Autonomous path-to-path movement for a vehicle with mecanum wheels

Mobile platform for the leaf cutting robot

I. Güçlü

Master of Science Thesis

Delft University of Technology

Delft Center for Systems and Control

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December 18, 2014

Confidential Report

Faculty of Mechanical, Maritime and Materials Engineering (3mE) - Delft University of Technology

The work in this thesis was supported by Priva B.V. Their cooperation is hereby gratefully acknowledged.

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Abstract

Automation has played a big role in the development of the industry in the last century. Despite the desire to automate the tedious and repetitive work in greenhouses by robots, the automation level in the horticulture is still far from desired. However, the last decade shows a lot of progress in the horticulture automation and more is expected due to the increasing need for automated processes in this area. Priva B.V. started the Tomation project in 2002 to automate the task of cutting off the leaves of tomato plants. Cutting off the leaves of tomato plants is one of the crop handling tasks done on a regular basis to ensure optimal growth and ripening of the tomatoes.

This report presents research concerning the Tomation Project of Priva B.V., aimed at solving the problem of autonomous movement of the leaf-cutting robot in the greenhouse. The robot has to move autonomously in the path and periodically change from path to path. The focus in this report is on the path-to-path movement in the greenhouse. This is a movement where the vehicle rides off the rail, moves to the next path and finally drives back on the rail again to continue with the leaf cutting process. The robot platform is a vehicle equipped with omni-directional mecanum wheels and powered by stepper motors from Nanotec®. These mecanum wheels are omnidirectional wheels and are able to move the vehicle in a lateral direction. The vehicle will move with mecanum wheels on the concrete path and with flanged wheels on the rail.

The vehicle with the mecanum wheels encountered difficulties driving sideways at a critical weight on the platform. Undesired movements occur at these weights, because the stepper motor is not performing all the steps. The scope of the project includes the autonomous path-to-path movement of the robot. The vision system for navigational purposes is not installed yet on the platform. Hence, the inputs from the system are entered manually in this project. It has to be taken into account that the vision system can only look at the front. The path-to-path movement should meet requirements on accuracy, time, speed and the payload of the vehicle. Furthermore, the vehicle has to be able to cope with cracks and obstructions on the road during the movement. Finally, it has to deal with rails that are shifted, because they are not fixed properly on the concrete path. Using the positional feedback of the encoders of the available stepper motor and inputs of a vision system a proper control system is required.

To get a good starting point to develop the autonomous movement of the platform, it was important to have a good understanding of the stepper motor and a clear view on the possibilities and modes of use of the motor. The working principle of the stepper motor is explained by describing the common step modes: the full step, the half step and the micro step mode. The

difference between the stepper motor and a servo motor is explained. Based on the differences between these motors, the choice on the stepper motor has been reasoned. The technical specifications and the Software Development Kit of the motors are presented. These were needed to learn the possibilities in controlling and using the motors.

The mecanum wheels of the vehicle of the Tomation Project serve for omnidirectional purposes. The possibility to move in a lateral direction with these wheels was the main reason for using them. The wheels offer a way to do compact movements on the path, without obstructing the path more than necessary to avoid possible conflicts with other (moving) objects. The omnidirectional movement is realized by appropriately controlling the angular velocity of each wheel separately. Depending on each individual wheel rotation direction and velocity, the resulting combination of the wheels produces a total movement in the desired direction without changing the orientation of the wheels.

The navigational purposes of the Tomation project required a proper kinematic model of the vehicle. The equations of motion are used to derive the ideal kinematic model to reach a desired position and orientation. The measured position errors are dealt with by adjusting the kinematic model with experiments. The sources of these errors were slippage, bearing friction and point contact friction. A comprehensive research on rollers of the wheels during omnidirectional movements is performed. This was needed to understand the motion of the rollers and its contribution to the omnidirectional movements. The analyses have shown that as the movement with the vehicle gets more lateral, the rollers will contribute more to the movement. This was also observed during movements of the vehicle. These observations and analyses on the rollers are used to explain the dynamics of the wheels.

To understand why the lateral movement of the vehicle needs more phase current than the forward movement, the dynamics of the mecanum wheels are investigated. A misconception in the literature on the dynamic model is explained. The literature neglects the force perpendicular to the rollers without a proper reasoning. The aspect of motion in the rollers is not taken into account. Hence, it is decided to reject the theory in the literature on the dynamics of these vehicles. With observations and analyses on the wheels a new dynamic model has been developed. This model takes also the friction in the rollers into account. This friction causes the main difference between the required force for the forward and lateral movement. It is seen that as the movement gets more lateral, the rollers will have more contribution, so the movement will be more affected by friction. Hence, the lateral movement needs more force to overcome the friction compared to a forward movement.

The vehicle of the Tomation project encountered practical problems related to the navigational features of the vehicle. The effects of these problems are analysed and solutions are presented when needed. To navigate properly in the greenhouse a function is developed that provides the number of steps needed per wheel for a given omnidirectional movement. Furthermore, the undesired effects, caused by rounding the target speed of the motor, are dealt with by looking for the nearest movement without these errors. Next, the asynchronous start of the motors caused by the serial connection is solved with an Arduino board that generates a signal to start all the motors simultaneously. Finally, an ultrasonic proximity sensor is used to detect the concrete path when riding off the rail backwards. The vision system could not be used here, since the cameras are facing forward. These functions and additions improve the reliability and robustness of the movement in the greenhouse.

With the aforementioned functions and findings from the analyses a reliable and proper path to path movement in the greenhouse is ensured. The movement is split into three separate movements: riding off the rail, moving across to the next path and driving on the rail of the new path. After analysing alternatives for these movements, it has been decided that the vehicle will move just with two motors in the area where transition from the mecanum wheels to the flanged wheels occurs. A lateral movement with the current setup was not feasible for the required payload. If we disregard the payload of the robot, the remaining conditions did meet the requirements of the movement.

The research in this project has contributed to the autonomous movement for the vehicle of the Tomation Project of Priva. The path-to-path movement of the vehicle is realized in a reliable way, provided that the motors are strong enough to deliver the required force for the movements. The results will be used for further steps in the project.

Table of Contents

Acknowledgements

During my first year in the master as a Control Engineer, my interest in robotics and automation had severely grown. This graduation project and the assignment are in line with my interests.

This graduation project is the last assignment before graduation. Because of my preference to graduate at a company, Prof. Dr. R. Babuska helped me to come in contact with Priva, for a challenging project in robotics and mechatronics. Priva came up with an assignment to develop the autonomous movement of the vehicle used in the Tomation Project. The opportunity to design this innovative automated vehicle appealed to me.

Therefore, I want to thank Priva for giving me the opportunity to graduate at their company on a challenging project. Secondly, I would in particular like to thank my supervisors R. Babuska and from the TU Delft and T. ten Kate and R. Zeelen from Priva with their help and contribution to the project.

Chapter 1

Introduction

Priva is a Dutch company, specialized in developing systems for measurement and control in the areas of climate, water, energy, labour and production. These systems are applied to achieve optimal efficiency of the primary processes in horticulture, a healthy inside climate and a sustainable energy management in living and working environments.

Automation has played a big role in the development of the industry in the last century. Using various control systems for operating equipment one can reduce costs in production processes. Automation can be used to reduce human intervention in operations, or even remove it by complete automation. The benefit arises by saving labour costs. However dealing with the drive systems by measurement and control technologies, automation is also used to save energy and materials and to improve quality, accuracy and precision. As a result of automation the last few decades production capacities are scaled up and the production costs reduced significantly.

Despite the desire to automate the hard work in greenhouses by robots, the automation level in the horticulture is still far from desired. Due to the organic, unpredictable and fragile nature of the plants, and not in the least because of the unstructured environments, automated solutions in the horticulture are lagging behind other industrial areas. However, the last decade shows a lot of progress in the horticulture automation and more is expected due to the increasing need for automated processes in this area. This need is not only driven by cost effective considerations, but also because it is difficult to get the necessary work force. The repetitive work is arduous and thus not popular. In the Netherlands crop operations are low paid jobs and are done for a large part by workers originating from Eastern Europe. Anyway, it is laborious and repetitive work and it is attractive for the grower to automate this work to reduce the cost component of labour in crop production to stay competitive. A more comprehensive research on automation in the horticulture is described in a separate literature study [1].

Figure 1: A greenhouse with tomatoes and tomato plants.

The cost of labour in the horticulture industry is a significant part of the total costs of crop production. Crop operations in greenhouses are monotonous and physically demanding. Priva is currently working on the Tomation Project to deal with this problem. The company is working on developing an efficient and economically feasible robot that will be used for cutting off the leaves of tomato plants in greenhouses. Figure 1 shows a picture of a greenhouse with tomatoes and tomato plants. Conventional platforms are lifted and then moved manually with an auxiliary platform to the next path. This method requires additional power to lift the platform.

In the current state of the project a prototype of the robot is available that is able to recognize and cut off the leaves of the plants. The prototype robot is designed to move through the greenhouse on top of a special developed vehicle. This vehicle is based on the *mecanum wheel* principle. Mecanum wheels are omnidirectional wheels and are able to move the vehicle in a lateral direction. With these wheels a compact platform is provided to manoeuvre in a very limited space. The purpose with these wheels is to enable moving sideways to the next path and then to drive forwards and backwards to get on and off the rail. The prototype vehicle with the mecanum wheels currently suffers from difficulties driving sideways at a critical weight on the platform. The stepper motor is not performing all the steps correctly at a certain payload.

This report is the sequel of the previous report [1] where a literature study on relevant topics has been presented. Localization and object detection techniques used in the automation industry are discussed. Subsequently, the concept, the kinematics and dynamics of the mecanum wheels presented in the literature are described. Finally, a survey has been done on existing projects of motion control with mecanum wheels.

Problem description

The main goal of this project is to develop a robust control system for the autonomous path-to-path movement of this vehicle in greenhouses. The path-to-path movement of the vehicle in the greenhouse contains riding off the rail, moving across the next path and driving on the rail of the new path. The robust system should reliably move in all required directions needed in the greenhouse in an energy efficient way. The movement should occur without bringing any changes to the infrastructure of the greenhouse. The process of harvesting and transporting the tomatoes in the greenhouse should not get obstructed by any parts of the system. Hence, no parts of the transporting system are allowed to be left behind on the concrete path during the cutting process.

This report discusses and presents the analyses, experiments, methods and choices that have been made to realize a robust, reliable and autonomous movement of the vehicle in the greenhouse. Chapter 2 gives a clear description on the given system and on the situation in the greenhouse. Also, the specifications on the problem and the plan of approach for the project are discussed in the chapter. Chapter 3 discusses the working principle of the stepper motors used for the movement of the vehicle. Advantages and disadvantages of these motors are mentioned to reason the choice on the stepper motor. Chapter 4 contains a comprehensive research on the concept and properties of the mecanum wheels. Analyses and experiments on the kinematics and the dynamics of these wheels are discussed in this chapter. Chapter 5 deals with practical problems related with navigational features for the path-to-path movement. These known problems are analysed and solutions to circumvent these problems are proposed. The chosen solutions for the problems are presented and described in detail. Chapter 6 presents the tests for the path-to-path movement and the results on these tests. Possible methods for moving from path to path in a greenhouse are discussed. Decisions on the movement that are made to ensure the proper movement are argued and explained. Finally, Chapter 7 gives the conclusion of the project and discusses recommendations for further research within this project.

Chapter 2:

Project Description and Approach

The main goal of this project is the development of a robust and reliable system for the autonomous movement of a platform in a greenhouse. The platform must be able to move on a rail between plants and switch at the end of the rail automatically to the other rail. This is called a path to path movement. This autonomous behaviour facilitates robotic manipulation of plants to be able to operate on a 24 hour basis. In this chapter a description on the available system of the project and the specifications are given. Requirements on the movement of the vehicle that are of interest are presented. Furthermore, the scope of this research that has contributed to the Tomation Project is discussed. Finally, the plan of approach for this project is described in this chapter.

System Description

To ensure optimal growth of the tomatoes, cutting off the leaves of the tomato plants on a regular basis is a necessary task in greenhouses. Priva B.V. started the Tomation project in 2002. The goal was to develop a robot that is able to cut off leaves of tomato plants in greenhouses autonomously. After two failed attempts the project continued in 2007 with a new concept using a vision system and a new way of grasping and cutting of the leaves. In the current state of the project there is a prototype of the robot available that is able to recognize and cut off the leaves of the plants and can move from the beginning to the end of the rail. The chassis of the robot needs to be designed in such a way that the movement from path-to-path in a greenhouse can occur easily. Figure 2 shows a schematic representation of a part of a greenhouse. The grey coloured area is the concrete path in a greenhouse, the green parts represent the tomato plants, the black lines correspond to the rails in a greenhouse and the brown coloured areas represent the paths in a greenhouse. The centre to centre distances of the paths are defined as 1.6 m. However, this distance may vary a number of centimetres because the rails are not fixed properly and maybe shifted on the concrete path.

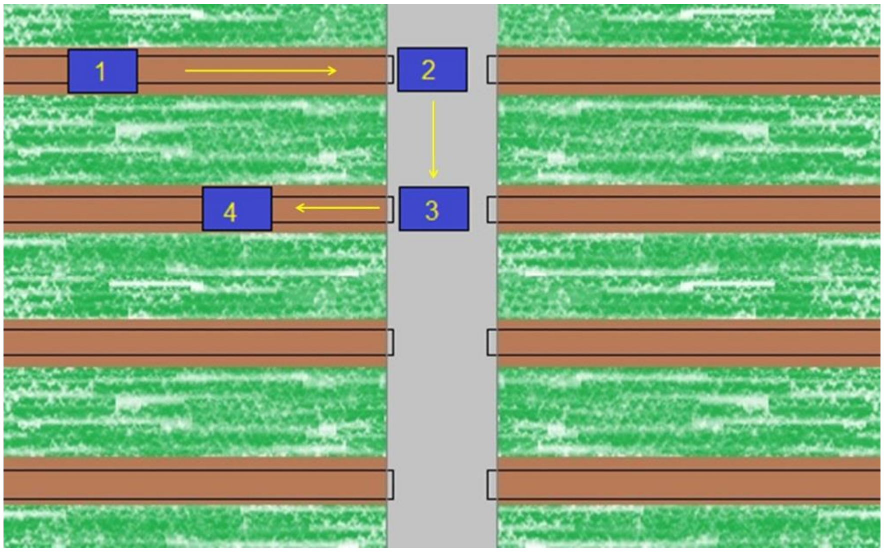

Figure 2: Schematic representation of a part of a greenhouse, where the movement of the vehicle in the greenhouse is shown. The movement starts on the rail (1), moves backwards to the concrete path (2), travels lateral to the next path (3) and gets forwards back on the rail again (4).

The robot of the Tomation project should be able to move autonomously from the concrete path on the rail to cut the tomato plants. Subsequently after cutting the plants, the robot has to get back on the concrete path again. Finally, the robot needs to move to the next path. This whole movement will be a continuous process in the greenhouse, until the last path is processed.

The movement should occur without bringing any changes to the infrastructure in the greenhouse. No other parts of the transporting system are allowed to be left behind on the concrete path during the cutting process. The process of harvesting and transporting the tomatoes in the greenhouse should not get obstructed by parts of the robot that are left behind on the concrete path. Hence, a transporting system that can perform both the movement on the rail as well as on the concrete path without an auxiliary platform is desired. Conventional platforms are lifted and then moved manually with an auxiliary platform to the next path. This method requires additional power to lift the platform.

It has been decided that the chassis of the robot of the Tomation Project will move using mecanum wheels. These mecanum wheels are omnidirectional wheels and are able to move the vehicle in a lateral direction. There is no need to lift the platform as is used in conventional platforms. The purpose with these wheels is to enable moving in a lateral direction to the next path and then to drive forwards and backwards to get on and off the rail respectively, as shown in Figure 2. This way the vehicle can ideally perform its full movement for the process without changing its orientation or using other equipment for the movement.

Another reason for this solution is that it is very compact and the platform can manoeuvre in a very limited space. The vehicle will move with mecanum wheels on the concrete path and with flanged wheels on the rail. The diameters of the mecanum wheels and the flanged wheels are 0.2032 m and 0.1035 m respectively. The experimental chassis of the vehicle that will be used for the Tomation Project is shown in Figure 3.

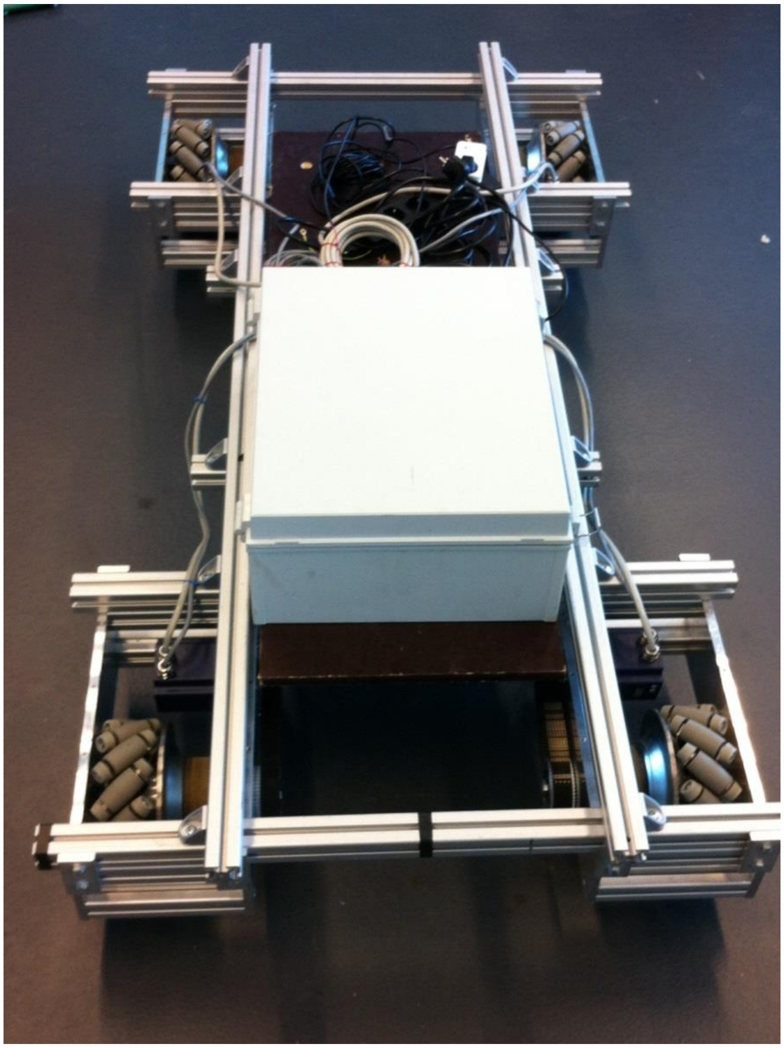

Figure 3: The vehicle of the Tomation project with the mecanum wheels.

The wheels of the vehicle are powered by stepper motors. Each mecanum wheel is driven by a separate motor. The stepper motors chosen for the prototype are the plug & drive PD6-N89 motors from Nanotec® each equipped with an encoder. The schematics of these stepper motors can be seen in Appendix A. There is a complete Software Development Kit (SDK) available to program and control the stepper motors. The motors are connected with the RS485 cable and controlled with the Component Object Model (COM) interface via Matlab® [2]. It is determined that traveling one meter with the mecanum wheels and the flanged wheels correspond to 1157 and 2272 steps respectively in the operation modes.

Experiments with these wheels and motors have shown expected and unexpected observations. In the greenhouse it has been seen that the vehicle can be pushed on and off the rail easily. The size of the flanged wheels has been chosen in a proper way such that lifting of the vehicle is not needed for this purpose. Another observation with the vehicle is that the movement for a lateral direction needs significantly more phase current from the motors than a forward movement. Furthermore, it has been seen that the motors do not move in sync with each other during autonomous movements. Due to the serial connection the motors are controlled one by one separately which causes a delay between the wheels.

Requirements

The movement of the vehicle has to meet specific application requirements for the commercial purpose of the project. An autonomous movement of the vehicle has to deal with practical issues. It has to ensure that the motors should not encounter any difficulties when moving the vehicle with the payload of the robot. The motors should perform the specified steps in a given time frame to meet the commercial purposes. The requirements for the vehicle are pointed out below.

- Within the project it is assumed that the total mass of the vehicle with the robot is approximately 350 kg. Since the robot is not installed yet on the platform with the mecanum wheels, the experiments are performed with different weights.
- The vehicle has to take the rails into account that are not fixed properly on the concrete path. The distances between the centrelines can vary and are not fixed at 1.6 meters. A variation of 0.1 m is not rare in the greenhouse.
- The vehicle should be able to deal with cracks with a depth < 0.01 m and a length < 0.5 m
- A reliable way should be devised to handle obstructions on the concrete path.
- The accuracy of the translations and rotations should be less than 0.04 m and 5° respectively.
- The vehicle should deal autonomously with the transition when riding on and driving off the rail.
- The movement in the desired directions should occur in an energy efficient way.
- The process of harvesting and transporting the tomatoes in the greenhouse should not get obstructed by any parts of the system. No parts of the robot are allowed to be left behind on the concrete path during the cutting process.
- For commercial purposes the vehicle needs to be able to travel 0.2 m on the rail less than a second. This corresponds to a movement with an average speed of 454 Hz. approximately with the current setup.
- The whole path changing movement should take less than 90 seconds. There are no hard requirements on the speed of the vehicle on the concrete path, as long as the path to path movement does not exceed 90 seconds.

Scope of the project

The scope of the project is the development of the autonomous path-to-path movement of the robot in the greenhouse in a robust and reliable way. The path-to-path movement of the vehicle in the greenhouse contains riding off the rail, moving across the next path and driving on the rail of the new path. The focus was on ensuring the movement in a reliable and robust way. Hence, the power consumption of the vehicle is disregarded in this project. Using the encoders of the available stepper motors a proper control of the vehicle should be realised, when driving off and riding on the rail. The missed steps of the motor should be compensated in a proper way.

In this project for the movement of the vehicle, it is assumed that the vision system, used for the cutting process on the robot, is also used for the autonomous navigation of the robot. Figure 4 shows schematically the chosen parameters $[x_c, y_c, \alpha_c]$ in this report that will be gained from the vision system for navigational purposes on the concrete path. These parameters are combined in the vector Υ_c in this report. Parameter x_c is the distance from the camera to the end of the concrete path, parameter y_c corresponds to the distance to the heart line of the rail and α_c is the angle that the vehicle has with the distance line to the end of the concrete path. It has to be taken into account that the vision system can only look at the front. Within this report the parameters are entered manually, since the vision system is not installed yet on the vehicle with the mecanum wheels. It is also assumed that the camera is located in the centre of the vehicle as shown in the figure. The parameter b corresponds to the distance of the rail on the concrete path. The length and width of the vehicle are shown with L and W respectively.

