio
200 W	24 VDC	**BLV620KM□S-◇**	**5, 10, 15, 20, 30, 50, 100, 200**
400 W	48 VDC	**BLV640NM□S-◇**	**5, 10, 15, 20, 30, 50, 100, 200**

The following items are included in each product.
Motor, Driver, Gearhead, Connection Cable*, Power Connector, Mounting Screws, Parallel Key, Operating Manual
*A cable of 1 m, 2 m or 3 m long is included.

◇Combination Type – Hollow Shaft Flat Gearhead

Output Power	Power Supply Voltage	Model	Gear Ratio
200 W	24 VDC	**BLV620KM□F-◇**	**10, 15, 20, 30, 50, 100**
400 W	48 VDC	**BLV640NM□F-◇**	**5, 10, 15, 20, 30, 50, 100**

The following items are included in each product.
Motor, Driver, Gearhead, Connection Cable*, Power Connector, Mounting Screws, Parallel Key, Safety Cover (with screws), Operating Manual
*A cable of 1 m, 2 m or 3 m long is included.

◇Round Shaft Type

Output Power	Power Supply Voltage	Model
200 W	24 VDC	**BLV620KMA-◇**
400 W	48 VDC	**BLV640NMA-◇**

The following items are included in each product.
Motor, Driver, Connection Cable*, Power Connector, Operating Manual
*A cable of 1 m, 2 m or 3 m long is included.

Specifications

●Standard Type

◇200 W, 400 W (RoHS)

CE

Model			BLV620K□S-◇	BLV640N□S-◇
Model	Combination Type – Parallel Shaft Gearhead		BLV620K□S-◇	BLV640N□S-◇
	Combination Type – Hollow Shaft Flat Gearhead		BLV620K□F-◇	BLV640N□F-◇
	Round Shaft Type		BLV620KA-◇	BLV640NA-◇
Rated Output Power (Continuous)		W	200	400
Power Source	Rated Voltage	VDC	24	48
	Permissible Voltage Range		±10%	
	Rated Input Current	A	13	11
	Maximum Input Current	A	25	18
Rated Torque		N·m	0.65	1.3
Starting Torque*1		N·m	1.15	1.8
Rated Speed		r/min	3000	
Speed Control Range		r/min	100~4000 (Analog setting) 80~4000 (Digital setting: can be set in 1 r/min increments)*2	
Round Shaft Type Permissible Load Inertia J		$\times 10^{-4}$ kg·m^2	8.75	15
Rotor Inertia J		$\times 10^{-4}$ kg·m^2	0.61	0.66
Speed Regulation	Load		±0.5% (±0.2%)*2 max. (0~Rated torque, at rated speed, at rated voltage, at normal ambient temperature)	
	Voltage		±0.5% (±0.2%)*2 max. (Rated voltage ±10%, at rated speed, with no load, at normal ambient temperature)	
	Temperature		±0.5% (±0.2%)*2 max. [0~+40°C, at rated speed, with no load, at rated voltage]	

●Electromagnetic Brake Type

◇200 W, 400 W (RoHS)

CE

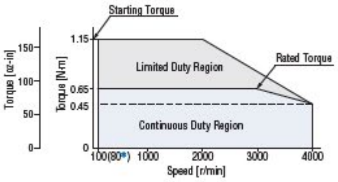
Model			BLV620KM□S-◇	BLV640NM□S-◇
Model	Combination Type – Parallel Shaft Gearhead		BLV620KM□S-◇	BLV640NM□S-◇
	Combination Type – Hollow Shaft Flat Gearhead		BLV620KM□F-◇	BLV640NM□F-◇
	Round Shaft Type		BLV620KMA-◇	BLV640NMA-◇
Rated Output Power (Continuous)		W	200	400
Power Source	Rated Voltage	VDC	24	48
	Permissible Voltage Range		±10%	
	Rated Input Current	A	13	11
	Maximum Input Current	A	25	18
Rated Torque		N·m	0.65	1.3
Starting Torque*1		N·m	1.15	1.8
Rated Speed		r/min	3000	
Speed Control Range		r/min	100~4000 (Analog setting) 80~4000 (Digital setting: can be set in 1 r/min increments)*2	
Round Shaft Type Permissible Load Inertia J		$\times 10^{-4}$ kg·m^2	8.75	15
Rotor Inertia J		$\times 10^{-4}$ kg·m^2	0.61	0.66
Speed Regulation	Load		±0.5% (±0.2%)*2 max. (0~Rated torque, at rated speed, at rated voltage, at normal ambient temperature)	
	Voltage		±0.5% (±0.2%)*2 max. (Rated voltage ±10%, at rated speed, with no load, at normal ambient temperature)	
	Temperature		±0.5% (±0.2%)*2 max. [0~+40°C, at rated speed, with no load, at rated voltage]	
Electromagnetic Brake*3	Brake Type		Power off activated type, automatically controlled by the driver	
	Static Friction Torque	N·m	0.65	1.3