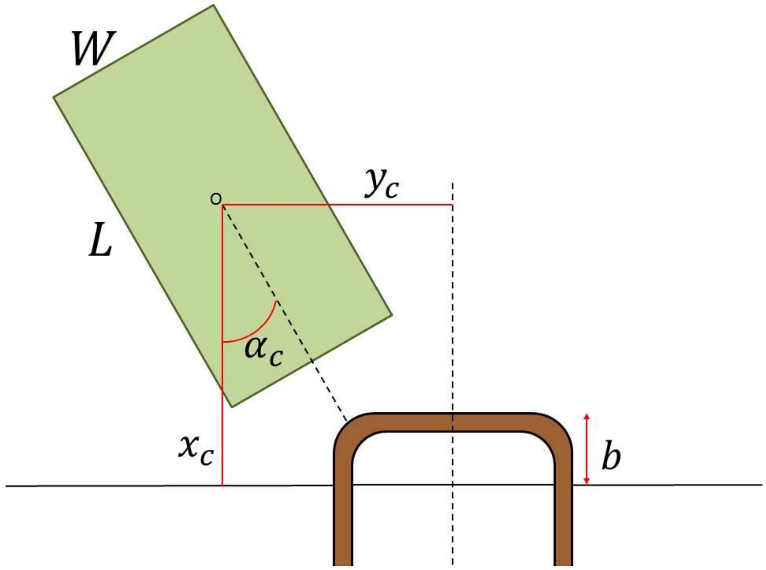

Figure 4: The sensory inputs coming from the vision system. The system measures the distance from the centre of the vehicle to the end of the concrete path (x_c), the distance to the heart line of the rail (y_c) and the angle that the vehicle has with the distance line to the end of the concrete path (α_c).

Plan of approach

All these aforementioned problems should be dealt with using a proper structure and plan. In this subsection a plan of approach for the problems of the project is presented below.

- To ensure the movement with the mecanum wheels for the whole project, it is first important to understand the working principle of the stepper motors. The software and hardware of these motors should be investigated before using them. These stepper motors from Nanotec® have multiple modes that can be used for the project. These different modes should be analysed and chosen properly for the movements.

- For simulations on the movement of the vehicle a model should be available. This model should describe the kinematic and dynamic behaviour of the vehicle. The kinematic model will ensure a movement of the vehicle to the desired position and orientation. The dynamic model will present the forces acting on the vehicle and will tell which maximum payload the vehicle can carry with the given movement and phase current. Using the model it may be explained why a lateral movement needs more phase current than a forward movement. These models should be verified by experiments and adjusted where needed.

- The encoders can tell whether the motor has performed the desired number of steps. For a robust control system the encoders of the vehicle should be used first in a control loop, to compensate missed steps from the stepper motors. Then the sensors from the vision system for the absolute position measurement will be used in an outer closed loop. The schematic representation of the loops is shown in Figure 5. In the figure P_{des} corresponds to the vector with the desired position and orientation. The first block corresponds to a function that converts the desired position into the number of steps for each motor, Δn_{mi}. After the movement the value of the encoders Δn_{ei} will be compared with the desired number of steps. Finally, the input vector of the vision system Υ_c will be converted to the global positions P_c and compared to decide whether the movement is achieved or not.

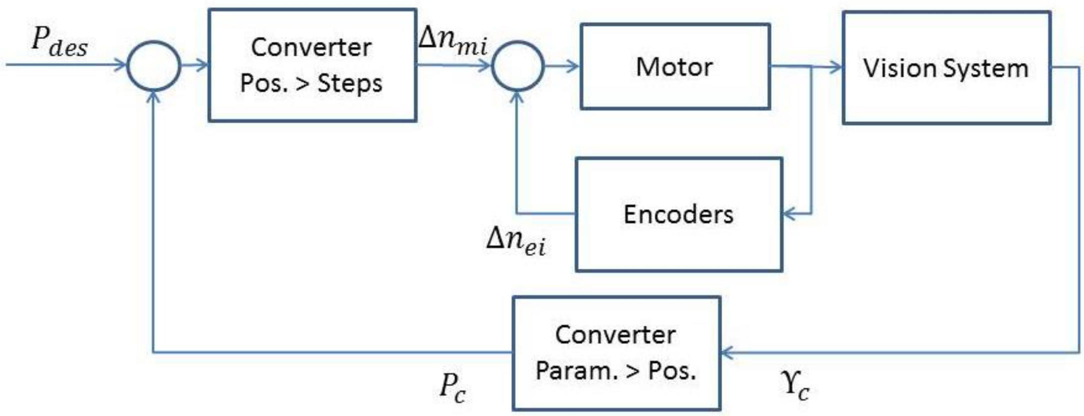

Figure 5: Schematic representation of the control loop for dealing with the problem.

- A method needs to be devised for driving up and riding off the rail. This method may use the inputs from the vision system while driving up the rail. However, when riding off the rail the vision system cannot be used, since the vision system will only see the front.

- A reliable movement with the vehicle needs a synchronous movement of the wheels. Using the available hardware and software, the wheels have to be controlled in such a way that the wheels will start and stop together at the same time instant.

- Finally, the tests for the movement will be done in the greenhouse. A plan should be prepared for the tests with desired requirements. The results of these tests will be used in further steps of the project.

Chapter 3:

The Stepper Motor

The automated movement of the vehicle of the Tomation Project in the greenhouse will be realised using mecanum wheels. In this setup the mecanum wheels are powered by stepper motors. Each wheel is driven by a separate motor. It is important to have a good understanding of the stepper motor and have a clear view on the possibilities and modes of use of the stepper motor. This will provide a good starting point to develop the autonomous movement of the platform in the greenhouse based on the mecanum wheels. In this chapter the working principle of the stepper motor is explained. We explain the difference between the stepper motor and the servo motor to argue the choice on the stepper motors. Finally, we present relevant specifications of the chosen motor and describe important possibilities from the SDK of the motors.

Working principle

The prototype of the robot of the Tomation project uses stepper motors for the movement in the greenhouse. A stepper motor system contains an indexer, a driver and a stepper motor (Figure 6). These elements are in general combined with an application programming interface (API) from which a user interface may be constructed.

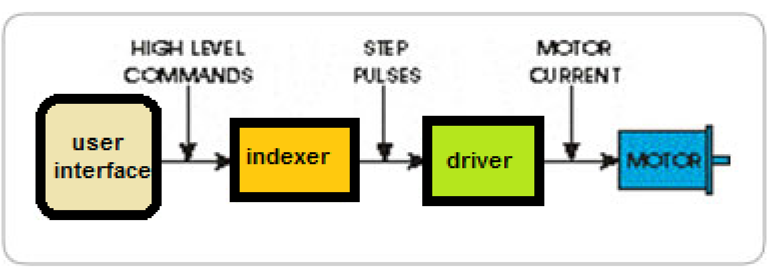

Figure 6: The three basic elements of a stepper motor combined with a user interface [3].

The indexer gets the inputs from the user interface and generates the step pulses and direction signals for the driver. The driver translates these signals into the power necessary to energize the motor windings. With the current the stepper motor ensures the mechanical shaft rotation of the motor.

The stepper motor is a brushless DC electric motor. The basic principle of a stepper motor is to use magnetic coils to pull a magnet in the motor from one position to the next one. The motor contains a rotor (rotating part) and a stator (static part). In general the rotor in a stepper motor contains permanent magnets and the stator is made up by electromagnets. Turning one electromagnet on, ensures that a pole of the permanent magnets in the rotor will be aligned with a pole in the electromagnets. The rotor will move to the position where magnetic equilibrium occurs. Turning the electromagnets on and off in a certain sequence, will ensure the rotor to spin constantly.

The stepper motor divides a full rotation into a large number of equal steps. It is able to rotate incrementally the desired number of steps. Because of this principle, a stepper motor is widely used in low cost and open loop position control systems. Theoretically, the stepper motor does not need an additional feedback system to reach the given position. The advantages of stepper motors are its low cost, high reliability and a simple construction. Another advantage is that the motors are virtually maintenance-free. Since the motors are brushless, they experience little or no wear. The main disadvantages for users are the potential resonance effects exhibited at low speeds and significantly decreasing torque with increasing speed [3]. Another disadvantage is that a stepper motor does not contain a feedback loop, so the system can miss steps without noticing it. When the application is carefully designed this should not pose a problem. However, if the phase current through the motors is not sufficiently high enough, the motor will not be able to complete the given travel profile and loose steps in the process.

Step modes

Different driving techniques for these stepper motors have been developed. The common modes are the Full (one and dual phase), Half and Micro step modes and are presented in this research. These modes are used to explain the working principle of the stepper motor.

Full Step (one phase)

The first and the simplest mode that is presented is the full step mode, turning on one phase at a time instant. In Figure 7 a schematic representation of the 4 phases of a stepper motor in this mode is shown. This figure is used for explaining the working principle of this mode. The red and green colours in the figure correspond to the north and south poles respectively. Note that a real rotor will have more magnetized teeth than shown in the figure.

In the left top image, the upper and lower electromagnets are energized. The upper electromagnet will have a north pole and the lower electromagnet a south pole. This attracts the nearest opposite pole-teeth of the rotor and aligns it to the electromagnet. The left top image shows the motor just after the electromagnets are energized. So the rotor will rotate after this time instant to a position where the electromagnets are aligned to the nearest opposite pole of the rotor. The upper right image shows the motor after the rotor has moved, the upper and lower electromagnets are turned off and the other two are turned on. Here the energized electromagnets will push the tooth with the same pole and pull the nearest opposite pole. These first two steps will be repeated, by reversing the poles of the electromagnets as shown in the lower parts of the figure. The rotor will keep rotating by continuing this process.

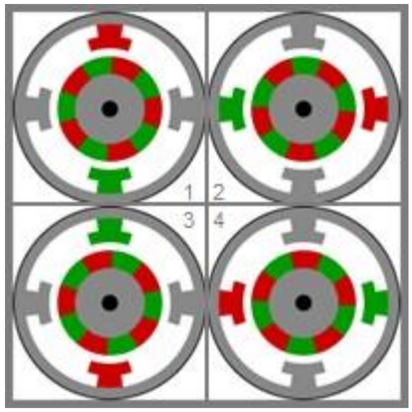

Figure 7: A schematic representation of the working principle of a stepper motor in full step mode with a single phase on.

Full step (two phases on)
A full step mode with a dual phase is realized by ensuring that at each time instant two electromagnets are energized. This is the usual method for full step driving the motor. As soon as one phase is turned off, another one will be turned one. With two phases turned on, a maximum rated torque will be provided by the motor. The two electromagnets with the same pole will both pull the nearest tooth with an opposite pole to a position between the two coils. This way, it works like the previous full step mode with the same number of steps, but different in the provided torque. Figure 8 represents a motor with a full stepping mode operating in dual phase. Note that in all four states, both coils are driven simultaneously. This generates more torque than produced in the one phase mode.

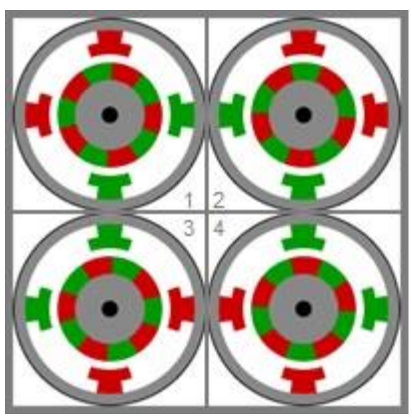

Figure 8: A schematic representation of a motor with a full stepping mode operating in dual phase.

Half step
Combining the previous modes and applying a correct sequence, a half step mode can be achieved. In the half step mode one or two phases will be energized constantly one after another. The drive alternates between two phases on and a single phase on. In this mode a twice higher resolution can be achieved without using a more expensive motor with a higher number of poles. Furthermore, half stepping usually overcomes resonance problems. A disadvantage with the half step drive is the torque variation that occurs. Switching from a one phase mode to a two phase

mode can cause vibrations and mechanical noise. The torque variation can be dealt with by increasing the current for the one phase mode. This way the torque in the one phase mode will be increased and a constant torque over all positions will be achieved. Figure 9 represents a stepper motor operating in a half stepping mode. It is seen from the figure that this mode is a combination of the phases of the two previous modes.

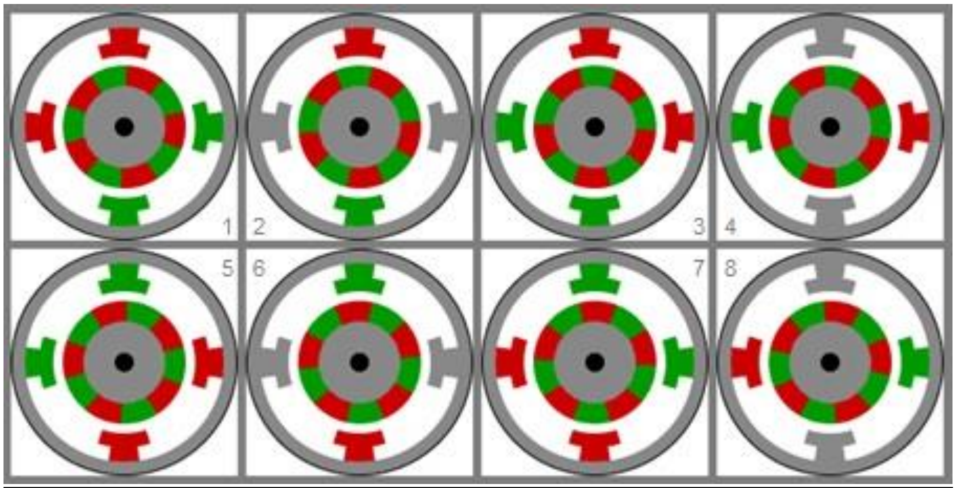

Figure 9: A schematic representation of a motor operating in the half step mode.

Micro stepping

It can be noticed that all combinations of inputs with fully turning on and off of the currents in the coil are represented when operating in half step mode. No other combination of the inputs can set the rotor to a position other than the eight from Figure 8. However, there is a technique that increases the motor resolution by controlling the direction and amplitude of the current flow in each winding. Micro stepping is a way of increasing the number of steps by sending a sine/cosine waveform to the coils inside the stepper motor. This ensures that a smoother and more accurate run of the stepper motor can be achieved. This mode will have low tendency for mechanical vibrations and can drive with high frequencies. A disadvantage is that moving between the pole-positions in the micro stepping mode will occur with significantly lower torque than in the full stepping mode. The micro stepping mode is in general used for applications with less friction and for overpowered motors.

Stepper motors vs. Servo motors

For the movement of the prototype for the Tomation Project stepper motors are chosen as the preferred driving source. A servo motor was also regarded before making a decision. In this subsection the main differences between these motors is discussed. Based on these differences, the choice on the stepper motor is reasoned.

The two types of motors differ in their basic construction and how they are controlled [4]. Stepper motors are known for their large number of magnetic poles, typically 50 to 100. Servo motors usually have 4 to 12 poles in contrast. The poles offer a natural stopping point for the motor. Hence, the large number of poles allow the stepper motors to move accurately and precisely between each pole. In this way a stepper motor can theoretically operate in a proper way without any position feedback for the applications. Servo motors require a position encoder to track the position of the motor shaft.

A single drive pulse moves the stepper motor shaft one step, from one pole to the next one. As the step size of the motor is fixed, the user can easily determine the number of steps needed for the movement. Servo motors read out the difference between the current encoder position and the desired position to adjust the current to move to the desired position.

The design of a stepper motor provides a constant holding torque. It can hold a stop position without depending on a mechanical break. The stepper motor has higher torques than a servo motor for low operation speeds. Other advantages for stepper motors are their relatively low cost price and availability. Servo motors in contrast are more expensive and are often harder to find than stepper motors.

Servo motors will be used for applications with high speeds and high torques. They can operate many times faster compared to a stepper motor. Servo motors also are able to operate with a high torque rating at high speeds. Up to 90% of the rated torque is available from a servo at high speed. For stepper motors in contrast, a loss of 80% of the rated torque at 90% maximum speed is typical.

Accurate position estimation with the vehicle is one of the requirements and is vital for the Tomation Project, since it needs to position properly on the rail when cutting the tomato plants. Also, because no extreme high velocities are needed for this purpose, the stepper motor will therefore be more suited to ensure an accurate movement with the given specifications.

The Nanotec® PD6-N89 Motor

The movement of the vehicle of the Tomation Project is powered by stepper motors. The motors chosen for the prototype in the project are the plug & drive PD6-N89 motors from Nanotec®. In this subsection, the specifications of these motors and the possibilities in controlling the stepper motor with the available SDK of the motor are discussed.

The chosen motors for the movement are the PD6-N89 plug & drive motors [5]. For the movement the PD6-N8918M9504 models will be used. The schematics of these motors can be found in Appendix A. These motors are connected with the drivers of the system. It will be controlled through the RS485 bus via the Component Object Model (COM) interface with MATLAB®. The COM is a software architecture that allows applications to be built from binary software components. RS485 is a serial communication method for computers and devices.

Technical Data

The technical data of the PD6-N89 plug & drive motors are presented in Table 1.

Table 1: Technical Data of the PD6-N89 motors [6].

Operating voltage	24 – 48 VDC
Max. phase current	Adjustable in 1% increments, up to max. 10.5 A/phase, 7 A nominal current
Position monitoring	Automatic error correction up to 0.9 °
Step Frequency	0 to 50 kHz in clock-direction mode, 0 to 25 kHz in all other modes
Operating mode	1/1, 1/2, 1/4, 1/5, 1/8, 1/10, 1/32, 1/64 adaptive (1/128) step
Inputs	6 opto-coupler inputs (5–24 V), analogue input
Interface	RS485 or CANopen
Encoder	Resolution 500 increments

The motors of the project operates with a 24 V DC operating voltage. A half step operating mode is used in the project to get high resolution and an accurate positioning system without losing torque.

The motor has a holding torque of 5.90 Nm. The speed-torque diagram of the motors is shown in Figure 10. The optimal range to drive these motors is from 0-100 RPM which is equivalent to 0-667 Hz. Beyond this range there is a severe drop in torque.

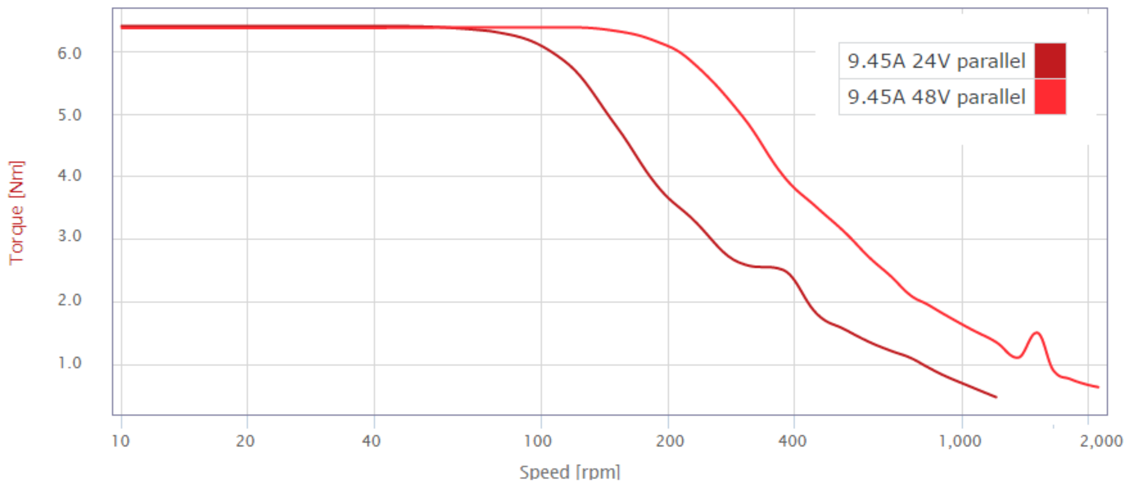

Figure 10: The speed-torque diagram of the PD6-N8918M9504 model Nanotec motor chosen for the prototype of the Tomation Project [6].

Movement modes

The Nanotec motors have a particular SDK program as a user interface: NanoPro. This program facilitates users to experiment with the stepper motors, providing different travel profiles, speeds and accelerations. Several pre-programmed movement modes are installed in NanoPro. Below an overview is shown from the Nanotec website of the application modes and their areas of application in Table 2 [5].

Table 2: Overview of the operating modes and their applications [5].

Operation mode	**Application**
Relative positioning	Use this mode when you wish to travel to a specific position. The motor travels according to a specified drive profile from a Position A to a Position B.
Absolute positioning	
Internal reference run	During the internal reference run, the motor travels to an internal reference point at the set minimum speed (index mark of encoder, only in combination with an encoder).
External reference run	During an external reference run, the motor travels to a switch connected to the reference input
Speed mode	Use this mode when you wish to travel with a specific speed (e.g. a conveyor belt or pump speed). In the speed mode, the motor accelerates with a specified ramp from the starting speed (start frequency "V Start") to the specified maximum speed (maximum frequency "V Normal"). Several inputs enable the speed to be changed on-the-fly to different speeds.

Flag positioning mode	The flag positioning mode offers a combination of the speed and positioning modes. The motor is initially operated in speed mode; when a trigger point is reached, it changes to the positioning mode and the specified setpoint position (relative to the trigger position) is approached. This operating mode is used for labelling, for example: the motor first travels with the set ramp to the synchronous speed of the conveyed goods. When the labels are detected, the preset distance (position) is travelled to apply the labels.
Clock direction mode, left Clock direction mode, right Clock direction mode, Int. Ref. Clock direction mode, Ext. Ref.	Use this mode when you wish to operate the motor with a superordinate controller (e.g. CNC controller). In the clock direction mode, the motor is operated via two inputs with a clock and a direction signal from a superordinate positioning control (indexer). Depending on the mode selected (Int. Ref./Ext. Ref.), the internal and external reference runs are supported.
Analogue and joystick mode	The motor is controlled in this operating mode simply with a potentiometer or a joystick (–10 V to +10 V). Use this mode if you want to use the motor in a simple application: • Setting a specific speed, e.g. via an external potentiometer, • Traveling synchronously with a superordinate controller with analogue output (–10 V to +10 V).
Analogue positioning mode	Use this mode when you wish to travel to a specific position. The voltage level on the analogue input is proportional to the required position
Torque mode	Use this mode when you require a specific output torque independent of the speed as is the case in typical winding and unwinding applications. The maximum torque is specified via the analogue input.

A programmer's manual for the NanoPro control software for the Plug & Drive stepper motor controllers can be found at the website of Nanotec® [6]. The programmer's manual is aimed at designers and developers for programming their own control software for the motors using a COM interface, and is also available at the website.

NanoPro provides the control of the motors with different available travel profiles. A trapezoidal, sinusoidal and a jerk-free profile can be used. The target speed, the (braking) ramp and the number of steps are required for the movement. The jerk-free profile also requires the (braking) jerk for the movement.

Closed Loop mode

A new mode in the PD6-N89 motors is the closed loop operating mode. Here, the encoders of the motors are used to monitor the following error of the stepper motor at each time instant. The following error is the difference between the desired position and the actual position at that time instant. The stator magnetic field is controlled in this mode to behave more like a servo motor using a rotary encoder when using sinusoidal commutation. Here, the stepper motor behaves similar to a multi-pole servo motor. Classic noises and resonances from stepper motors are gone. The motor is now capable of no longer loosing steps to its maximum torque. The current will be modified to the needed torque by the motor, instead of using a constant current through the whole movement. This means that a movement in the closed loop mode will result in a significant reduction of the current consumption and heat generation. The controller in the closed loop mode is a PID controller. The parameters of the PID controller can be entered in NanoPro manually or automatically. The closed loop mode should be used in combination with the mentioned movement modes from Table 2.

Summary

In this chapter the motors that drive the mecanum wheels are discussed. The advantages and disadvantages of these motors are mentioned. Common modes for the stepper motor in applications are briefly described and analysed. Furthermore, the difference between a servo motor and a stepper motor is explained. Technical specifications of the chosen stepper motor and the SDK of the motor with its possibilities are introduced. The research in this chapter will be used in controlling the Nanotec® stepper motors for the movement of the vehicle for the Tomation Project.

Chapter 4:

Mecanum wheels

The vehicle of the Tomation Project is equipped with special designed wheels, the mecanum wheels. The mecanum wheels serve for omnidirectional purposes. The vehicle of the Tomation Project will move in the greenhouse laterally on the concrete path to the next path with the mecanum wheels. As it has to move in required directions in a reliable and robust way, the control and the movement of a vehicle with these wheels should be analysed. Hence, this chapter describes comprehensively the concept of the mecanum wheels. The first section explains how omnidirectional movement with the wheels occurs. Subsequently the kinematics of a vehicle with mecanum wheels is described. Finally the dynamics of these wheels are explained. Experiments that are used for the kinematics and the dynamics of the vehicle are discussed in these sections.

Omnidirectional movement

Most vehicles in the industry are constrained by its steering system in controlling all degrees of freedom independently for a planar motion. A car on the road has two control inputs, but still its configuration space has three dimensions. Using complicated manoeuvres and complex path planning a car is able to reach the whole defined space. The conventional steering system in a car is causing the constraint for moving perpendicular to its drive direction. This constraint is called a non-holonomic constraint.

A vehicle that is not hampered with these constraints is capable of *omnidirectional* mobility. An omnidirectional vehicle is able to move the car in different directions. This feature in the vehicle decreases the complexity of manoeuvres and may provide a faster and more accurate movement. Moreover, it provides a way to manoeuvre in a more compact space. A more comprehensive research on omnidirectional wheels is described in a separate literature study [1].

Omnidirectional movement is desired in the Tomation Project to ensure the path-to-path movement through the greenhouse with a compact platform that can manoeuvre in the limited space on the concrete path. The omnidirectionality of the platform of the Tomation Project is realised with *mecanum wheels*. A mecanum wheel, shown in Figure 11, is a special designed omnidirectional wheel. A number of rollers are attached to the circumference of the wheel. These rollers are commonly orientated at an angle of 45° from the axis of rotation of the wheel.

Figure 11: The mecanum wheel used for the Tomation project.

Omnidirectional movement with the mecanum wheels is realized by appropriately controlling the angular velocity of each wheel separately. Depending on each individual wheel rotation direction and velocity, the resulting combination of the wheels produces a total movement in the desired direction without changing the orientation of the wheels [1].

Mecanum wheels are especially known for its property of moving in a lateral direction. By rotating the wheels on one side against each other and on the other side towards each other, a lateral motion of the vehicle will be realized. The possibility to move in a lateral direction with these wheels was the main reason for using them at the Tomation project. The idea with these wheels is to travel in a greenhouse from path to path in a lateral direction without lifting the robot or using complicated manoeuvres. The wheels offer a way to do compact movements on the path, without obstructing the path more than necessary to avoid possible conflicts with other (moving) objects.

Of course the mecanum wheels are not only suitable for a lateral motion. If all the wheels will rotate in the same direction with equal angular velocities, forward or backward motion of the vehicle is achieved. A rotation about the axis running through the origin of the frame perpendicular to the surface is possible by rotating the wheels of one side in one direction and the other side in the other direction. Figure 12 shows some possible motions of a vehicle with mecanum wheels. A more detailed survey on the design of the mecanum wheels and on applications in the industry with these wheels is presented in [1].

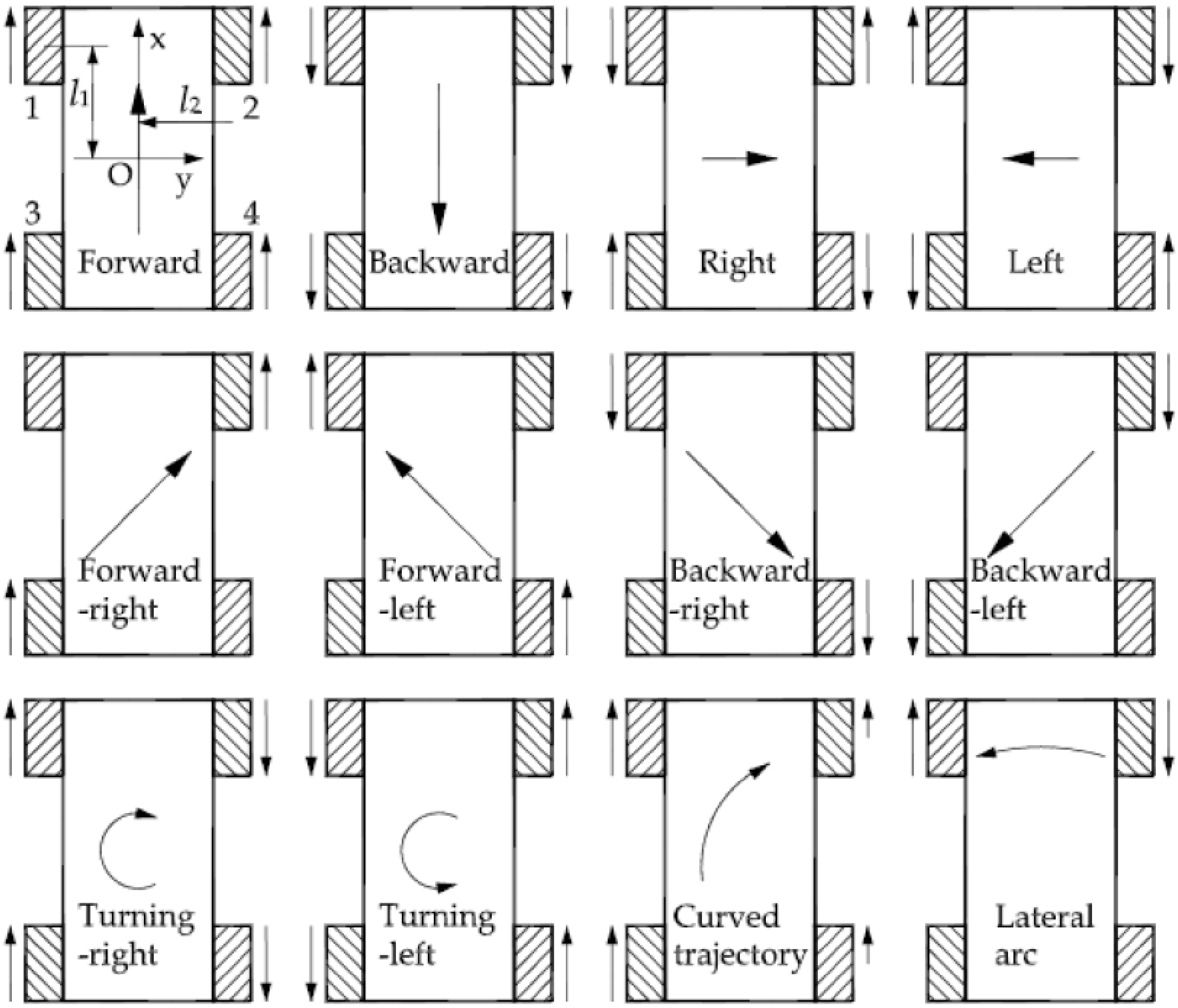

Figure 12: The motions of the vehicle with mecanum wheels according to the direction and angular velocity of the wheels [1].

Kinematics

The vehicle of the Tomation project will use the mecanum wheels to move autonomously from path to path in greenhouses. To control the vehicle and to take properly advantage of the properties of the mecanum wheeled vehicle, the kinematics of these wheels should be analysed. Using the kinematics, a proper model of the vehicle can be created. This section starts with an analysis of the kinematic model of a vehicle with mecanum wheels. Next, some analytical findings on the kinematics and the rollers of the wheel are discussed. Finally, an experiment for obtaining a practical model by adjustments to the kinematic model is described and analysed.

Kinematic Modelling

The kinematics of the vehicle with mecanum wheels is essential in creating a model for the navigational purposes of the project. The first step in the kinematics is to find the equations of motion. These equations should use the angular rotation of the wheels to determine the new position and orientation of the vehicle. The equations of motion that are used are analysed in the previous work [1]. In Figure 13 a mecanum wheeled vehicle is illustrated for the analysis of the kinematic equations. The origin of the chosen coordinate system is located in the centre of the vehicle. The X-axis is pointing forward, the Y-axis is pointing to the left and the Z-axis corresponds to the line through the centre perpendicular to the surface. Positive rotation is defined as counter clockwise around the origin.

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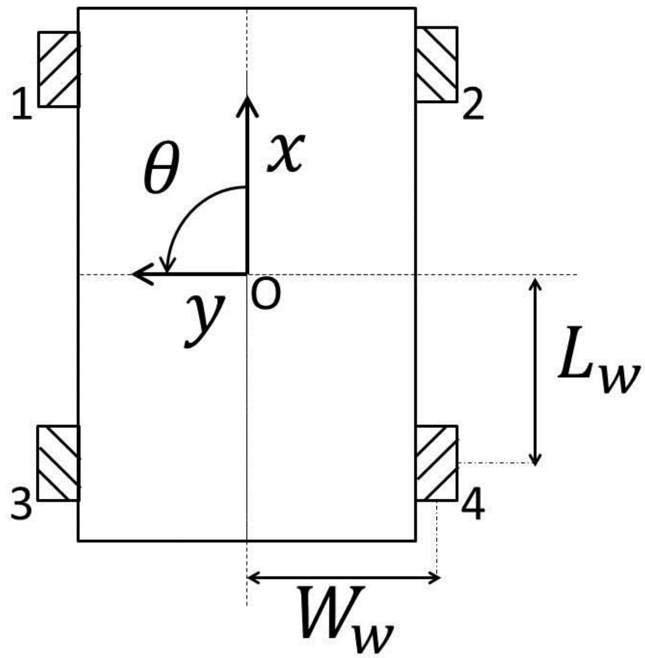


Figure 13: Mecanum wheel with the shown coordinate system where the origin is located in the center of the car. The z-axis corresponds to the line through the centre perpendicular to the surface.

The forward and inverse kinematic problems are both considered. The forward kinematics will determine the vehicle motion, given the angular velocities of the wheels. The inverse kinematic problem uses the velocities of the vehicle to determine the angular velocities of the wheels. The forward and inverse kinematic equations are discussed in [1] and presented in equation (1) and (2) respectively.

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = \frac{R_w}{4}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & -1 & 1 \\ -\dfrac{1}{L_w + W_w} & \dfrac{1}{L_w + W_w} & -\dfrac{1}{L_w + W_w} & \dfrac{1}{L_w + W_w}\end{bmatrix} \cdot \begin{bmatrix}\omega_1\\ \omega_2\\ \omega_3\\ \omega_4\end{bmatrix} \tag{1}$$

$$\begin{bmatrix}\omega_1\\ \omega_2\\ \omega_3\\ \omega_4\end{bmatrix} = \frac{1}{R_w}\begin{bmatrix} 1 & 1 & -(L_w + W_w) \\ 1 & -1 & L_w + W_w \\ 1 & -1 & -(L_w + W_w) \\ 1 & 1 & L_w + W_w \end{bmatrix} \cdot \begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} \tag{2}$$

For the sake of convenience, it is assumed that $R_1 = R_2 = R_3 = R_4 = R_w$, where R_i is the radius of the wheel i. Furthermore, $\boldsymbol{\omega_w} = [\omega_1, \omega_2, \omega_{3,}\omega_4] \in R^4$ are the angular velocities of each wheel and $L_w + W_w$ are given as the distances between the wheel and the centre of gravity in length and width direction respectively. It is assumed that the centre of gravity of the vehicle is located in the middle point of the vehicle. The given equations are valid for an ideal situation and model.

The velocities and the angular velocity of the vehicle from equations (1) and (2) are given in the local frame of the vehicle. For the purpose in the Tomation project a model is needed, which describes the position and orientation of the vehicle in a global frame. When describing this model the vector $[x_G \; y_G \; \theta_G]^T$ denotes the position and orientation of the vehicle in the global frame. Using a rotation matrix for this purpose the forward kinematics in a global frame is expressed with the following equation.

$$\boldsymbol{V_G} = J^{+}(\theta)\boldsymbol{v_w} \tag{3}$$

In the equation, the vector $\boldsymbol{v_w} = [v_{1w} \; v_{2w} \; v_{3w} \; v_{4w}]^T = R_w[\omega_{1w} \; \omega_{2w} \; \omega_{3w} \; \omega_{4w}]^T$ corresponds to the velocities of the wheels. $\boldsymbol{V_G}$ is the vector with the velocities in the global frame $[\dot{x}_G \; \dot{y}_G \; \dot{\theta}_G]^T$ and $J^{+}(\theta)$ is given as

$$J^{+}(\theta) = \frac{1}{4}\begin{bmatrix} \sqrt{2}\sin\theta_1 & \sqrt{2}\cos\theta_1 & \sqrt{2}\cos\theta_1 & \sqrt{2}\sin\theta_1 \\ -\sqrt{2}\cos\theta_1 & \sqrt{2}\sin\theta_1 & \sqrt{2}\sin\theta_1 & -\sqrt{2}\cos\theta_1 \\ -\dfrac{1}{L_w + W_w} & \dfrac{1}{L_w + W_w} & -\dfrac{1}{L_w + W_w} & \dfrac{1}{L_w + W_w} \end{bmatrix}$$

where $\theta_1 = \theta + \frac{\pi}{4}$. The matrix $J^{+}(\theta)$ is the pseudo inverse matrix of $J(\theta)$, which is given by

$$J(\theta) = \begin{bmatrix} \sqrt{2}\sin(\theta_1) & -\sqrt{2}\cos(\theta_1) & -(L_w + W_w) \\ \sqrt{2}\cos(\theta_1) & \sqrt{2}\sin(\theta_1) & (L_w + W_w) \\ \sqrt{2}\cos(\theta_1) & \sqrt{2}\sin(\theta_1) & -(L_w + W_w) \\ \sqrt{2}\sin(\theta_1) & -\sqrt{2}\cos(\theta_1) & (L_w + W_w) \end{bmatrix}$$

Finally, the inverse kinematic model of the mecanum wheeled vehicle in a global frame is governed by

$$\boldsymbol{v_w} = J(\theta)\boldsymbol{V_G} \tag{4}$$

Roller analysis

The research on the mecanum wheels described in literature discusses mainly the motion of the vehicle. An adequate analysis and explanation on the motion of the rollers of the wheel is not presented yet. To explain how the rollers participate in the total motion of the vehicle some movements are investigated more closely. The focus point in this subsection is the movement in the rollers. The forward, lateral and diagonal movement are taken into account. Finally, the analysis on the rollers is expanded by looking at different translations in multiple directions.

For the analysis of the motion of the rollers, the mecanum wheeled vehicle of the Tomation project is considered. The wheels will not rotate about an axis trough the centre of the wheel perpendicular to the surface. Hence, there will only remain two components that contribute to the movement of the vehicle: the wheel axle rotation velocity and the roller rotation velocity. Figure 14 illustrates with a worms-eye view at a particular roller. The figure presents the velocity lines of both components. The vertical line is the rotation velocity line of the wheel axle and the diagonal line is the rotation velocity line of the roller. A given movement of the vehicle is ensured by a combination of both velocity lines.

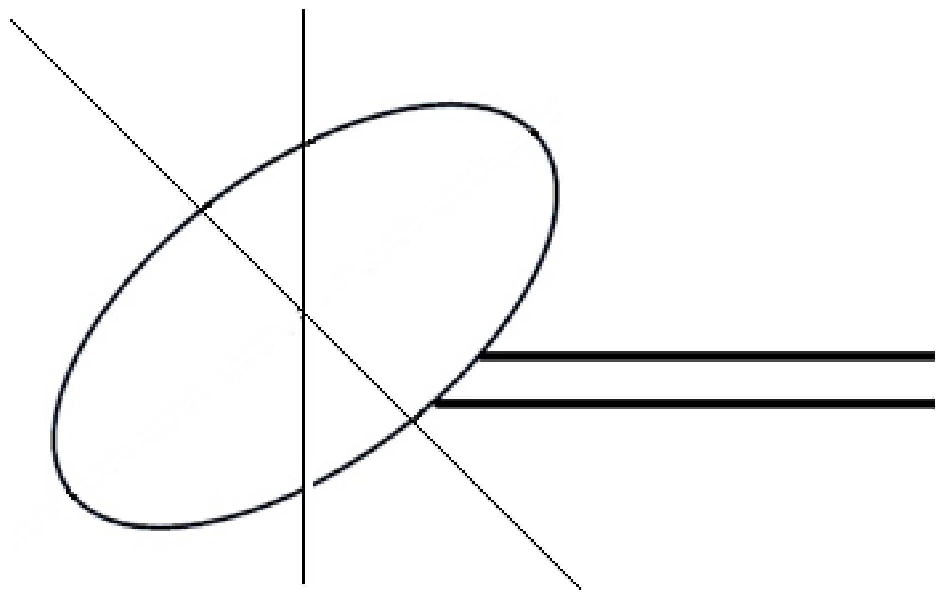


Figure 14: The velocity lines of both rotations. The vertical line is the velocity line of the wheel axle and the diagonal line is the velocity line of the roller.

The first movement that is considered is the forward movement. Figure 15 illustrates a roller of a vehicle that has a forward velocity. The only combination with the velocity lines that ensures a forward movement is by not rotating the rollers of the wheel at all, as illustrated in the figure. The wheel axle rotation is the only component that is used for the forward movement.

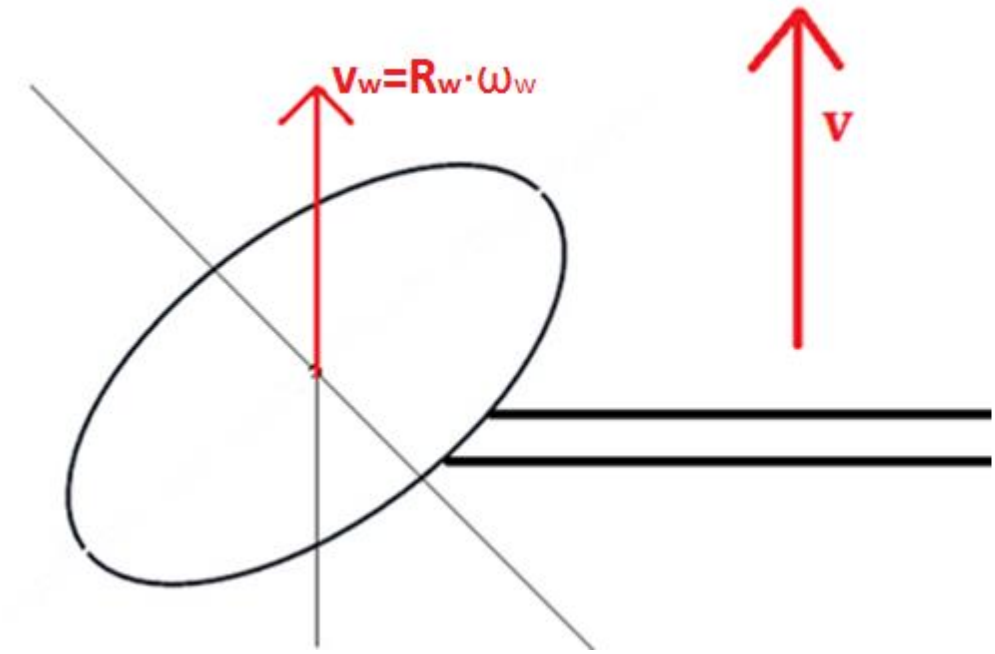


Figure 15: The velocity components of a forward movement.

The second movement that is analysed is a lateral movement to the right. In this situation, the lateral movement cannot be achieved without a rotation of the roller. As illustrated in Figure 16, a combination of the two velocity lines is needed for the lateral movement of the vehicle. It can be seen that the velocity ensured by the rollers should be 1/sin(45°) times the velocity ensured by the rotations of the wheel. Thus the angular velocity of the rollers will be determined as

$$\omega_r = \frac{R_w \cdot \omega_w}{R_r \cdot \sin 45°} \tag{5}$$

Here the subscripts w and r correspond to the wheel of the vehicle and the roller of the wheel respectively.

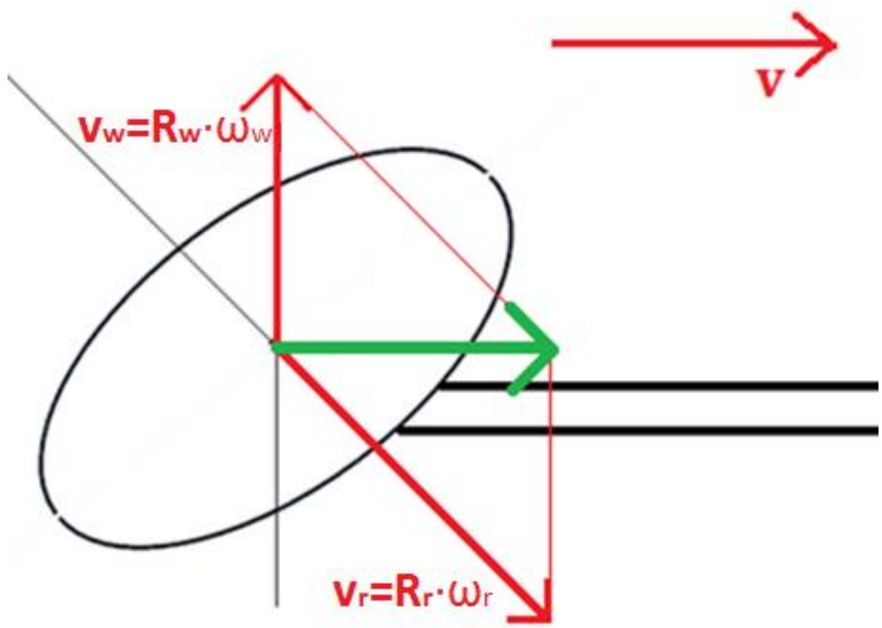


Figure 16: The velocity components of a lateral movement.