*1 The time during which the starting torque is effective is no more than five seconds.
*2 These specifications apply when a separately sold control module (**OPX-2A**) or communication is used.
*3 Do not start or stop the motor by turning on/off the power supply, as it will cause the electromagnetic brake to wear abnormally.
●The values for each specification apply to the motor only.

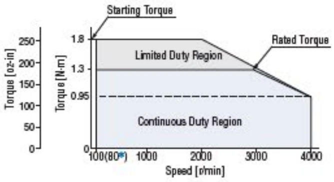
Speed – Torque Characteristics

Continuous Duty Region: Continuous operation is possible in this region.
Limited Duty Region : This region is used primarily when accelerating. When a load that exceeds the rated torque is applied continuously for approximately five seconds, overload protection is activated and the motor coasts to a stop.

BLV620K□S-◇/BLV620K□F-◇/BLV620KA-◇
BLV620KM□S-◇/BLV620KM□F-◇/BLV620KMA-◇



BLV640N□S-◇/BLV640N□F-◇/BLV640NA-◇
BLV640NM□S-◇/BLV640NM□F-◇/BLV640NMA-◇



*Values in parentheses indicate specifications that apply when a separately sold control module (**OPX-2A**) or communication is used.
●For the combination types, the values apply to the motor only.

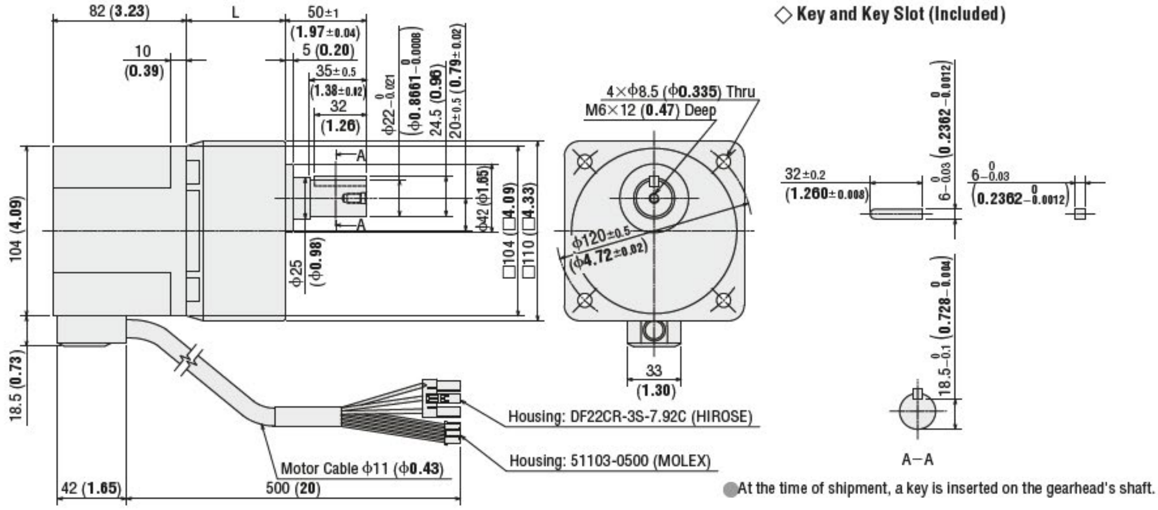
Dimensions Unit = mm

- Mounting screws are included with the combination type.