A diagonal movement is more complex than the forward and the lateral movement. Figure 12 shows that two wheels that are diagonally placed against each other ideally do rotate and the other two wheels do not rotate for a diagonal movement. An illustration of the rollers of two wheels placed at the same side for the diagonal movement is shown in Figure 17. It can be seen that the upper wheel that is not spinning, just uses its rollers for the movement. The wheel that is rotating is using a combination of both components for the diagonal movement. The angular velocity of the roller from the rotating wheel is determined as

$$\omega_r = \frac{R_w \cdot \omega_w}{2R_r \cdot \sin 45°} \tag{6}$$

This means that for the same velocity magnitude of the vehicle, the rollers for the lateral movement spin twice faster than for the diagonal movement.

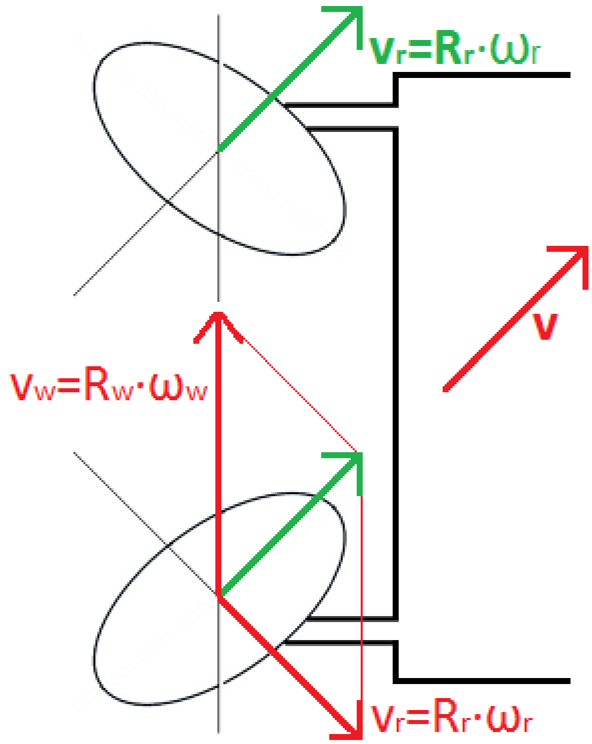


Figure 17: The velocity components of a diagonal movement.

These analyses on the rollers show that for each direction of the vehicle, the rollers on the wheels have different angular velocities. These statements on the rollers are verified by looking closely to the rollers when moving the platform experimentally. It can be seen that the rollers of the wheel are not rotating when the vehicle moves forwards or backwards. The analyses on the movements will now be expanded to movements in various directions to get a better view and understanding in the movements and total displacements of the rollers.

The expansion on the analysis will be done for translations only, without changing the orientation of the vehicle and the wheels. As seen for the diagonal movement, the front and the back wheel of one side of the vehicle will have different angular velocities, hence different movements in the rollers. However, the wheels that are facing each other diagonally will have the same angular velocity for translations, thus the same movement in the rollers. The focus in this analysis is put on one front and one back wheel of one side of the vehicle. The front wheel will be denoted with subscript 1 and the back wheel with subscript 3.

In Figure 18 the velocity components of one side of the vehicle are shown for a translation in a given direction. This vehicle will exhibit different motions on the rollers when the value of the angle α in the figure will change. The magnitude of the angular velocity of the rollers depends on the direction and the speed of the total movement.

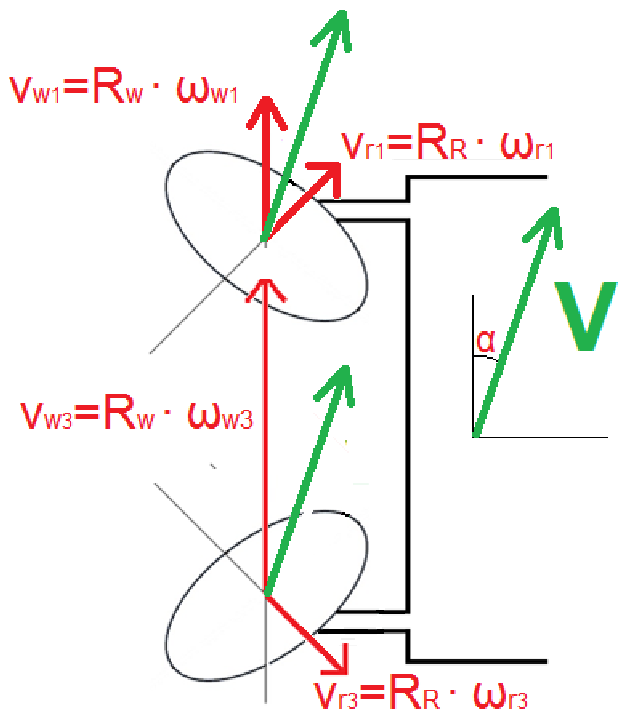


Figure 18: The velocity components for the roller analysis of a vehicle translating in a given direction.

For the sake of convenience we consider a constant speed for the movements in each direction. The lateral velocity vectors in the figure can be written as

$$V_{1,y} = V_1 \sin\alpha = V_{r1} \cos 45 \tag{7}$$

$$V_{3,y} = V_3 \sin\alpha = V_{r3} \cos 45 \tag{8}$$

The forward vectors of the given velocities will be

$$V_{1,x} = V_1 \cos\alpha = v_{w1} + v_{r1} \sin 45 \tag{9}$$

$$V_{3,x} = V_1 \cos\alpha = v_{w3} - v_{r3} \sin 45 \tag{10}$$

Rewriting both equations and substituting equation (7) and (8) into equation (9) and (10) the following formulas of the angular velocity of the rollers are derived for a translation in the α-direction.

$$\omega_{r1} = \frac{v_{r1}}{R_r} = \frac{R_w \omega_{w1}}{R_r} \frac{1}{\frac{\cos 45}{\tan\alpha} - \sin 45} \tag{11}$$

$$\omega_{r3} = \frac{v_{r3}}{R_r} = \frac{R_w \omega_{w3}}{R_r} \frac{1}{\frac{\cos 45}{\tan\alpha} + \sin 45} \tag{12}$$

With these equations one can determine the angular velocities, hence the angular displacements of the rollers for a given translation. To get a better view on these equations and to compare the results of different directions, these are entered in the equations and will be discussed next. With this comparison, one can easily see how the rollers are contributing to translations in different directions. The contribution of the rollers is used to determine the effect of friction in the rollers in the next section.

The equations are functions of the direction of the movement and the velocity of the wheel. For our purpose with the stepper motor of the Tomation Project the velocity of the wheels can easily held constant for comparing the angular velocity and displacement of the rollers in translations with different directions. In the next example the total displacement of the vehicle is held constant at 1 m for all movements and the direction of the movements will vary from 0° up to 90° in steps of 10°.

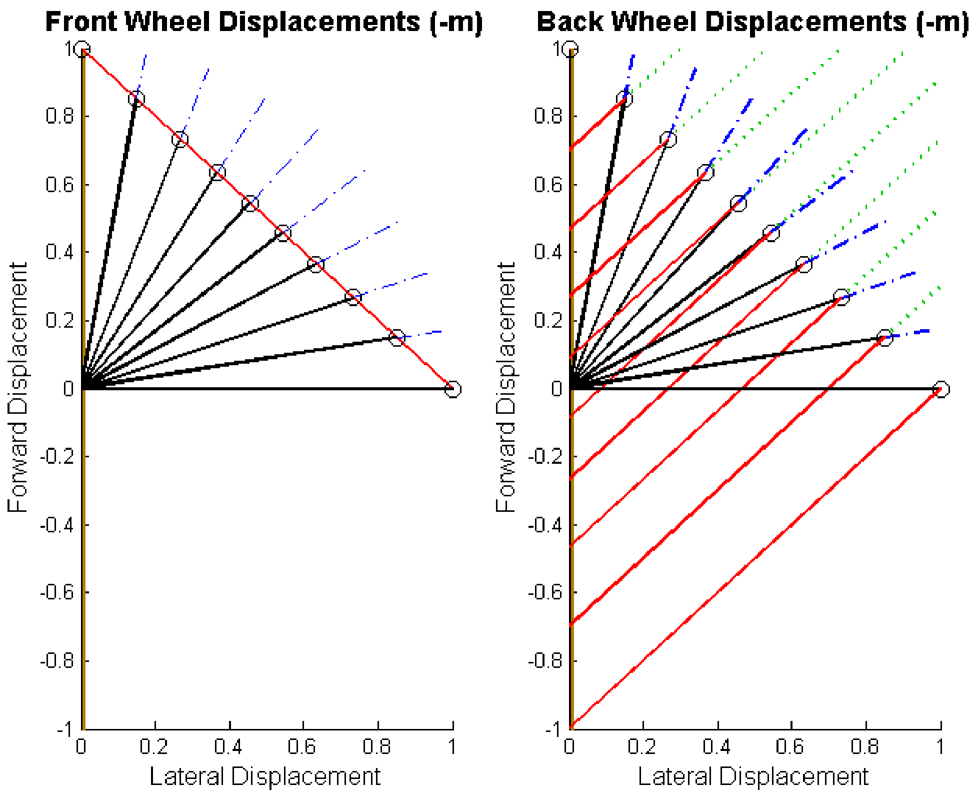


Figure 19: The roller analysis of the movements for different directions. The figure shows the contribution of the velocity of the wheel (brown) and the velocity of the roller (red) to the total movement (black) of the vehicle for multiple directions.

In Figure 19 the results of the analysis for the specified distance with different angles is shown for the front and back wheel. The first graph of the figure corresponds to the front wheel and the second to the back wheel. The blue dash dotted lines are the directions that are used in this example mentioned before. The black lines in the graphs correspond to the total movements that the vehicle is performing in different directions starting from the origin. The dotted green lines in the second figure are corresponding to directions of the magnitudes of the movements of the rollers. The directions of these lines are naturally 45°. The red lines are corresponding to the magnitude of the movement of the rollers, starting from the vertical axis. The intersection points between the black and red lines are marked with black circles and correspond to the final positions of the movements in the given directions. The brown line at the vertical axis corresponds to the movement of the wheel. In this example the value of the front wheel has been set to 1 m. That is why the red lines in the left figure starts all at the value 1 m on the vertical axis. The contribution of the back wheel is determined using the ratio between the wheels. This ratio is simply found by determining the needed angular velocities for each wheel with the equations of motion from the previous subsection. Summarized, the **total movement (black)** is a summation of **the movement of the wheels (brown)** and **the movement of the rollers (red)**.

The graph shows the relative contribution of the rollers and the wheels for the translations in given directions. It can be seen that as the movement gets more horizontal, the rollers will contribute more to the movement. Hence, the angular displacement of the rollers highly depends on the direction of the movement as expected. These results are gained by using the equations of motion from the previous subsection, which were presented for the ideal situation. The importance of the motion of the rollers is clarified in the next section on the dynamics.

Kinematic adjustment

To ensure an autonomous movement the kinematics have to be modelled properly. When creating a model, one has to deal with undesired but realistic effects like friction and slippage that can occur during the movement. These effects will change the outcomes of the kinematic model.

The kinematic model discussed before suffer from position errors. The measured position with a tape measure and the dead-reckoning position determined with the encoder data are not equal. The differences between these two values of the position are in general regular and repetitive. With experiments the kinematic model is adjusted in such a way that these errors are avoided.

This problem of the position errors of a vehicle with mecanum wheels is briefly described in [7]. The position errors can be slippage, bearing friction and point contact friction. By looking at the degrees of freedom the new equation of motion is determined and shown below.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \frac{R_w \alpha_x}{4} \begin{bmatrix} 1 & 1 & 1 & 1 \\ \alpha_r & -\alpha_r & -\alpha_r & \alpha_r \\ -\frac{\alpha_z}{L_w + W_w} & \frac{\alpha_z}{L_w + W_w} & -\frac{\alpha_z}{L_w + W_w} & \frac{\alpha_z}{L_w + W_w} \end{bmatrix} \cdot \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} \tag{13}$$

The above given equation refers to the vehicle illustrated in Figure 13. A comparison between equation (1) and (13) shows that the α’s are the only additions for the new model. In this equation α_x is related with the slippage of the wheel, α_r has to do with roller bearing and/or axle effects and α_z accounts for rotational friction at the point of contact. It can be noticed that for the ideal case these parameters are equal to 1.

The adjusted inverse kinematics of the vehicle with mecanum wheels is determined using the pseudo inverse of the forward kinematics. The inverse kinematic equation of motion of the vehicle is shown below in equation (14)

$$\begin{bmatrix}\omega_1\\ \omega_2\\ \omega_3\\ \omega_4\end{bmatrix} = \frac{1}{R_w \alpha_x}\begin{bmatrix}1 & \frac{1}{\alpha_r} & -\frac{(L_w+W_w)}{\alpha_z}\\ 1 & -\frac{1}{\alpha_r} & \frac{(L_w+W_w)}{\alpha_z}\\ 1 & -\frac{1}{\alpha_r} & -\frac{(L_w+W_w)}{\alpha_z}\\ 1 & \frac{1}{\alpha_r} & \frac{(L_w+W_w)}{\alpha_z}\end{bmatrix} \cdot \begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} \tag{14}$$

To obtain a good position measurement system with the encoders the unknown α's had to be identified. The parameters α_r and α_z are independent of each other. Hence, to obtain all parameters, first α_x has to be determined. This is done with a movement of 3 meters along the x-axis of Figure 13 in the forward direction. The actual moving distance is measured with a tape measure and compared with the computed dead-reckoning value of 3 meters from the encoders. After obtaining α_x the same method is used for identifying parameters α_r and α_z. The identification process for α_r is a movement of 3 meters along the y-direction of Figure 13. Identifying α_z is done by performing a rotation around the z-axis of 7200° (20 rotations) and measuring the travelled angle with a protractor. The measurements for these experiments are shown in Table 3.

Table 3: Results on the experiments, showing the measured traveled distances for each movement with its desired distance.

x-Distance (3000 mm)	**y-Distance (3000 mm)**	**Z-Rotation (20*360=7200°)**
3019 mm	2878 mm	7020°
3019 mm	2880 mm	7020°
3016 mm	2878 mm	7016°
3015 mm	2881 mm	7012°
3018 mm	2880 mm	7010°
3017 mm	2880 mm	7030°
3011 mm	2878 mm	7047°
3013 mm	2877 mm	7040°
3014 mm	2874 mm	
3013 mm	2874 mm	

With the average of these values for the experiments, first parameter α_x is determined. Next, the same method is done for identifying parameters α_r and α_z after substituting the value of α_x. Table 4 shows the results of the unknown parameters for the kinematic equations.

Table 4: Results on the experiment for the adjustments needed on the kinematic equations.

α_x	1.005
α_r	0.954
α_z	0.971

The results show that the biggest error comes from the rollers in the wheel. As shown before the rollers contribute significantly to the lateral movement. Since the rub-roller bearing is not completely free-rolling, the parameter differs significantly. This explains the observed difference in travelled distance between the forward and lateral movement for the same given distance. With this new model the position error will be removed when the stepper motor performs all the steps.

Dynamics

The vehicle of the Tomation project is using stepper motors for its movements. These stepper motors have a maximum force that they can exert for the movement. If the payload on the vehicle exceeds a specific weight the stepper motors encounter difficulties. Undesired movement occurs at these weights, because the stepper motors are not able to perform all the steps correctly. To determine which forces are needed by the motors, the dynamics of the mecanum wheeled vehicle should be analysed. This section discusses the dynamics of the vehicle of the Tomation project and gives an analysis of the experimental findings on the dynamics. It starts by describing a misconception in the literature. Next, an analysis of the dynamics in the ideal and practical case for a vehicle with mecanum wheels is given. Finally some experiments performed on the dynamics are described and analysed.

Misconception literature

To create a model that gives the force needed for a given movement, the dynamics of the mecanum wheels have to be analysed. The dynamics of mecanum wheeled vehicles are obviously more complex than conventional wheeled vehicles. There are many papers written about the dynamics of vehicles with mecanum wheels. A survey on the dynamics presented in the literature can be found in [1]. The papers in the literature agree for a great part on the dynamics of the vehicle. Below an overview will be given on how in the literature the dynamics of a mecanum wheeled vehicle are described.

The analyses of the dynamics presented in the literature are done on the vehicle from Figure 20. The dynamic equations of the vehicle are mainly determined using Newton's second law. The driving force $F_i$would act on a wheel i of the vehicle and decompose into two forces: one force $F_{i,p}$ parallel to the rotational axis of the roller and one in the transverse direction $F_{i,t}$, as shown in the figure. The latter force is neglected by the papers when describing the dynamics.

The motivation in neglecting this force has different views in the literature. The author in [8] describes this force as the roller ineffective slip force. The author from [9] ignores this force because the rollers would rotate freely around their axles and that would cause no traction along the transverse direction.

The force parallel to the rotational axis of the roller $F_{i,p}$ is being used for describing the system. The sum of all effective forces $F_{i,p}$ developed at the wheels would create a net force on the mobile platform. Assuming no friction, the dynamic equations of the vehicle illustrated in the figure are determined and seen below.

$$F_x = \sum_{i=1}^{4} F_{i,x} = \sin\alpha \cos\alpha \sum_{i=1}^{4} (-1)^i \operatorname{sgn}(\omega_i) F_i \tag{15}$$

$$F_y = \sum_{i=1}^{4} F_{i,y} = \sin^2\alpha \sum_{i=1}^{4} \operatorname{sgn}(\omega_i) F_i \tag{16}$$

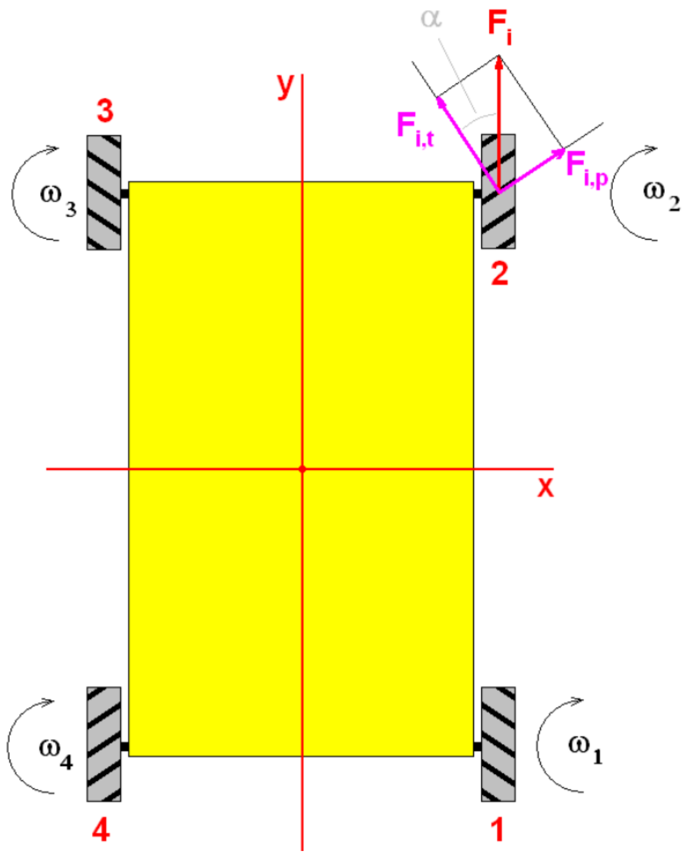


Figure 20: A mecanum wheeled vehicle with a force F_i parallel to the rotational axis of the roller, with its decomposition $F_{i,p}$ and $F_{i,t}$ [9].

Let us now closely examine the force $F_{i,t}$ perpendicular to the roller axis that is neglected in the literature. Authors disagree on their motivation of neglecting this force. Some authors do not even mention their reasons. A lot of authors just refer to other papers where this force is also neglected. Observing the wheels closely however brings a different view into the dynamics of this vehicle.

If there is a force perpendicular to a roller, Newton's second law of motion tells that a constant acceleration will arise assuming no friction. However, in the section on the kinematics of the rollers it is shown that for a forward movement the rollers will not even rotate at all. A lateral and a diagonal movement will also not have a constant acceleration in the rollers. It is shown that the angular velocities of the rollers should be constant for a constant velocity of the vehicle. This is also verified by observing the rollers during movements with the vehicle. No constant acceleration has been noticed. It is not possible to eliminate a force just because the calculations will be more suited. Because of these reasons it is decided to reject the theory in the literature on the dynamics of the mecanum wheeled vehicle.

Ideal case

It has been seen that the dynamics of a mecanum wheeled vehicle are not trivial. For the analysis of the dynamics the roller from Figure 21 is used given with a worms-eye view [10]. Before working on the realistic model with friction, the ideal case without friction is analysed first.

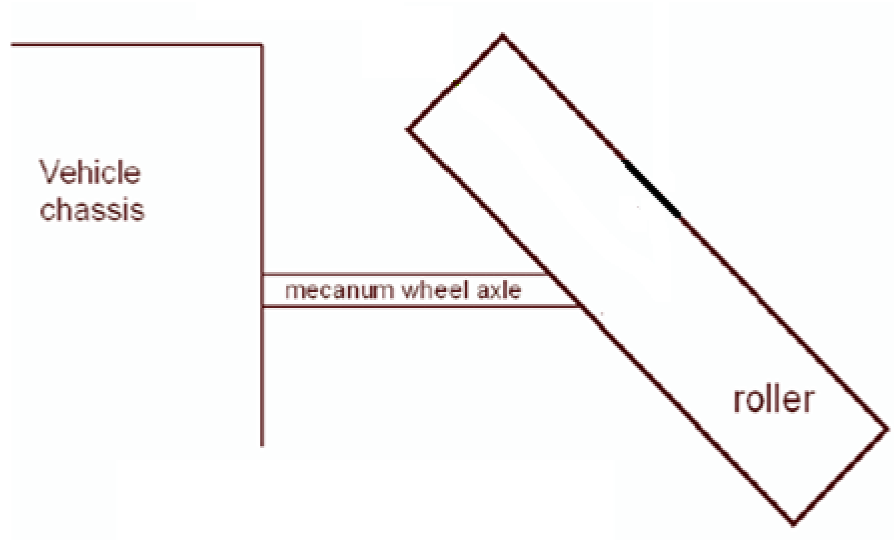


Figure 21: A roller of a mecanum wheel shown with a worms-eye view.

When there is a movement of the vehicle, a reaction force of the floor on the bottom of the roller will occur. This force must be aligned along the roller axis. This reaction force will have two components: one in the forward direction and one in the lateral direction. Since the angle of the orientation of the roller is 45°, both components will be exactly equal. The situation with both components and the reaction force is shown in Figure 22.

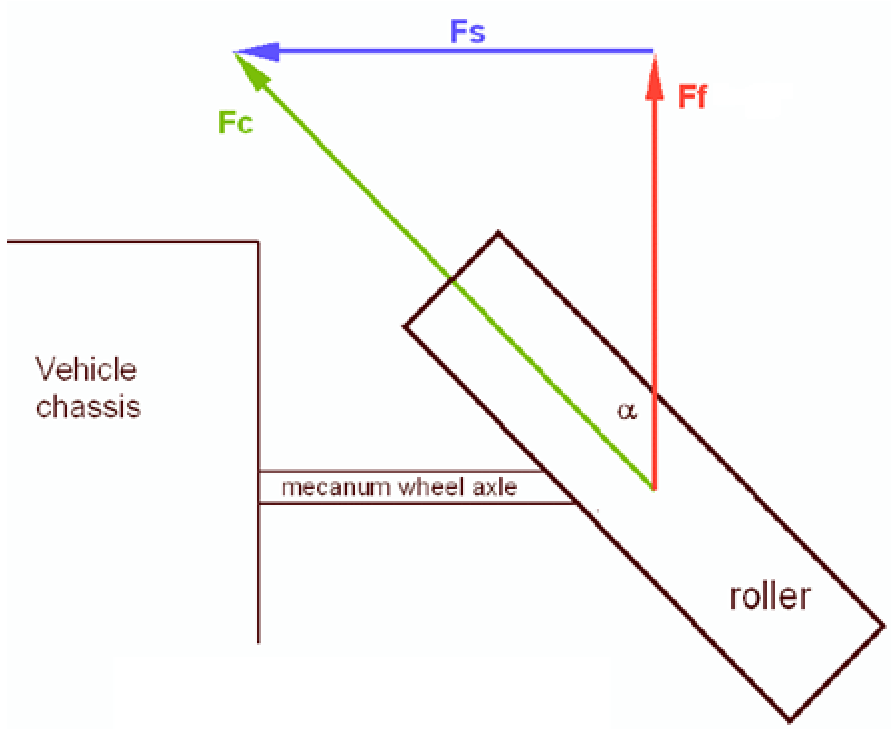


Figure 22: The two components of the reaction force on the roller [10].

The reaction force is given as the green vector F_c, the forward component as the red vector F_f and the lateral component as the blue vector F_s.

To get a better understanding of these forces, an analysis of a forward motion is performed. If the wheel on the other side of the vehicle is being driven with the same torque, F_s will be counterbalanced for the forward movement. So the forward component F_f will be the only vector that remains for the motion. For a non-accelerating wheel the net torque on the wheel must be zero. Therefore the forward component F_f must be equal to τ/R, where τ is the driving torque applied to the wheel and R is the radius of the wheel. This implies that the reaction force along the roller axis will have a value that is greater by a factor $1/\cos(\alpha)$ to the forward force component.

Furthermore the kinematic analyses have shown that the rollers do not spin during a forward motion. Hence it can be assumed that a vehicle with mecanum wheels can be modelled as a conventional vehicle for a forward movement.

As mentioned before, a lateral movement for the vehicle occurs when the wheels on one side of the vehicle turn against each other and on the other side turn towards each other. By rotating towards and against each other the forward component F_f will be counterbalanced by the other wheel on the same side. The lateral components will have the same direction for all the wheels and will be the only vectors remaining for the movement. Since the rollers are orientated with an angle of 45°, this lateral force will be equal to the value of the forward component. So the lateral force can also be modelled as τ/R in the ideal case.

Realistic case with friction

As presented in the section on the kinematics it is shown that the rollers do not rotate for a forward movement. However, for the other motions a rotation of the rollers is necessary. For these motions the force F_c will slide the roller along its axle until all the free play has been taken up and the roller encounters friction. This friction can be caused by the bearings in the rollers that make it impossible for the rotation parts to be completely free-rolling. Due to this friction the analysis of the dynamics will obviously change.

The modified analysis of the forces on the wheel with the friction in the roller bearings is shown in Figure 23. The dotted lines are drawn for reference only. For the forward movement the vehicle can still be seen as a conventional vehicle, since no friction from the rollers will occur. The forward component F_f remains unchanged and must equal τ/R for a constant velocity. The new vector F_b in the figure arises due to the roller bearing friction. As it is shown, this force reduces the angle and the magnitude of the reaction force F_c into F_c'. The lateral component F_s will be reduced by the friction into F_s' for the same motor-driving torque as the friction-free case.

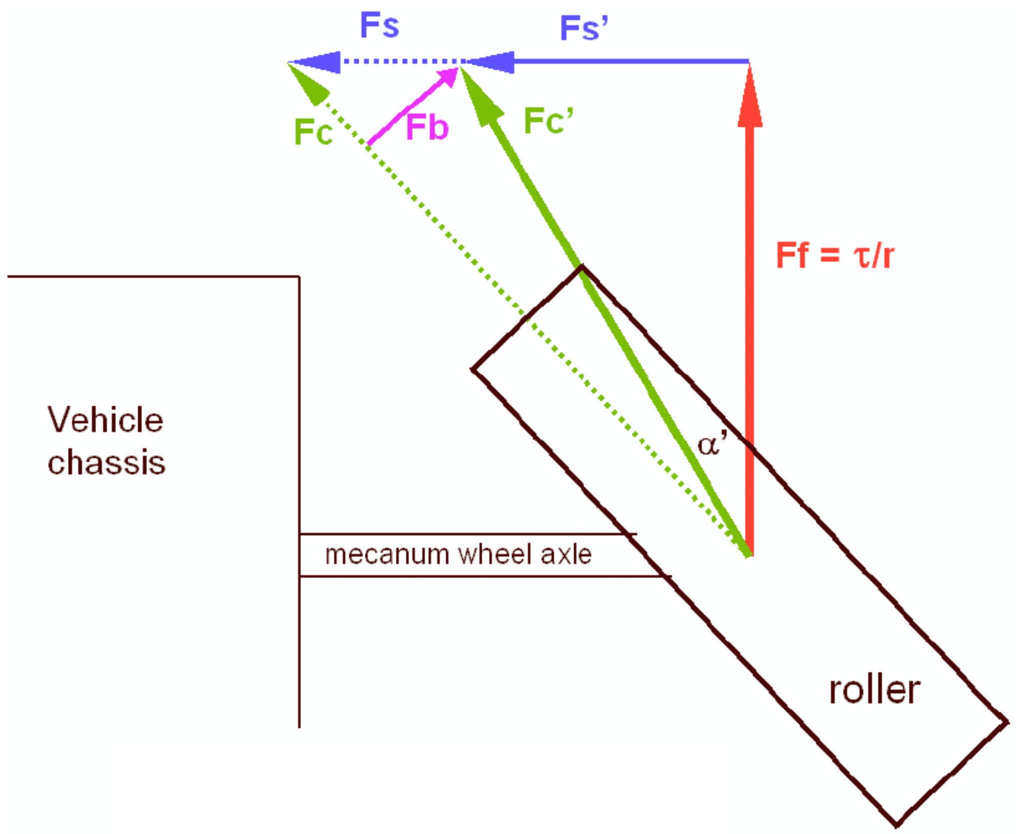


Figure 23: The acting forces on the mecanum wheel with friction in the roller bearings [10].

This friction caused by the roller bearings is the reason of the difference in needed phase currents between a forward and a lateral movement. To ensure a good model of the vehicle, the reduction of the angle should be determined. The difference between the forward and lateral component should be derived and used in the model of the vehicle.

The roller bearing friction also influences the traction during the movement. The reduced angle and magnitude of the reaction force on the ground, means that a greater forward force F_c can be applied before the roller breaks friction with the ground. So the roller bearing friction improves the traction of the mecanum wheel for a forward movement.

Since the magnitude of the lateral force for the movement will reduce, a higher force is needed for the lateral movement. The necessary lateral force will be obtained by increasing the motor torque. The increased motor torque for gaining the same lateral force will also increase the reaction force with the ground. The greater reaction force will cause the mecanum wheel to break friction with the floor and slip earlier than in the ideal case. So the roller bearing friction reduces traction in the lateral direction.

The other friction forces that were presented in the previous work [1] will still be used for the model of the mecanum wheeled vehicle. The rolling friction of the wheel and the viscous resistive friction will still participate in the dynamics.

Experiment for the forces for different directions

As discussed before the dynamics in the ideal case tell that the force needed for a lateral movement is equal to the force needed for a forward movement. However experiences on the vehicle have shown that this force is larger for the lateral direction. Also the analysis on the friction of the wheels from the previous subsection confirmed that. It is shown that there is no roller friction for a forward movement, since there is no contribution from the rollers.

To obtain a good model that can tell which force is needed at a specified pay load, the differences between the forces of a lateral movement and a forward movement are determined with experiments.

Both the movements are dealt separately. A standard travel profile was set for the whole experiment. The travel profile of the vehicle was a translation of 1 meter in the desired direction and 1 meter back. This profile is repeated 5 times with very low velocities. The experiment started without any weights on the vehicle. The maximum current was increased until the travel profile occurs smoothly, i.e. a motor misses in at most two movements more than 10 steps during the repetitions.

After the needed current was determined, the mass of the platform was increased and the experiment was repeated with a new weight. The experiments for both directions were repeated with higher payloads, until 100% of the maximum peak current was needed for the movement.

Table 5: The results for the experiment, where the percentage of the maximum phase current is shown for the vehicle with the given mass and movement.

Mass (kg)	Lateral (Percentage of the maximum phase current)	Forward (Percentage of the maximum phase current)
90	34%	18%
110	39%	20%
130	43%	22%
150	47%	25%
170	52%	27%
181,3	55%	28%
192	57%	30%
203,3	59%	31%
214	62%	32%
225,3	66%	33%
233,2	69%	34%
244,5	72%	35%
254,7	75%	36%
269,4	79%	37%
280,1	83%	38%
291,4	87%	39%
306,1	92%	41%
316,8	97%	42%
328,1	100%	43%

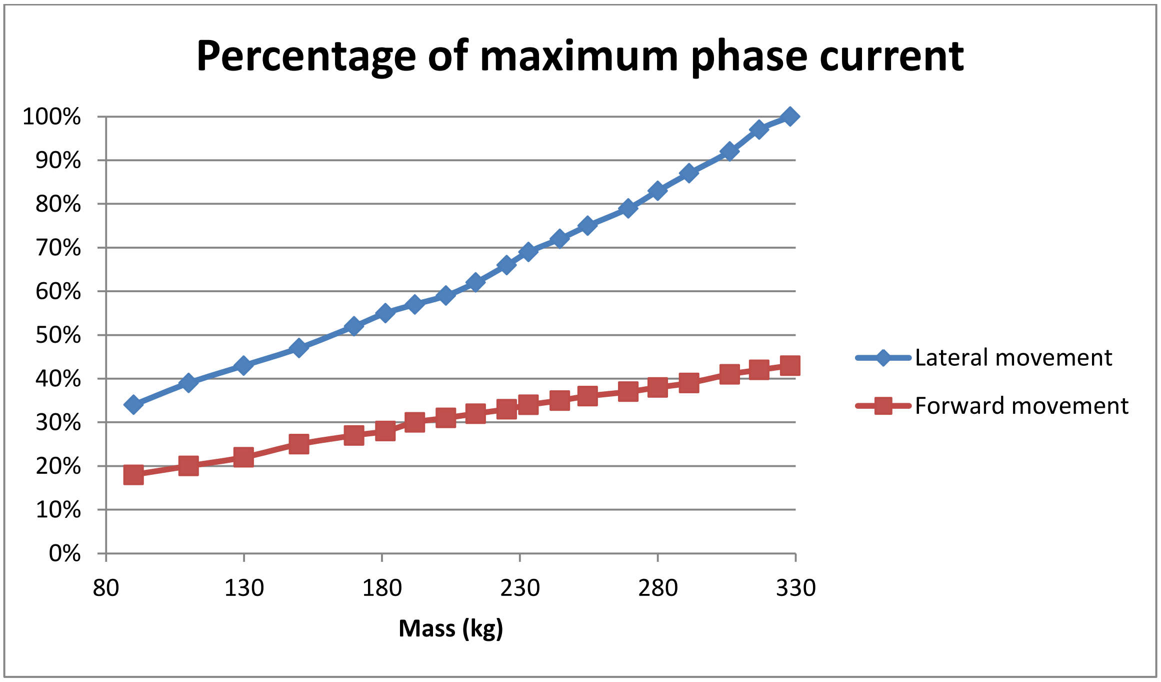


Figure 24: Results on the experiment for the difference between a forward and lateral movement.

Table 5 and Figure 24 show the results of the experiment on the vehicle. The values presented are the smallest percentage of the maximum peak current on which the desired direction has occurred with the given criteria and the given mass. The results show a significant difference between the forward and lateral motion of a vehicle. As expected, the lateral movement needs a higher phase current, which is proportional to the needed force for a movement. With the figure an approximation of the needed force for a movement with the vehicle of the Tomation Project can be determined. The approximation will be done for a vehicle with a mass of 350 kg. Including a safety margin of 30%, the torque should be increased with a factor of 1.5.

To obtain a good model of the dynamics, the angle of the reaction force should also be determined. The ratio between the needed percentage of the maximum phase currents for the forward and lateral movement is shown in Figure 25. With this figure a proper value of the angle of the reaction force can be found. As it can be seen, the ratio between the movements is not constant. It has a constant region until a mass of 200 kg, but after that it is increasing significantly. The ratio in the constant region is around 1.92. After it passes the constant region, it goes up until 2.35 in our experiment. Thus, the angle α of the reaction force in the experiments varies from 28° to 23°. Hence, one has to take the mass into account when creating a model. After the constant region, the angle of the reaction force is decreasing when the mass increases.

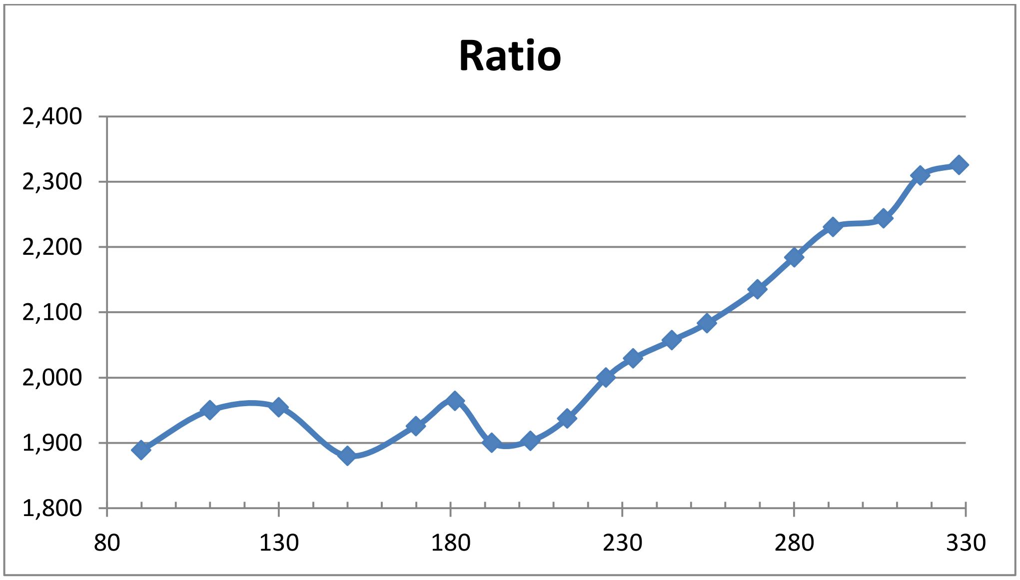


Figure 25: The ratio between the phase current needed for a forward and lateral movement.

Until now our experiments have only shown the differences between the forward and lateral movement. The hypothesis was that this difference comes from the friction of the roller bearings in the rollers. It is assumed that the rollers that have a high contribution to the lateral motion are ensuring a high friction force caused by the roller bearings. However, to verify this assumption and hypothesis the last experiment is expanded to translations in multiple directions. In the previous section it was shown that as the movement gets more lateral, the rollers will have more contribution. The assumption for the difference between the forward and lateral movement can be verified by investigating multiple movements with different directions.

The research on these different movements is similar to the previous experiment. However, this time the mass is kept constant and the direction of the movement is varied. The total mass of the vehicle has been set at 245.4 kg. Again, the orientation did not change for these movements. The least maximum percentage of the phase current that ensures a correct movement is noted down. The same angles as in the previous section on the rollers are explored, i.e. from 0° up to 90° with steps of 10°. A forward movement corresponds to 0° and a lateral to 90°. Based on the hypothesis, it was expected that as the movement gets more horizontal, more phase current is needed, since the rollers will contribute more to the movement.

The results on these experiments are presented in Table 6. The table shows that indeed the movement needs more phase current as the vehicle moves more horizontal. This means that the contribution by the rollers causes a significant difference in the needed force for the movement. It is also seen that the entrance of the rollers cause the biggest difference in needed force. There is a linear relation between the movements after 20°. A future research on the mecanum wheels can be performed to find the relation between the angles and the percentages of the maximum phase current.

Table 6: Results for the needed maximum phase current for the movement in different directions

Angle of the movement	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
Percentage of maximum phase current	33%	47%	55%	57%	58%	60%	62%	64%	66%	68%

Conclusion

In this chapter we discussed the mecanum wheels of the Tomation Project. It has been shown that these wheels provide omnidirectional movement for a vehicle. Omnidirectional movement by the mecanum wheels is realized by appropriately controlling the angular velocity of each wheel separately. Depending on each individual wheel direction and speed, the resulting combination of the wheels produces a total movement in the desired direction without changing the orientation of the wheels.

For the problem of the Tomation Project, a kinematic model should be available for navigational purposes. Using the kinematic equations of motion a model is derived for the movement of the vehicle with mecanum wheels. With this model a specified position and orientation can be reached by the vehicle. This ideal kinematic model is adjusted using experiments, to obtain a more realistic model without repetitive position errors. Furthermore, analysis of the forces involved in the movement of the rollers of the wheels has shown that the rollers behave differently for different movements. It has been seen that the rollers do not rotate at all for a forward or backward movement. The research has shown that as the movement gets more lateral, the rollers will have more contribution to the movement.

Finally in this chapter the dynamics of the mecanum wheeled vehicle of the Tomation Project is presented. First, a misconception in the dynamic models of the literature has been explained. The literature disregards the force perpendicular to the rollers without a proper reasoning. The aspect of the motion in the rollers is neglected. Hence, it is decided to reject the theory in the literature on the dynamics of these vehicles. Subsequently, the correct ideal and the realistic model of the dynamics of a mecanum wheeled vehicle have been discussed. With the realistic dynamic model the observed difference in needed phase current between a lateral and forward movement was explained. The hypothesis was that the difference between these movements comes from the friction in the bearings of the rollers. This causes a difference in the ratio of the needed forward and lateral force. To identify the ratio between these forces, experiments are conducted to complete the dynamic model.

This experiment is expanded to multiple translations. With this the hypothesis on the difference for the needed force between forward and lateral movement could be verified. The expanded experiment has shown that as the direction of the movement is more lateral, the motors need more phase current to perform an adequate movement. Hence, the conclusion for these experiments were that as the movement gets more horizontal, the rollers will have more contribution, and so the movement needs higher torque from the motors.

Chapter 5:

Navigational Features

The vehicle of the Tomation Project should be able to navigate autonomously in the greenhouse. For a robust and reliable movement practical problems related with navigational features should be dealt with. In this chapter these known problems are analysed and discussed and solutions to circumvent these problems are proposed. The chosen solutions for the problems are presented and described in detail.

The first problem in this chapter is to determine the needed steps of the motors for a given omnidirectional movement of the vehicle. The next problem comes from the NanoPro software, which requires integer values for some of the inputs of the travel profile. Furthermore, the delay between the motors caused by the serial connection is discussed. The last problem from this chapter is that the field of view of the vision system is not able to detect the concrete path when riding backwards on the rail. A method for riding off the rail should be devised.

The vehicle from Figure 26 is considered in the given examples in this chapter. The z-axis of the vehicle corresponds to the axis trough the origin perpendicular to the surface, indicated with an O.

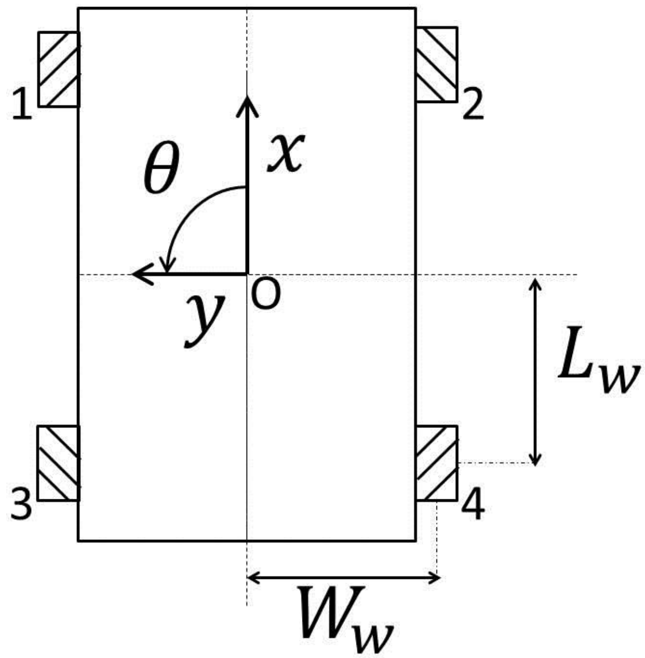


Figure 26: Schematic representation of a vehicle with mecanum wheels where the origin is located in the center of the car. The z-axis corresponds to the line through the origin perpendicular to the surface.

Desired omnidirectional movement

The vehicle of the Tomation Project needs to be able to move in the required directions in the greenhouse. The vehicle will perform omnidirectional movements on the concrete path. The vehicle should be able to move from a current position and orientation to a desired position and orientation. A function should be developed that determines the needed steps of each wheel for the desired translations and rotation, as summarized in equation (17).

$$(\Delta \mathrm{n}_{m1}, \Delta \mathrm{n}_{m2}, \Delta \mathrm{n}_{m3}, \Delta \mathrm{n}_{m4}) = f\left(\Delta x_g, \Delta y_g, \Delta\theta_g\right) \tag{17}$$

Here $\Delta \mathrm{n}_{mi}$ represents the needed steps of motor i for the desired forward and lateral translations and rotation in a global frame shown with $\Delta x_g, \Delta y_g$ and $\Delta\theta_g$ respectively. The subscript g in the equation corresponds to the global frame of the vehicle. The global frame has its origin at the centre of mass of the vehicle in the starting position. So the movement starts at $[x_0, y_0, \theta_0] = [0, 0, 0]$. The subscript 0 in the equation corresponds to the initial position of the vehicle.