Standard Type 200 W, 400 W

◇Motor/Parallel Shaft Gearhead

Model	Motor Model	Gearhead Model	Gear Ratio	L	Mass kg
BLV620K□S-◇ **BLV640N□S-◇**	BLVM620K-GFS BLVM640N-GFS	GFS6G□	**5~20**	60	5.4
			30, 50	72	
			100, 200	86	



- At the time of shipment, a key is inserted on the gearhead's shaft.

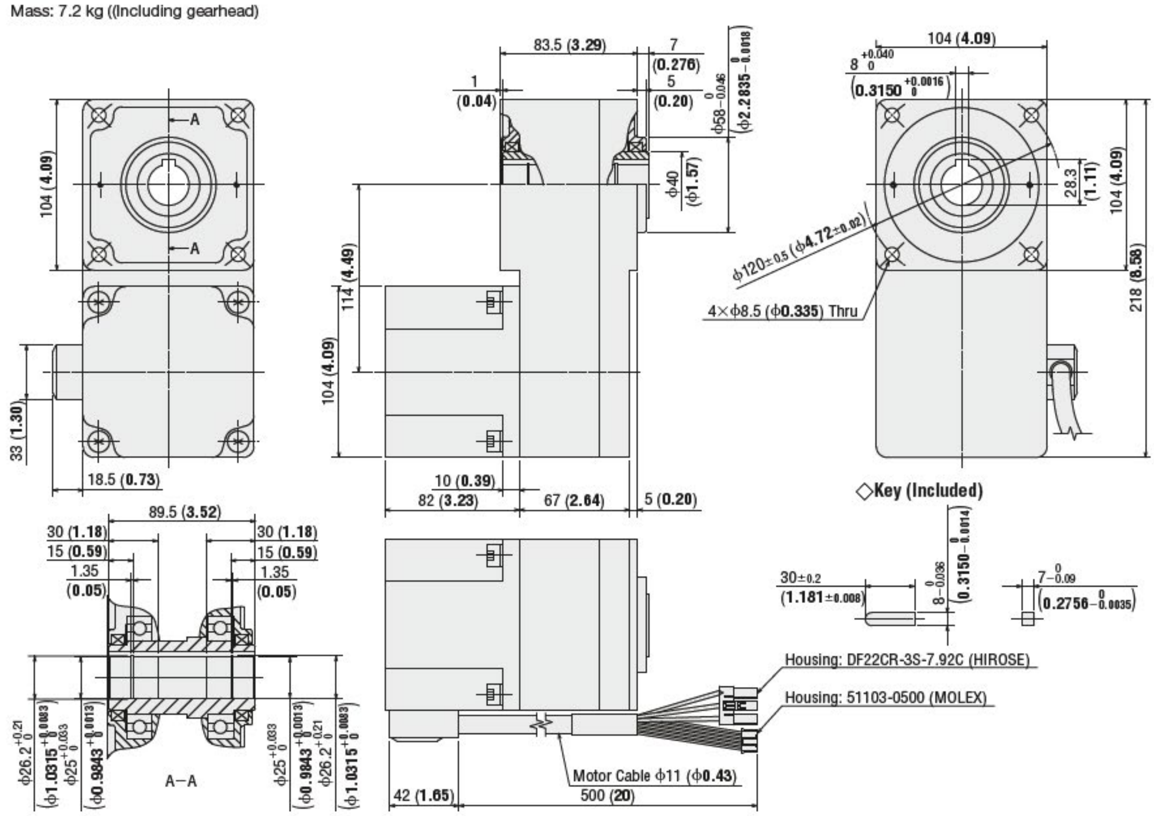
◇Motor/Hollow Shaft Flat Gearhead

BLV620K□F-◇, **BLV640N□F-◇**

Motor: BLVM620K-GFS, BLVM640N-GFS

Gearhead: GFS6G□FR

Mass: 7.2 kg ((Including gearhead)



FACULTY OF ENGINEERING AND ARCHITECTURE

Design and modelling of a modular robotic system to improve weed management in raised bed organic farming

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