To obtain the function from equation (17), the adjusted kinematic equations in the global frame and the identified parameters from the previous chapter are used. With these equations the global velocities of the vehicle can be determined, given the angular velocities of the wheels (ω_i), shown in equation (18).

$$\begin{bmatrix} \dot{x}_g \\ \dot{y}_g \\ \dot{\theta}_g \end{bmatrix} = \frac{R_w \alpha_x}{4} \begin{bmatrix} \sqrt{2}\sin(\theta_a) & \sqrt{2}\cos(\theta_a) & \sqrt{2}\cos(\theta_a) & \sqrt{2}\sin(\theta_a) \\ \alpha_r\sqrt{2}\cos(\theta_a) & -\alpha_r\sqrt{2}\sin(\theta_a) & -\alpha_r\sqrt{2}\sin(\theta_a) & \alpha_r\sqrt{2}\cos(\theta_a) \\ -\dfrac{\alpha_z}{L_w + W_w} & \dfrac{\alpha_z}{L_w + W_w} & -\dfrac{\alpha_z}{L_w + W_w} & \dfrac{\alpha_z}{L_w + W_w} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} \tag{18}$$

The parameter θ_a corresponds to $\theta + \frac{\pi}{4}$. For the sake of convenience, a constant target speed of the motors is used during the movement. A constant motor speed corresponds to a constant velocity of the wheel and thus a constant angular velocity of the vehicle around its z-axis. The angular velocity of the vehicle does not depend on the current orientation of the vehicle. With a given angular velocity, the orientation can be easily determined as a function of the time as follows.

$$\theta_g = t * \dot{\theta}_g + \theta_0 \tag{19}$$

To determine the needed steps for each motor, a total time span of 1 second is used for the calculations. This will only ease the calculations and will have no further effect on the process. From equation (19), it can be seen that the orientation in the global frame goes from 0 radians to $\dot{\theta}_g$ radians. Substituting equation (19) into equation (18), the following formula is determined.

$$\begin{bmatrix} \dot{x}_g \\ \dot{y}_g \\ \dot{\theta}_g \end{bmatrix} = \frac{R_w \alpha_x}{4} \begin{bmatrix} \sqrt{2}\sin\left(t\dot{\theta}_g + \frac{\pi}{4}\right) & \sqrt{2}\cos\left(t\dot{\theta}_g + \frac{\pi}{4}\right) & \sqrt{2}\cos\left(t\dot{\theta}_g + \frac{\pi}{4}\right) & \sqrt{2}\sin\left(t\dot{\theta}_g + \frac{\pi}{4}\right) \\ \alpha_r\sqrt{2}\cos\left(t\dot{\theta}_g + \frac{\pi}{4}\right) & -\alpha_r\sqrt{2}\sin\left(t\dot{\theta}_g + \frac{\pi}{4}\right) & -\alpha_r\sqrt{2}\sin\left(t\dot{\theta}_g + \frac{\pi}{4}\right) & \alpha_r\sqrt{2}\cos\left(t\dot{\theta}_g + \frac{\pi}{4}\right) \\ -\frac{\alpha_z}{L_w + W_w} & \frac{\alpha_z}{L_w + W_w} & -\frac{\alpha_z}{L_w + W_w} & \frac{\alpha_z}{L_w + W_w} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} \tag{20}$$

Integrating both sides of equation (20) over the specified time span will give the global translations and rotation of the vehicle. However, the aim was that a user enters the desired translations and orientation as an input and gets the angular displacements of the wheels as an output. The angular displacements are obtained by solving the intersection points for the integrated formula and the desired position and orientation. Since the matrix is not singular, a dependency on one of the wheels will occur. This dependency is dealt with by taking the motion with practical angular velocities for a vehicle with mecanum wheels. This is the case if the kinematic equation in a local frame from equation (13), combined with its pseudo-inverse from equation (14) will give the original angular velocities back. The angular displacements of the wheel will hereafter be rewritten into the needed steps of the motors. The function in equation (17) is developed in Matlab and named Position.m. The Matlab file is included in Appendix B

The effect of rounding errors

In the previous subsection a function is developed determining the required number of steps of the motors for a given omnidirectional movement. However, it may happen that these movements do not occur properly. It is observed, that a delay at the end of the movement between the wheels is not exceptional. The hypothesis was that the rounded values entered into the user interface cause critical errors in the movement. In this subsection this problem is analysed by determining the effects of these errors. Elements in the movement that are affected significantly by rounding errors are dealt with.

The first input that is considered, which desires an integer value or rounds entered values to integers, is the required number of steps for the movement. The magnitude of the error that may arise due to rounding the desired steps is considered below.

As discussed the stepper motor is connected to the wheels with a chain transmission. The transmission ratio from the stepper motor to the axis of the wheel is 26:48. Furthermore it is known that one rotation of the stepper motor consists of 400 steps. Hence, it follows that one step of the motor corresponds to an angular rotation of the shaft of $\frac{26 \cdot 2\pi}{48 \cdot 400}$ radians. As the size of the wheel is 0.1016 m, one step of the motor moves the vehicle $0.1016 \cdot \frac{26 \cdot 2\pi}{48 \cdot 400} = 8.6 \cdot 10^{-4}$m. This movement is relatively small in the purpose of the project. It will have negligible influences on the movement. A smaller resolution is not needed, thus the error caused by rounding the entered steps is neglected.

For an omnidirectional movement of the vehicle it is straightforward that the wheels will perform different rotations per wheel. To have a proper movement the rotations of the wheels should start and finish at the same time. Hence, different angular velocities should be chosen for each wheel if needed. The target speed of the motor should be entered as an integer value in Hz. The magnitude of the error caused by rounding the desired target speed of the motor is considered below. The magnitude and importance of this error is shown with a practical example for the vehicle from Figure 26.

Suppose, the desired track consists of a movement with 3000 steps of motor 1 and 4 and 1000 steps of motor 2 and 3. This is a simple linear angled movement without changing the orientation. To ensure that the motors finish at the same time, the speed of motor 1 and 4 should be 3 times the speed of motor 2 and 3. If motor 1 and 4 will have a target speed of 200 Hz, the travelled time will be 15 seconds, assuming a constant velocity. Motor 2 and 3 would have ideally a speed of 66.67 Hz, but due to the resolution in NanoPro this will be rounded to 67 Hz. Now the travelled time for motor 2 and 3 will not be 15 seconds but 14.93. The vehicle will move the last 0.07 seconds just with motor 1 and 4 turned on. This will create undesired effects to the movement, since it is the combination of the velocities of all the wheels that creates a movement in the desired direction. Traveling 0.07 seconds with a speed of 200 Hz corresponds to 14 steps of a motor. This is a significant amount for a motor where a full rotation consists of 400 steps. For a proper movement a solution to this problem should be found.

This problem can be tackled in two ways. The first is by preventing a situation where the target speeds needed to be rounded. The second way is by correcting the movement with a second movement right after the first one. It is observed that a movement where two wheels are finished earlier has undesired effects like missing steps and moving to an undesired direction. Since there is no proper position measurement system, this effect is not desired. Hence, the problem is dealt with by preventing the movements where target speeds need to be rounded.

Preventing a situation where the target speeds needs to be rounded is done by searching in a span of none rounded movements and choosing the movement with the smallest error compared to the desired movement. To obtain the span of movements without rounded target speeds, the following algorithm is used.

$$\text{for } i = 1 \colon \max(\text{setpoint})\,, \qquad \frac{\mathrm{i}}{\max(\text{setpoint})} * \text{speed} == \text{int} \tag{21}$$

In this function *setpoint* is the vector corresponding to the original needed steps of the motors for the desired movement. *Speed* corresponds to the maximum target speed that is given to the motors. A movement will have no rounded target speeds, if the ratio between any given number of the setpoint vector and its maximum value times the speed is an integer value.

This function searches up to the maximum number of setpoint and stores all values that meet equation (21) in a list. The possible realistic movements with a combination of these listed values are used. To obtain a larger span and better possibilities, the value of the maximum of setpoint in equation (21) will be varied by taking different values around the original value. The total obtained movements with different maximum steps will all be compared with the desired movement. The movement with the minimum mean square error will be chosen as the best alternative without any rounding errors. The Matlab function that finds this alternative movement is called *Similarmov.m* and is listed in Appendix B.

The algorithm does not provide the exact desired movement. The deviation of this function is investigated by implementing an optimization process. The purpose here was to determine the maximum error that can occur using this function. The cost function of this optimization process is defined as follows.

$$f = \left(X_{per} - X_{des}\right)^2 + \left(Y_{per} - Y_{des}\right)^2 + \left(\theta_{per} - \theta_{des}\right)^2 \tag{22}$$

Subscript “des” and “per” correspond respectively to the desired and performed translation or rotation.

In general, the error between the movements increases for larger movements. The relative accuracy will remain in the same order, so the absolute error between the movements will increase. Hence, the optimization process is performed in a specified frame. The span of the process contains movements, where the magnitudes of the translations and rotation have a maximum of 2 meters and 2 radians respectively. Since the error increases for larger movements, the outcome of the optimization process was expected to be near the end of the frame.

This highly nonlinear optimization process has an infinite number of local minima. The global search method of Matlab is used in combination with the *fmincon* approach. The target speed that is needed from equation (21) is set at a 200 Hz, which is a practical value on the concrete path. The outcomes of the optimization process are presented in Table 7.

Table 7: The results of the optimization process for finding the best alternative movement in the worst case

	Desired movement	Performed movement
X translation	1.5247 m	1.6283 m
Y translation	1.6075 m	1.6210 m
Z rotation	-1.9499 rad	-1.8968 rad

The results show the biggest difference that can occur with the specified target speed and window frame. There is a significant error that should be dealt with after the movement. This can be done by performing an extra movement with the known differences. The differences between the errors occur due to the high nonlinearity of this function. Taking another value for the speed would give completely different results. But the order of the maximum error will be similar. The error between the desired movement and the performed movement can be reduced with a speed twice as high as the current one. This will increase the numbers that meet equation (21) and the number of movements that are listed. But for the application in the greenhouse a realistic target speed is necessary.

Though, it is observed that a movement with a rotation requires significantly more steps than a movement with just a translation. More steps in a movement cause less reliability with this function. The same optimization process is performed to compare the results for a translational movement only. The results for this optimization process are presented in Table 8. The error between the movements is reduced significantly. Even though, this is not a desired solution to tackle the problem, with the available system there is no other way to handle this. As the error between the movements is known, it can be determined whether a second movement is needed with the platform.

Table 8: The results of the optimization process for finding an alternative movement of translations only

	Desired movement	Performed movement
X translation	1.9225 m	1.9533 m
Y translation	-0.5058 m	-0.4661 m
Z rotation	0 rad	0 rad

Delay with the serial connection

For a robust movement of the vehicle it is necessary for the motor to start and stop at the same time. However, it is observed that the motors do not start at the same time instant for a movement. A repeating delay occurs in the movements of the vehicle. The control with the motors occurs by Matlab that communicates through the COM interface with the application programming interface (API) of the Nanotec motors. The RS-485 connection is chosen as the serial communication method with the motors. The motors are controlled in serial one after another and will start in sequence. It is explored that sending two consecutive commands trough the serial connection to the motors takes 0.025 sec.

Before discussing the solution to this problem, the magnitude of this error is determined with a realistic example. A forward movement with a practical target speed of 200 Hz of the motors is considered for this example. Since the time needed for two consecutive commands to the motors is 0.025 sec, it will take 0.075 sec. to start the last motor after the first command. In combination with the specified target speed, this means a delay of 15 steps between the first and last motor. For the given application this corresponds to a delay of 1.2 cm between the first and last motor. This sounds relatively small, but mecanum wheels only function properly when all the wheels are controlled simultaneously. When one of the wheels does not contribute as expected, undesired movements will occur. A solution needs to be found for a proper and accurate movement.

This problem is tackled by using the available digital inputs of the motor system. This process starts by implementing the movement profiles in the motors as usual. After the profiles are loaded, a signal is send to a digital input of the motor systems. With NanoPro this signal can be used as a trigger to start the connected motors. Using the same signal to a digital input of all the motors ensures that they can start simultaneously. This signal is executed using an Arduino [11] board via Matlab. The Arduino board will give a voltage signal to a digital input of the motor systems. This signal activates the movement and ensures a synchronous start of the motors. The Arduino file programmed to ensure the voltage signal can be found in Appendix C.

Riding off the rail

To travel autonomously in the greenhouse, the inputs of a simulated vision system from Figure 27 will be used. The vision system is aiming at the front of the vehicle. Hence this system cannot be used when riding backwards off the rail for detecting the concrete path. This section describes the new approach for detecting the path when the vehicle is located on the rail.

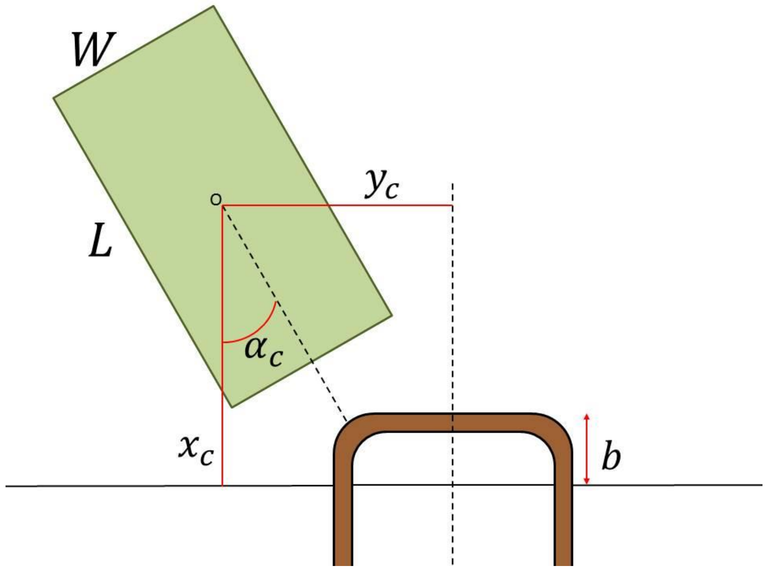


Figure 27: The sensory inputs coming from the vision system. The system measures the distance from the centre of the vehicle to the end of the concrete path (x_c), the distance to the heart line of the rail (y_c) and the angle that the vehicle makes with the distance line to the end of the concrete path (α_c).

In the greenhouse the concrete path is significantly higher than the path where the rails are located. Figure 28 is an illustration of the vehicle on the rail moving towards the concrete path. The difference in height between the paths where the rails are located and the concrete path is used in detecting the transition line. The transition line is shown in the figure as the black vertical line. An ultrasonic proximity sensor is added at the rear of the vehicle, the HC - SR04 sensor [12]. The datasheets of this sensor can be found in Appendix D. More about ultrasonic sensors can be found in [1]. The sensor will operate using the same Arduino board via Matlab. The sensor will measure the distance downwards at each time sample. This way it can detect the transition that will occur when the concrete path is reached. The significant difference in height ensures a simple detection of the transition line. The Arduino file for the ultrasonic sensor is added to Appendix C.

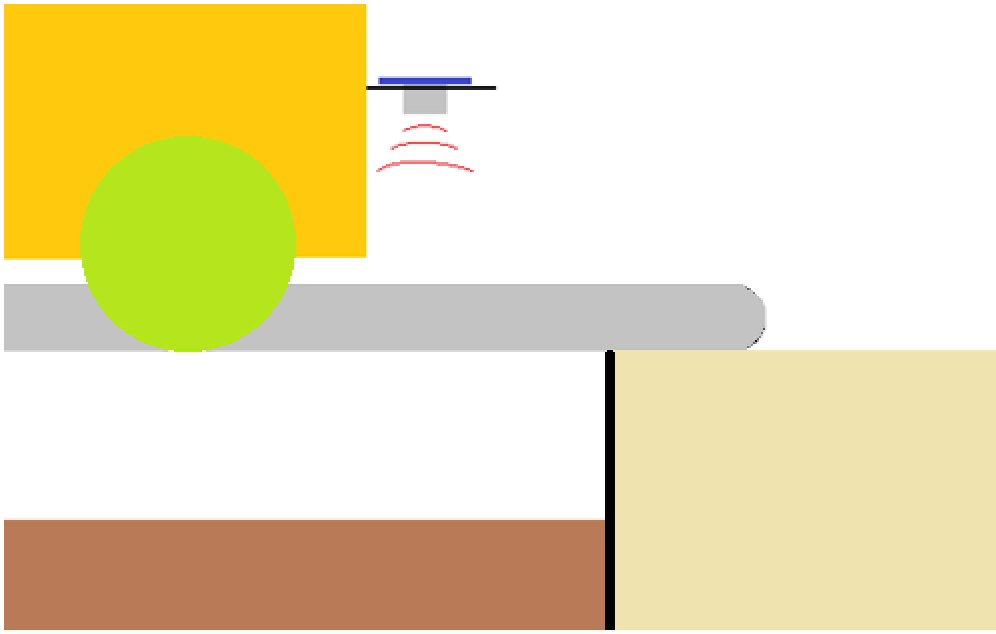


Figure 28: Illustration of the transition area. The figure shows a vehicle (the yellow chassis and the green wheels) on the (grey colored) rail moving backwards to the right towards the (beige colored) concrete path. The black line in the figure corresponds to the transition line.

Conclusion

In this chapter practical problems related to navigational properties in the greenhouse are mentioned. The effects of these problems are analysed and a solution is presented when needed.

First a function is developed that provides the steps of the motors for any desired movement. Now the vehicle could take fully advantage of its omnidirectional property. Furthermore, undesired effects arising due to the rounding errors are dealt with by avoiding movements that require the desired speed to be rounded to the nearest integer. The vehicle will not perform the desired movement, but will move to an alternative position and orientation. The larger the movement, the greater the error. An additional movement may be required if the error between the desired and performed movement is significant. Next, an Arduino board is used to start the motors simultaneously. By applying a signal on the digital inputs, the motors will be triggered at the same time and will move synchronously. Finally, an ultrasonic proximity sensor is added to the vehicle to detect the concrete path when riding off the rail.

The mentioned functions and additions in this chapter will improve the movement in the greenhouse significantly. The function for the omnidirectional movement and the ultrasonic proximity sensor increases the autonomous performance of the vehicle. The function for dealing with rounding errors and the trigger method increases the reliability and the robustness of the movement.

Chapter 6:

Path to Path movement

The purpose of the platform is to move the robot of the Tomation project in the greenhouse. It should move autonomously from the concrete path on the rail to cut the leaves of the tomato plants. Subsequently, after completing a row of cutting the leaves of the plants, the robot needs to get back on the concrete path again. Finally, the robot needs to move laterally to the following path. This whole movement will be a continuous process in the greenhouse, until the last path is processed.

This chapter discusses the path-to-path movement from the vehicle in the greenhouse. Important criteria that were taken into account for this movement are discussed. Possible methods for moving from path to path in a greenhouse are discussed. Decisions on the movement that are made to ensure the proper movement are argued and explained. Subsequently, the chosen alternative for the movement is presented comprehensively. Finally, the obtained results on the test for the path-to-path movement are presented and discussed.

Features of the movement

In the Tomation project the robot needs to move in a greenhouse autonomously. The movement should meet the requirements presented in chapter 2 and the important ones are listed below.

- The path to path movement should take less than 90 seconds.
- The vehicle should deal autonomously with the transition when riding on and driving off the rail.
- The accuracy of the translations and rotations should be less than 0.04 m and 5° respectively.
- The vehicle with the robot has a mass of approximately 350 kg that needs to be transported.
- Obstacles and cracks on the surface should be dealt with properly.

The experiments on the dynamics of Chapter 4 have shown that with the current platform a payload with a maximum weight of 328 kg can be transported with very low velocities. Hence, the requirement for the payload of the robot is left aside in this project. To achieve a movement with the required mass, the platform of the vehicle should be changed. To increase the maximum payload that can be transported with these motors, the pulleys of the motors may be changed or a gearbox may be added to the platform.

As discussed in chapter two the vehicle will move with mecanum wheels on the concrete path and with flanged wheels on the rail. The diameters of the mecanum wheel and the flanged wheel are 0.2032 m and 0.1035 m respectively. For a reliable movement the transition from the mecanum wheels to the flanged wheels and vice versa should be taken into account. The vehicle velocity should not be affected by the transition. This can be achieved by keeping the velocity of the vehicle constant during driving on and riding off the rail. Hence, the target speed of the motors on the rail should be 1.96 times the target speed on the concrete path. Figure 29 corresponds to the vehicle on the rail moving backwards towards the concrete path. The black vertical line in the figure corresponds to the place where transition occurs from the flanged wheels to the mecanum wheels and vice versa. This line is considered in this chapter as the transition line in the greenhouse.

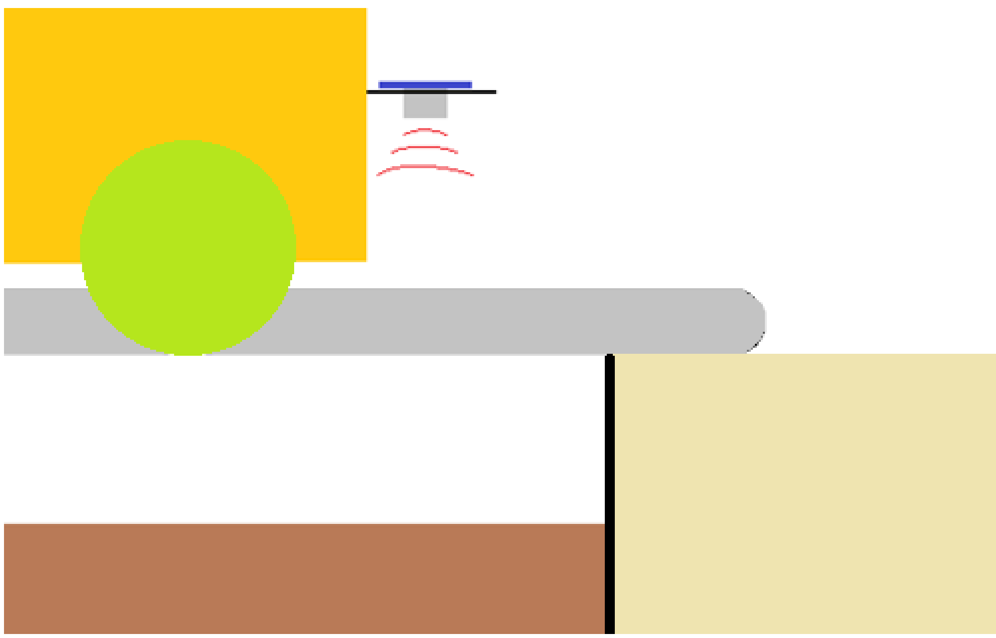


Figure 29: The vehicle (the yellow chassis and the green wheels) on the (grey colored) rail moving backwards to the right towards the (beige colored) concrete path. The black line in the figure corresponds to the transition line.

Riding off the rail backwards means that the back wheels will reach the concrete path first. Beyond the transition line, the back wheels should have decreased target speeds with the given ratio. Subsequently, the target speed of the front wheels should be decreased, after passing the transition line. Driving on the rail forwards will have a similar approach. The target speed of the front wheels should be increased after the transition line is passed. Subsequently, the speed of the back wheels should be increased. It is important for a robust and smooth movement that increasing and decreasing the speed will happen properly at the right time. If this does not happen correctly the front and back wheel will both provide different wheel velocities. This will cause that the motor will miss steps in the movements, which is undesired for having an accurate position system.

For a reliable and robust movement it is necessary that the motors perform the given steps correctly on the concrete path. Missing steps may lead to fatal situations in the project. In chapter 2 the closed loop mode in NanoPro was presented. Using the integrated closed loop mode the motors are capable of no longer loosing steps up to its maximum torque. A PID controller is used to damp the following error monitored with encoders. The closed loop increases the reliability and robustness of the movement as desired and is used in the path-to-path movement

The PID controller is tuned manually with the available scope in NanoPro. Figure 30 shows a screenshot of the scope in NanoPro during a movement in the closed loop mode. In this figure the red line corresponds to the desired target position with the given travel profile. The yellow line corresponds to the following error of the motor at that time instant between the desired and current position of the encoders. Observing the following error on the scope the parameters are tuned in such a way that this error is minimised.

Figure 30: Available scope of NanoPro. The red line is the target position of the motor and the yellow line is the following error at that time instant. Note that the scales for both lines are different.

Alternatives for the movements

Prior to the final choice of the preferred method on the path to path movement some possible methods were analysed to perform the movement. The starting position in all these situations is where the vehicle has finished cutting the leaves in a path and is ready to drive off the rail. The vehicle rides backwards off the rail, moves laterally to the next path and drives forward up on rail of the new path. As discussed before the vision system is used on the concrete path and the ultrasonic sensor on the rails to detect the transition line. Three possibilities are considered for the path to path movement. These methods are explained briefly without going into the details in the next paragraphs.

The first method divides riding off and driving up the rail each into separate motions. Riding off the rail starts by using the ultrasonic sensor to detect the concrete path when driving backwards. When the concrete path is detected, the vehicle will stop immediately. Next the front wheels will start moving backwards again and push the vehicle towards the concrete path. This will ensure a smooth transition from the rail to the concrete path, since the back wheels will rotate freely. When the vehicle is moved partially on the concrete path and the back wheels are located on the concrete path, it will stop. Finally when the back wheels are on the concrete path, the driving power of the motors of these wheels will be turned on and this will pull the vehicle entirely on the concrete path. Driving from the concrete path on the rail exhibits a similar approach. The vision system will measure the distance to the transition line. The vehicle will drive forwards towards the rail and stop when a specified safety distance is reached. In contrast with riding off the rail, the power of the motors of the back wheels will be turned on first and this will push the vehicle partially on the rail. The vehicle will stop when the front wheels have passed the transition line and are located on the rail. Finally, these front wheels will be powered to pull the vehicle entirely on the rail.

The second alternative differs from the first one, mainly by performing the movement without stopping the vehicle. When the ultrasonic sensor detects the concrete path, the driving power of the motors of the back wheels will be turned off. The vehicle will be pushed by the front wheels towards the concrete path. The driving power of the motors of the back wheels will be turned on again when these are on the concrete path with the adjusted lower velocity. The movement will proceed with all four wheels. When the front wheels are near the transition line, the motors of these wheels will be turned off. The back wheels will pull the vehicle entirely on the concrete path. Finally, the power of the motors of the front wheels will be turned on again after they are on the concrete path. Driving on the rail will be similar, but vice versa. Here the movement will be in the forward direction and the vision system will be used for detecting the transition line.

Finally, the last method will be a movement without turning off the power of a motor at all. The proximity sensor will be used again to perceive the transition line. The velocity of the back wheels will be decreased at the precise moment, when the wheels are passing the transition line. Subsequently, the velocity of the front wheels will be decreased, when they are passing the transition line. Using this principle all the wheels will contribute to the movement for riding off the rail. A similar approach will be used when driving in the forward direction on the rail. The vehicle will use the vision system for detecting the transition line.

To make a sound decision on the method of choice, the pros and cons of the movements will be discussed. The first alternative will not be performed with one movement, hence it will need more time with the same target speed compared to the other alternatives. Accelerating with two motors only to the target speed may cause difficulties for the motors in the needed force. Accelerating the vehicle with the payload of the robot with four motors will increase the robustness of the movement. For this reason the first movement will not be used for the project, even though it is the most simple to implement. The second alternative accelerates with all the motors, but uses just two of them in the transition area. The last alternative is using all motors during the whole motion. Hence, the last method will provide the most force coming from the motors for the movement. The last method desires a change in the velocity right at the moment when transition occurs. When this does not happen correctly at the right time instance, undesired effects will occur, like missing steps from the motor. So for practical reasons, the second alternative is used for ensuring a robust path-to-path movement. The comparison of this paragraph is summarized in Table 9 with plus and minus marks. It is shown that alternative 2 is overall the most appropriate method for the path-to-path movement.

Table 9: Comparison of the alternatives for the path-to-path movement.

	Alternative 1	Alternative 2	Alternative 3
Time	--	++	++
Req. power per motor	--	+	++
Practicability	++	++	--

The chosen path-to-path movement

In this subsection the chosen alternative for the path-to-path movement in the greenhouse is elaborated. The steps in the movement are explained in detail. The movement contains riding off the rail, moving lateral to the next path and driving on the rail. In the sequel of the report, turning on and off the power of the motor of a wheel is written as turning on and off the motor.

Riding off the rail

The starting position for this movement is on the rail. The ultrasonic proximity sensor starts measuring after the operations in the path are processed. The motors will rotate towards the concrete path with a relatively low frequency for a movement on the rail of 147 Hz. When the sensor detects the concrete path, the motors will immediately change its direction and move the vehicle 0.15 m back into the path again. This way the vehicle has enough space to accelerate with all the wheels before reaching the concrete path. A low velocity was preferred for the pre-movement, because the motors need to stop and change its direction immediately after the sensor detects the concrete path. The vehicle does not get on the concrete path yet, thus a low velocity is appropriate. The pre-movement is added to ensure reliable measurements and to increase the robustness during the transition.

The vehicle has moved 0.15 m back now into the path again, from the point where the concrete path is detected by the sensor. The current position of the encoders of the front wheel will be saved. Now the vehicle will start accelerating backwards towards the concrete path with all the motors having a target speed of 393 Hz. 393 Hz with the flanged wheels corresponds to 200 Hz with the mecanum wheels. The motors of the back wheels should be turned off just in front of the transition line. This is ensured by monitoring the value of the encoders. When the current position of the encoders reaches the number that corresponds to 0.10 m, the motors of the back wheels will be turned off. The front wheels will push the vehicle now partially on the concrete path.

The motors of the back wheels will be turned on again after the vehicle has moved 0.15 m further. This way, it can be said with certainty that the back wheels are on the concrete path. This will be measured using the encoders of the motors of the front wheels again. The motors of the back wheels will get a target speed of 200 Hz to have the same wheel velocity as the front wheels. The vehicle will move with all four motors partially on the concrete path and partially on the rail. The motors of the front wheels will be turned off and on in the same way. The motors will be turned off just in front of the transition area and turned on with a target speed of 200 Hz. right after the wheels are on the concrete path. Finally the vehicle will move with all the motors backwards to a safe position on the concrete path.

Lateral movement

The vehicle is now on the concrete path across the processed path and will perform a motion towards the next path. Before the motion will occur, the vision system will be used to provide the measurements on the old path. The new path may not be in the field of view of the cameras. It is firstly assumed that the new path is located at a distance of 1.6 m. from the current path. After driving laterally towards the next path, a function using new measurements of the vector Y_c from the vision system will decide whether a new movement is needed or not. This function will take all the inputs of the system into consider. Figure 31 will be used for deriving the function. With the specified margin from chapter 2 for driving on the rail, the following inequalities are derived.

$$\left| y_c - \left(\left(x_c - \frac{L}{2} \right) - b \right) \sin \alpha_c \right| < 0.04 \tag{23}$$
$$|\alpha_c| < 6°, \qquad x_c < 2 + \frac{L}{2}, \qquad |y_c| < 0.2$$

Parameter b that is taken as the distance that the rail is on the concrete path is measured and set at 0.15 m. The purpose of these inequalities is to ensure that a forward movement only is enough to get the vehicle on the rail. The first condition determines whether the vehicle will reach the rail by moving only forward. The other inequalities are required to give a boundary on the location of the vehicle. Conditions in a greenhouse like cracks may cause disturbances on the vehicle. To reduce the influence and effect of these disturbances, boundaries are applied to the inputs of the vision data, which the vehicle needs to meet before driving on the rail.

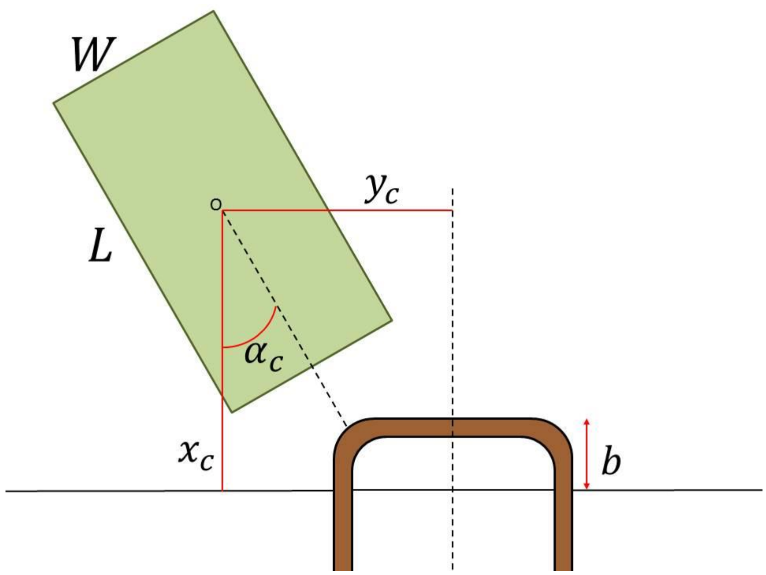


Figure 31: The sensory inputs coming from the vision system. The system measures the distance from the centre of the vehicle to the end of the concrete path (x_c), the distance to the heart line of the rail (y_c) and the angle that the vehicle makes with the distance line to the end of the concrete path (α_c).

If the above given conditions are not met, a new movement with the new inputs will be performed. The robot will try to reach the conditions up to 3 times. If the vehicle still does not meet the conditions, an error will be sent and the vehicle will stop. This is needed to avoid any risks that can damage the crop in the greenhouse.

Driving on the rail

The vehicle stands across the rail of the new path and is ready to drive on the rail. Since the conditions of the previous subsection are met, the vehicle is able to drive on the rail with a forward movement.

The vision system will be used to measure the distance to the transition line. The forward movement will start with all 4 motors accelerating towards a target speed of 200 Hz. Subsequently, the motors of the front wheels will be turned off 0.05 m before the transition line is reached. The back wheels will push the vehicle beyond the transition line. The motors of the front wheels will be turned on again 0.05 m after the transition line, with an increased target speed of 393 Hz. The vehicle will move then forwards partially on the rail and partially on the concrete path with all the motors. Next, the back wheels will be turned off again 0.05 m before they reach the transition line and turned on 0.05 after the line with the increased target speed. The vehicle will now be entirely on the rail and ready for the crop operations.

Experiment of the movement

In this subsection the experiment in the greenhouse is discussed. Additions to ensure a reliable and robust path to path movement are introduced. The results and outcomes of these experiments are presented.

All movements that are used for the path to path movement should take less than 90 seconds together. Since the vision system is not installed on the vehicle yet, the inputs from the vision system are entered manually when needed. The distances and the angle for the rotation are measured with a tape measure and a printed protractor.

Before we were able to experiment, the conditions for the ultrasonic sensor had to be measured. It is observed that an output around 0.10 m corresponds to the concrete path. The distance measured by the sensor to the floor on the rail was approximately 0.17 m in the greenhouse. After implementing this, the vehicle was brought to its starting position. This would be on the rail, with its rear towards the concrete path, on a distance between 0.10 m and 2 m from the concrete path. If the vehicle moves more than 2 meters before detecting the concrete path, the vehicle will be stopped. Before starting the movement the robot checks whether the sensor provides realistic values. An error is given if the sensor does not measure correctly and provides a distance beyond 0.20 m and 0.05 m.

The vehicle should be able to deal with obstacles and disturbances on the road. Since unexpected and undesired movements will occur when one of the motors will lag behind, a following error with a significant number of steps of is fatal. Using the closed loop mode it is ensured, that the movement will stop, after one of the motors exceeds a specified following error with its target position at that time instant. The number of the maximum allowed following error is set at 50 steps. This corresponds to a movement of 0.05 m with the mecanum wheels. Since accurate positioning for this project is necessary, a bigger accepted following error may cause danger for the crop in the greenhouse.

Experiments have shown that the closed loop mode is not applicable for the movement on the rail. This is caused due to the Back Electromotive Force (Back EMF) on DC motors The Back EMF is the voltage caused by a magnetic induction that works against the current which induces it. If there is motion in the motor, a voltage will be generated from the magnetic field in the motor. The polarity of this voltage generated by the motors will always be the opposite of the input voltage present in the motor. The law of Faraday tells that this voltage will be proportional to the magnetic field, length of wire and the speed. Because of the opposite polarity of the Back EMF, the net voltage that drives the current in the circuit will be lower than the input voltage. Using Ohm´s law, it can be determined that the overall current flowing through windings will be lowered with Back EMF. Since current generates heat, Back EMF is an additional advantage of DC motors. The Back EMF also has negative effects on the situation. When the motor needs to stop, the direction of current running through the coils is reversed. Since the motor is still running in the same direction because of its inertia, the direction of the voltage generated by the motor does also not change. Hence, it will have the same polarity as the motor supply when decelerating. In this case the Back EMF is added to the input voltage. The high requirements on the velocity and payload of the vehicle causes that with this Back EMF, the voltage exceeds the safety limit of the supply. Hence, the closed loop mode is only applied for the lateral movement.

The problem that occurred with the back EMF is a well-known phenomenon in the electronics. A common solution to this problem is by adding a braking unit resistor. The braking resistor is switched on when the voltage exceeds a specified voltage. The surplus energy caused by the back EMF will be absorbed by the resistive load into the motor circuit. It converts the energy into heat and at the same time a braking effect is created [13]. Another solution for this problem is placing a Transient-Voltage-Suppression (TVS) diode. The TVS diode is a device to protect circuits from voltage transients [14]. It is designed to clamp a transient-surge voltage. A braking unit resistor is used for relatively big applications and it is an expensive device. Applications in the industry using a braking unit are cranes and elevators. A TVS is in contrast a small and low-cost device. For the commercial purposes of the Tomation Project, a TVS is more suitable to apply in future work.

The experiments performed in the greenhouse are listed below

- Riding off the rail
- Lateral movement of 1.6 m. in the closed loop mode
- Driving on the rail
- Testing the margins for driving on the rail
- Movements with obstacles or cracks on the road
- Performing omnidirectional movements

The experiments in the greenhouse have shown that the vehicle is able to move smoothly from path to path. The required accuracy was achieved with good results. The travelled distance of the lateral movement was measured as 1.6 m as desired. The manual entered values for the vision system were correctly entered and the vehicle moved properly to the desired positions. When the rails of the paths are shifted and the distance of the centre line is not equal to 1.6 m, the function containing equation (23) determined that a new movement was needed before driving on the rail. No additional movements were required for getting across the rail, when the centre lines of the two paths were at a distance of 1.6 m. The time required to perform the total movement was 77 seconds. Hence, the movement was a reliable and robust movement meeting the specified criterion.

The closed loop mode in NanoPro ensured that the vehicle dealt properly with cracks or obstacles on the road. If these affected the movement significantly, the closed loop mode would detect the following errors exceeding the specified limit and the vehicle would be stopped. Testing an omnidirectional movement is performed by first performing a lateral translation, a forward translation and a rotation one after another. Finally, the reverse of these three movements are all performed at once. The vehicle was returned back to its initial position with just one movement. Hence, the omnidirectional movement with the vehicle was realised.

Summary

This chapter has dealt with ensuring the path to path movement in the greenhouse. The movement is split into three separate movements: riding off the rail, moving across the next path and driving on the rail of the new path. After analysing alternatives for these movements, it has been decided that the vehicle will move with two motors near the transition line and else with four motors.

Errors from the proximity sensor are dealt with by only accepting realistic values, which are specified for the environment in the greenhouse. The movement did not start when the provided distance gave unrealistic values. The closed loop mode was activated for dealing with obstacles or undesired cracks on the surface. The following error was monitored and used to stop the movement when the error exceeded a given number of steps. The experiments have shown that the required vehicle velocity on the rail caused, that the closed loop mode was not applicable here. When decelerating, the generated back EMF will be added to the voltage of the power supply and exceeds the safety limit. Hence, the closed loop mode was used during the lateral movement only.

Chapter 7:

Conclusion

In this report a research has been presented concerning the Tomation Project of Priva B.V. This research was aimed at solving the problem of autonomous movement of the leaf-cutting robot for a greenhouse. The main goal of this project was to develop a robust control system for the movement of the vehicle that ensures a reliable movement in the required directions. The vehicle uses mecanum wheels to move laterally from path to path and the flanged wheels to move on the rail. The vehicle encounters difficulties driving sideways at a critical weight on the platform. Undesired and unpredicted movement occurred at these weights, because the stepper motor is not able to perform all the steps.

With this research the path-to-path movement of the vehicle is realized in a reliable way, provided that the motors are strong enough to deliver the required force for the movements. The current setup is not able to move the vehicle sideways with the specified payload and the required velocities. If we disregard the payload of the robot, the remaining conditions do meet the requirements of the movement. The movement occurred within 77 seconds and a good accuracy was achieved with an error that was not even measurable with a tape-measure.

The following results and conclusions were used to achieve a proper movement.

- With a comprehensive research on the kinematics of mecanum wheels, a new kinematic model is implemented for omnidirectional movement without positioning errors
- The misconception in the literature is explained and a new dynamic model is implemented.
- An analysis on the rollers has shown that the contribution of the rollers increases as the movement gets more horizontal. This concludes that more force is needed for a lateral movement because it is more affected by friction in the bearings.

Literature research on the mecanum wheels has been performed in a separate literature study. The kinematic model described in the literature was presented here. This model was developed for the ideal case. Some practical points were not considered by the authors. Repetitive errors between the dead – reckoning position and the actual measured position occurred during the movements.

The position errors were provided by slippage, bearing friction and point contact friction. A new model is built that considers these error sources and deals with the position errors. This new model contains parameters that were identified with experiments before using the model. By performing simple movements and measuring the travelled distances the values of the parameters were found and implemented in the new model. A comprehensive research on the rollers of the wheels during omnidirectional movements is performed to understand the motion of the rollers. Analyses have shown that as the movement with the vehicle gets more lateral, the rollers of the wheel will contribute more to the movement. This is also verified by observing the rollers during movements of the vehicle. These observations and analyses on the rollers of the wheel are used to explain the dynamics of the wheels.

The dynamic model from the literature was also presented in the separate study. However, experiments and observations have shown important misconceptions of the dynamics in the literature. The free-body-diagram covered in the literature was based on these misconceptions. The authors neglect the force perpendicular to the rollers without a proper reasoning. With observations and analyses on the motion of these wheels a new model of the free-body-diagram has been developed for the mecanum wheels. This new model takes the friction experienced in the rollers of the wheel into account, which has a significant impact on the motion of the vehicle. This model was used to explain the difference between the required force for the forward and lateral movement. It is concluded that as the movement gets more lateral, the rollers will have more contribution, so the movement needs higher torque from the motors.

The working principles of the motors that drive the mecanum wheels are studied. This helped us explaining the observations with the movement and the behaviour of the stepper motor. It is shown that the closed-loop mode of the software is not applicable during the movement on the rail with the chosen setup. The relatively high velocity of the requirements and the given mass of the robot causes that the Back EMF added to the power supply of the motor when decelerating, exceeds the safety limit of the motor power supply.

Investigating the possibilities of the motors and its SDK has shown practical limitations in controlling these motors. The API requires an integer value for the target speed of the motor. As driving the platform in different angles theoretically requires floating point precision in the driving speed the integer input was one of the limitations that needed to be taken into account. The importance of this limitation and the necessity of a solution to this problem were shown with an example of a movement. A significant difference may occur between the travel times of the wheels if no measures are taken for this problem. A function is developed for this problem that modifies the entered desired movement into the nearest practical movement with integer target speeds. Another limitation of the setup with these motors is the delay that occurs with the RS-485 connection. An asynchronous movement occurs when controlling these motors. The available hardware of the motor was used to deal with this problem. When the motors are ready for the next movement, a signal via the Arduino board to the digital inputs is generated to start the movements of all the wheels synchronously.

These developed models and functions were necessary items in ensuring a robust and reliable movement of the vehicle with mecanum wheels. Using the manually entered values of the vision system and the added proximity sensor a reliable path to path movement was realised in this project. The effects of disturbances and obstructions on the concrete path are taken into account with the available closed loop mode of NanoPro.

Future work

A major contribution to the Tomation Project would be adding a position measurement system to locate the vehicle in the greenhouse properly. This way the vehicle can handle disturbances on the movement autonomously. By measuring its position, it will be able to determine whether the movement undergoes any risks for the crops in the greenhouse. The position measurement system can also be used to locate the transition line, when it is outside the field of the vision system. Since the greenhouse has a fixed environment, adding a map of the greenhouse to the motor can ease up the localization process.

The absence of the vision system was a significant limitation for the project. We were not able to obtain measurements in real-time. Hence, real-time control was not feasible without the vision system. After installing and implementing the vision system on the vehicle, the reliability of the movement will highly increase. Real-time measurements with the vision system will ensure a smoother movement. If the rail on the paths is shifted significantly, the current approach deals with this problem with a second or maybe third movement. However, with real-time measurements this can be performed at once. The feedback from the vision system in real-time would provide the covered distance and the required distance at each time sample to ensure that the vehicle would come across the rail at once.

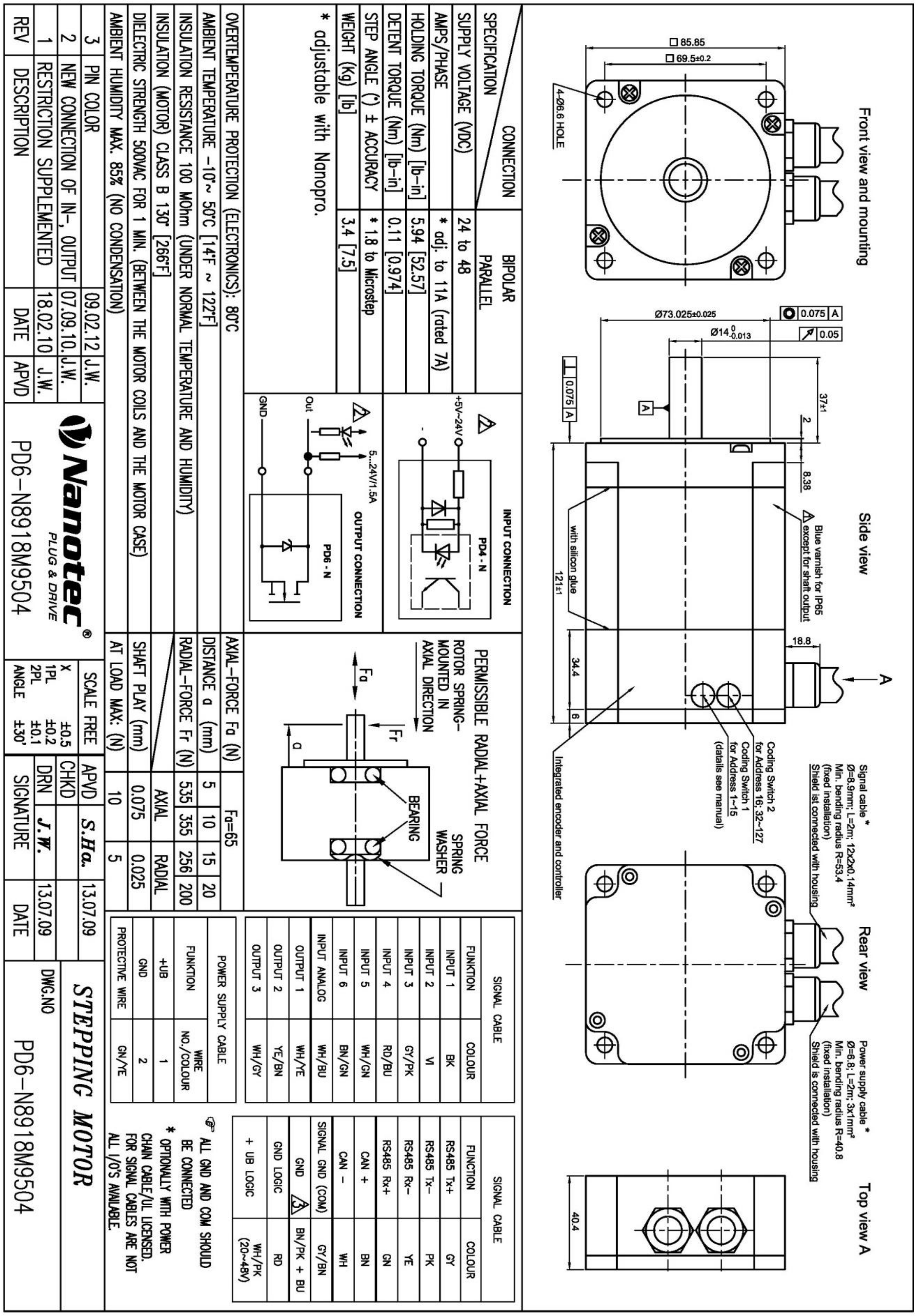
The current platform was not able to move the vehicle sideways with the required payload. The torque generated by the motors was not enough to overcome the friction. To increase the maximum payload that can be transported with these motors, the pulleys of the motors can be changed or a gearbox can be added to the platform.

The closed loop mode in NanoPro increases the robustness of the movement. Hence, implementing this mode during all movements of the vehicle in the greenhouse is desirable for the project. It is shown that this mode is not applicable with the requirements, when driving on the rail. The overvoltage generated by the back EMF exceeds the safety limit of the motor supply. Adding a transient-voltage-suppression diode, introduced in Chapter 6, to the setup will protect the circuit by suppressing overvoltage. In this way the closed loop mode can be applied to the motor even at high velocities and high payloads.

A final interesting point for future work is a more comprehensive research on friction in mecanum wheels. It is found in this research which role the rollers have in the dynamic model of the vehicle. However, the relation between the needed forces, that increases as the movement gets horizontal, is not linear. Hence, a model that describes the friction on the wheels properly may have a significant contribution in this field.

Appendix

Appendix A: Schematics Nanotec PD6-N8918



Appendix B: Matlab codes for the path-to-path movement

Position

This function determines the needed steps per motor for the desired translations and rotation.

```
function setpoint=position(x,y,rot)
%position Determines the angular displacements for each wheel with the
given desired
%position and orientation
if nargin==3
    pos=[x,y,rot];
elseif nargin==1 && length(x)==3
        pos=[x(1),x(2),x(3)];
else
    disp('Error: wrong input')
    return
end



R=8*0.0254/2;
L=1.40/2; %half of distance from wheel to wheel in length direction
W=0.72/2; %half of distance from wheel to wheel in width direction
d=1.00516; %experimental
e=0.954402; %experimental
f=0.970593; %experimental
t=sym('t');
theta1=sym('theta1');
theta2=sym('theta2');
theta3=sym('theta3');
theta4=sym('theta4');



% equations of motion for a movement with mecanum wheels
A=d/4*R*[sqrt(2)*sin(t*pos(3)+pi/4) sqrt(2)*cos(t*pos(3)+pi/4) ...
    sqrt(2)*cos(t*pos(3)+pi/4) sqrt(2)*sin(t*pos(3)+pi/4);
    e*[sqrt(2)*cos(t*pos(3)+pi/4) -sqrt(2)*sin(t*pos(3)+pi/4) ...
    -sqrt(2)*sin(t*pos(3)+pi/4) sqrt(2)*cos(t*pos(3)+pi/4)];
    f*[-1/(L+W) 1/(L+W) -1/(L+W) 1/(L+W)]];


theta_w=[theta1;theta2;theta3;theta4];

dfdt=A*theta_w; %% velocities in a local orientation

F=int(dfdt,t,0,1); %positions t.o.v. de rotatie wielen
BT4=solve(F-pos'==0); % Berekening voor welke rotatie nodig is voor deze
beweging
%3x4 matrix dus ze zijn afhankelijk van theta_4
DT4=[BT4.theta1;BT4.theta2;BT4.theta3;theta4];


L=sym('L');W=sym('W');R=sym('R');a_r=sym('a_r');a_x=sym('a_x');a_z=sym('
a_z');
```

```
matA=R*a_x/4*[1 1 1 1; a_r -a_r -a_r a_r; -a_z/(L+W) a_z/(L+W) -
a_z/(L+W) a_z/(L+W)];
matB=pinv(matA);
parameters=[R,L,W,a_x,a_r,a_z];
a=8*0.0254/2;
b=1.40/2;
c=0.72/2;
new=[a,b,c,d,e,f];
clear a b c d e f
matA=double(subs(matA,parameters,new));
matC=double(subs(matB,parameters,new));
T=matC*matA*DT4;
DT4new=solve(DT4(2)-T(2)==0);
D=double(subs(DT4,theta4,DT4new));
setpoint=round(D*48/26/(2*pi)*400);
end
```

Similarmov

This function determines the most suited alternative movement without any rounding errors.

```
function
[new_coor,new_vel,new_set,old_coor,old_vel,old_set]=similarmov(speed,a,b
,c,d)

%% determine coordinates and setpoints of given input
if nargin==5
    D=[a;b;c;d];
    x=velocities(D);
elseif nargin==2
    if length(a)==4
        D=[a(1),a(2),a(3),a(4)];
        x=velocities(D);
    elseif length(a)==3;
        x=[a(1);a(2);a(3)];
        D=position(x);
    end
elseif nargin==4
    x=[a;b;c];
    D=position(x);
else
    disp('Error: wrong input')
    return
end
setpoint=round(D*48/26/(2*pi)*400);

%% Searching the best possible movement
% If there is a difference in time between the real and ideal case,
other
% possible movements will be searched for. The closes movement will be
% chosen as replacement

[T_r,T_i]=checkdifference(speed,D);
if all(setpoint)==0
    new_set=setpoint;
    new_coor=x;
```

```
    new_vel=D;
    old_coor=x;
    old_vel=D;
    old_set=setpoint;
    disp('not modified')
elseif all(round(T_i*10e5)==round(T_i(1)*10e5))==0
    keyboard
else

    %keyboard
    if find(~(T_r==T_i))
        Gold=pos_motions(setpoint,speed); %The ang. vel. of the possible
motions
        [~,N]=size(Gold);
        k=1;

        for i=1:N
            if find((sign(Gold(:,i)).*sign(setpoint))==-1)
            else
                Gold2(:,k)=Gold(:,i);
                k=k+1;
            end
        end
        N=k-1;

        j=1;
        for i=1:k-1
            if all(abs(Gold2(:,i))*1.5<abs(D)) ||
all(abs(Gold2(:,i))*1/1.5>abs(D)) || all(abs(Gold2(:,i)-(D))<10)
                Gnew(:,j)=Gold2(:,i);
                j=j+1;
            end
        end
        size(Gnew);
        for i=1:j-1
            P(:,i)=velocities(Gnew(:,i)); %The positions with the given
ang. vel.
        end
        M=zeros(size(P));
        for i=1:j-1
            M(:,i)=P(:,i)-x;
        end
        [~,Imin]=min(sum(M.^2)); %Find the best suited point

        %solutions
        new_coor=P(:,Imin);
        new_vel=position(new_coor);
        new_set=round(new_vel*48/26/(2*pi)*400);
        old_coor=x;
        old_vel=D;
        old_set=setpoint;
        disp('modified')
    else
        new_set=setpoint;
        new_coor=x;
        new_vel=D;
        old_coor=x;
```

```
        old_vel=D;
        old_set=setpoint;
        disp('not modified')

    end
    % max(abs(old_set))/max(abs(new_set))
    % max(abs(old_set))-max(abs(new_set))
    % abs(new_set)
end
end
```

Pos_motions

This function lists the alternative movements without any rounding errors

```
function [G]=pos_motions(setpoint,speed)
%pos_motions gives all the possible similar motions with the given
setpoint
%and the used speed.

%% %% Determine the forwards and iverse kinematics
L=sym('L');W=sym('W');R=sym('R');a_r=sym('a_r');a_x=sym('a_x');a_z=sym('
a_z');
matA=R*a_x/4*[1 1 1 1; a_r -a_r -a_r a_r; -a_z/(L+W) a_z/(L+W) -
a_z/(L+W) a_z/(L+W)];
parameters=[R,L,W,a_x,a_r,a_z];
par.a=8*0.0254/2;
par.b=1.40/2;
par.c=0.72/2;
par.d=1.00516;
par.e=0.954402;
par.f=0.970593;
new=[par.a,par.b,par.c,par.d,par.e,par.f];

matC=double(subs(pinv(matA),parameters,new));
matA=double(subs(matA,parameters,new));
clear a b c d e f new L R W a_r a_x a_z parameters
%%
% The condition for a successful movement is when you can make sure that
% the ratmax(=a setpoint divided by the biggest setpoint) times the
given
% speed will be an integer. In this algorithm the biggest setpoint will
be
% a variable in a set around the biggest setpoint. All possible
setpoints
% for the variable that ensure that the condition for a successful
movement
% will be achieved are listed. From that list each setpoint will pick
out
% the 5 closest points to that point. These points will together create
a
% 4x5 matrix. From these matrix all possible movements will be picked
out
% and checked whether the motion is a realistic motion or not. Then all
% realistic motions will go through the function.


[~,U]=max(abs(setpoint)); % find the biggest setpoint
```

```
F=setpoint(U)-
floor(abs(0.006*setpoint(U))):setpoint(U)+ceil(abs(0.006*setpoint(U)));
% create a set around the maximum setpoint
Q1=[];
for m=1:length(F) % for each value in this set
    G=[];
    B=[];
    j=1;
    CC=[];
    %% search for every setpoint that will give an integer value for
ratmax*speed
    %keyboard
    if F(m)>0
        if abs(min(setpoint)-20)>F(m)
            add_val=abs(min(setpoint)-20)-F(m);
        else
            add_val=0;
        end
        for i=min(setpoint)-20+add_val:F(m)
            if rem(i*speed,F(m))==0
                B(j)=i;
                B(j+1)=-i;
                j=j+2;
            end
        end
    elseif F(m)<0
        if (max(setpoint)+20)<F(m)
            add_val=F(m)-(max(setpoint)+20);
        else
            add_val=0;
        end
        for i=F(m):max(setpoint)+20+add_val
            if rem(i*speed,F(m))==0
                B(j)=i;
                B(j+1)=-i;
                j=j+2;
            end
        end
    elseif setpoint(1)==0 && setpoint(2)==0 && setpoint(3)==0 &&
setpoint(4)==0
        G=[0;0;0;0];
    else
        keyboard
    end
    BB=sort(unique(B','rows'));

    %%
    % if you have enough setpoints, find the closest 5 points to all the
    % original setpoints and list them in a matrix CC. If you don't have
    % enough values, then take them all.
    if length(BB)<5
        CC=[BB BB BB BB];
    else

        for o=1:4
            [~,I_closest] = min(abs(BB-setpoint(o)));
```

```
            if I_closest>2 && I_closest<length(BB)-1
                CC(:,o)=BB(I_closest-2:I_closest+2);
            elseif I_closest>2
                CC(:,o)=BB(end-4:end);
            elseif I_closest<length(BB)-1
                CC(:,o)=BB(1:5);
            end
        end
    end

    AA=round(CC*100000/(48/26/(2*pi)*400))/100000; % give the angular
velocities of these sets from the matrix CC
    S=round(F(m)*100000/(48/26/(2*pi)*400))/100000; % give the angular
velocities of your chosen maximum setpoint F(m)

    [a,~]=size(AA);
    ang_vel=ones(4,1);
    k=1;

    %% search all possible motions with the given max motion
    for i=1:a
        for ii=1:a
            for iii=1:a
                for iiii=1:a
                    switch U
                        case 1
                            ang_vel(1)=S;
                            ang_vel(2)=AA(ii,2);
                            ang_vel(3)=AA(iii,3);
                            ang_vel(4)=AA(iiii,4);
                        case 2
                            ang_vel(1)=AA(i,1);
                            ang_vel(2)=S;
                            ang_vel(3)=AA(iii,3);
                            ang_vel(4)=AA(iiii,4);
                        case 3
                            ang_vel(1)=AA(i,1);
                            ang_vel(2)=AA(ii,2);
                            ang_vel(3)=S;
                            ang_vel(4)=AA(iiii,4);
                        case 4
                            ang_vel(1)=AA(i,1);
                            ang_vel(2)=AA(ii,2);
                            ang_vel(3)=AA(iii,3);
                            ang_vel(4)=S;
                    end
                    x=matA*ang_vel;
                    D=matC*x;
                    %check if it a realistic ang_vel, if it is, you can
                    %take the value as a possible motion
                    if round(D*10e5)==round(ang_vel*10e5)
                        G(:,k)=ang_vel;
                        [T_r,T_i]=checkdifference(speed,ang_vel);
                        if find((T_r-T_i)>1e-10)
                            if isnan(T_r(1))&& isnan(T_r(2)) &&
isnan(T_r(3)) && isnan(T_r(4))
                            else
```

```
                                keyboard
                            end
                        end
                        k=k+1;
                    end
                end
            end
        end
    end
    clear i ii iii iiii k j x D T_r T_i

    Q1=[Q1 G];

end
%G=unique(G','rows')';
G=unique(Q1','rows')';
end
```

Global_search

This optimization file is used in combination with the optisimilarmov-function to find the chosen alternative movement with the biggest errors.

```
gs=GlobalSearch;
Problem=createOptimProblem('fmincon','x0',[1;-
1;1],'objective',@optisimilarmov,'lb',[-2;-2;-2],'ub',[2;2;2]);
[x,fval,exitflag,output,solutions] = run(gs,Problem);

function f= optisimilarmov( pos1 )
%optisimilarmov determines the least square error of the new and old
%coordionations
pos=[pos1;0];
[new_coor,~,~,old_coor,~,~]=similarmov(200,pos);
f=-(new_coor-old_coor)'*(new_coor-old_coor);
```

Appendix C: Arduino codes for the path-to-path movement

The Arduino file used for the ultrasonic sensor and the trigger to the digital inputs of the motors:

```
/*
 VCC to Arduino 5v GND to Arduino GND
 Echo to Arduino pin 13 Trig to Arduino pin 12
 */

#define trigPin2 2
#define echoPin13 13
#define trigPin7 7
#define echoPin5 5

//initializing variables
int mode = -1;

void setup()
{
  //initialize serial communications at 9600 bps:
  Serial.begin(9600);
  Serial.setTimeout(20000);
  pinMode(trigPin2, OUTPUT);
  pinMode(echoPin13, OUTPUT);
  pinMode(trigPin7, OUTPUT);
  pinMode(echoPin5, INPUT);
  digitalWrite(trigPin2,LOW);

  //check serial communication - acknowledgement routine
  Serial.println('a'); //sending a character to PC
  char a='b';
  while(a != 'a')
  {
    //wait for a specific character from the PC
   a=Serial.read();
  }
}

void loop() {
  if (Serial.available() > 0 ) //check if any data has been sent by the PC
  {
    mode = Serial.read();  //check if there is a request for distance values
    switch (mode) //used to set different modes for various operations. I is used to read IR distance
values
    {
       case 'T':// Trigger
       digitalWrite(trigPin2, HIGH);
       digitalWrite(echoPin13,HIGH);
       delay(1000);
       digitalWrite(trigPin2, LOW);
       digitalWrite(echoPin13,LOW);
       Serial.println(1); //Out Trigger
```

```
      break;

      case 'D':// distance sensor
       int duration, distance;
       digitalWrite(trigPin7, HIGH);
       delayMicroseconds(1000);
       digitalWrite(trigPin7, LOW);
       duration = pulseIn(echoPin5, HIGH);
       distance = (duration/2)/29.1;
       Serial.println(distance);


      break;


      //default:
       //digitalWrite(trigPin2,LOW);
       //Serial.println(0);  //No Trigger

    }
    //wait 2 milliseconds before next loop for the analog-to-digital converter to settle after last
reading:
    delay(20);
  }
}
```

Appendix D: Datasheets HC – SR04

The datasheets of the ultrasonic proximity sensor HC – SR04 [12]

Ultrasonic ranging module : HC-SR04

Specifications:

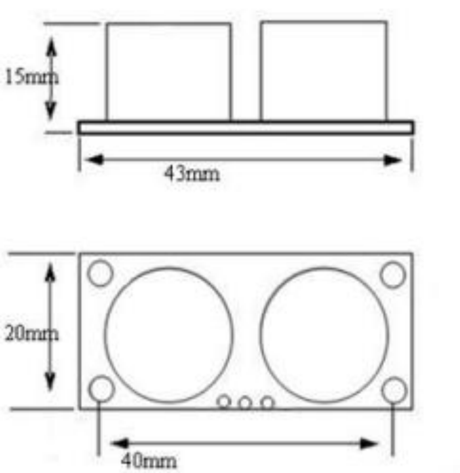
power supply :5V DC

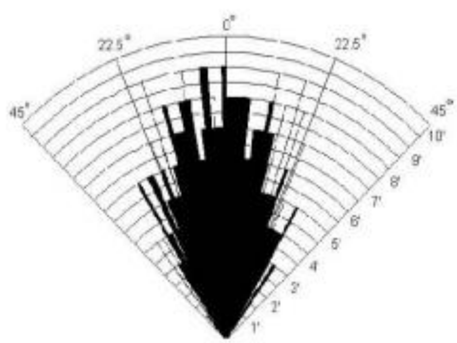
quiescent current : <2mA

effectual angle: <15°

ranging distance : 2cm – 500 cm

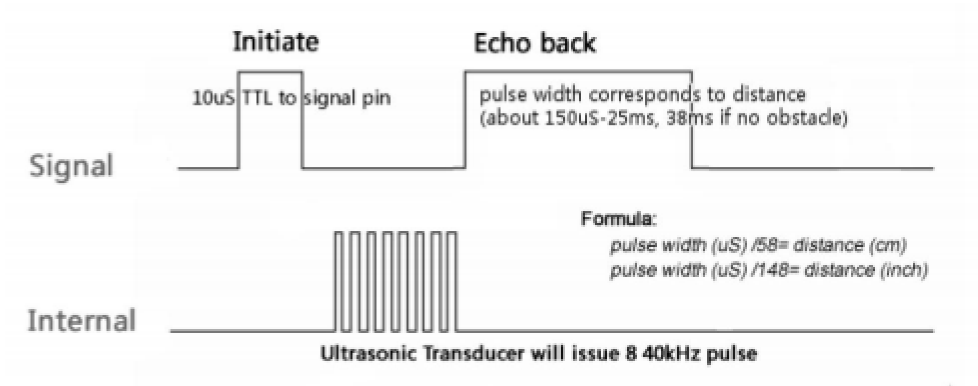
resolution : 0.3 cm





Practical test of performance,
Best in 30 degree angle

Sequence chart



A short ultrasonic pulse is transmitted at the time 0, reflected by an object. The senor receives this signal and converts it to an electric signal. The next pulse can be transmitted when the echo is faded away. This time period is called cycle period. The recommend cycle period should be no less than 50ms. If a 10μs width trigger pulse is sent to the signal pin, the Ultrasonic module will output eight 40kHz ultrasonic signal and detect the echo back. The measured distance is proportional to the echo pulse width and can be calculated by the formula above. If no obstacle is detected, the output pin will give a 38ms high level signal.

Library:
http://iteadstudio.com/store/images/produce/Robot/HCSR04/Ultrasonic.rar

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Glossary

List of Acronyms

API	Application Programming Interface
COM	Component Object Model
SDK	Software Development Kit

List of symbols

Υ_c	The vector with the inputs provided by the vision system containing x_c, y_c and α_c
x_c	The distance from the centre of the vehicle to the end of the concrete path in [m]
y_c	The distance from the centre of the vehicle to the centre line of the rail in [m]
α_c	The angle that the vehicle has with the distance line to the end of the concrete path in [rad]
P_c	The vector with the inputs provided by the vision system converted to the translations and rotation in the global frame.
P_{des}	The vector with the desired translations and rotation in the global frame.
Δn_{mi}	The number of steps for motor i.
Δn_{ei}	The position of the encoder of motor i.
W	The width of the vehicle with the mecanum wheels in [m]
L	The length of the vehicle with the mecanum wheels in [m]
W_w	The distance between the wheel and the centre of gravity of the vehicle in width direction in [m]
L_w	The distance between the wheel and the centre of gravity of the vehicle in length direction [m]
R_w	The radius of the mecanum wheel in [m]
R_r	The radius of the rollers of the mecanum wheel in [m]
ω_w	The angular velocity of the wheel in [rad/s]
ω_r	The angular velocity of the roller of the wheel in [rad/s]