Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 50-1 (2017) 4588–4593

Thorvald II - a Modular and Re-configurable Agricultural Robot

Lars Grimstad and Pål Johan From

Department of Mathematical Sciences ant Technology,
Norwegian University of Life Sciences, Ås, Norway.
(e-mail: larg@nmbu.no, pafr@nmbu.no)

Abstract: This paper presents Thorvald II, a modular, highly re-configurable, all-weather mobile robot intended for applications in the agricultural domain. Researchers working with mobile agricultural robots tend to work in a wide variety of environments such as open fields, greenhouses, and polytunnels. Until now agricultural robots have been designed to operate in only one type of environment, with no or limited possibilities for customization. Thorvald II is a new module-based robot design that allows for vastly different robots to be built using the same basic modules, and rebuilt using only basic hand tools. The modules are designed to enable high quality robots that can quickly be customized for a given application in a given environment.

Keywords: Agricultural robots, Field robotics, Mobile robots, Robotics technology, Agriculture

1. INTRODUCTION

When modern tractors and other farm machines drive across farm fields, they damage the soil structure and cause what is known as soil compaction. This widespread problem leads to lower yields and flooded fields (Batey (2009); Nawaz et al. (2013)). If tractors are to be made smaller and lighter so that they do not harm the soil, productivity per unit will drop, and therefore more tractors will be needed to cover the same area compared to operations using conventional tractors. This is not a viable solution as it will be too costly for the farmer to have a driver for every single tractor. Another solution that is made possible with the introduction of autonomous systems may be to replace each heavy tractor with several light-weight, autonomous robots. Every farm will then have a swarm of self-driving robots that can work day and night without causing damage to the soil. Before this becomes a reality, there is a wide variety of problems related to safe and robust autonomous operation that need to be solved. For this purpose, mobile research robots are required.

Many interesting and impressive agricultural robot designs have emerged over the last few years. Some robots are based on conventional tractors like the APU by Oksanen (2015), but there are also several new, light-weight robot designs that have appeared over the last few years. Many of these robots can be equipped with exchangeable tools or implements like a conventional tractor, but as they have lower mass, they will not harm the soil. Examples of these robots are the tracked Robotti by Green et al. (2014), the four wheel drive, four wheel steering Bonirob (V2) by Bangert et al. (2013) and RIPPA by the Australian Centre for Field Robotics (ACFR), University of Sydney, Australia, and the differential drive AgBot II by Bawden et al. (2014) at Queensland University of Technology, Australia. Other robots are more specialized towards one specific task, one example is the SW 6010 by Agrobot, which is a semi-automatic robot for harvesting strawberries. Robots can also be applicable in tasks normally not associated with machines, like the SwagBot developed at the ACFR which can herd and monitor cattle. Furthermore, robots have also been developed for use indoors in greenhouses. One example is the fully automatic S55 spray robot by Wanjet, Sweden.

What is common for all the robots above is their fairly fixed physical appearance. It is important to note that some robots have the ability to modify certain parameters. The BoniRob (V2) is, for example, capable of changing its track-width. This can be useful for researchers working with different track-widths on different research projects, or for adapting to narrow farm roads. However, there are (to the author's knowledge) no robotic system that allows for custom built, re-configurable agricultural robots.

Fig. 1. The standard configuration of the Thorvald II robot

2405-8963 © 2017, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.08.1005

While working with Thorvald I (Grimstad et al. (2015a), Grimstad et al. (2015b)) in the field, the authors have experienced the limitations imposed by the robot's fairly fixed configuration. Although the track width can be changed by replacing only one single part, namely the front frame beam, the process of changing other parameters is more complicated or time consuming. Rebuilding the four-wheel drive, four-wheel steering robot into a differential drive version with passive caster wheels would require a considerable amount of work. New parts would have to be designed and manufactured, and fitting the new parts to the robot would take time and require the use of advanced tools. The lack of adaptability and the fact that these limitations apply to all current agricultural robots was the motivation behind the modular, re-configurable Thorvald II platform.

With the system presented in this paper, it is possible to create an array of different all-weather robots using the same basic modules and only basic hand tools. A robot that is configured for working outdoors, driving in wide tractor tracks, can easily be reconfigured to be used in narrow rows inside a greenhouse. A four wheel drive, four-wheel steering robot can be rebuilt into a differential drive robot (with caster wheels at the front or at the rear) by changing two of the active drive modules for passive wheel modules. Furthermore, a four-wheel version can easily be rebuilt to one or more three-wheeled robots.

The idea of the system is to contain all complex and costly parts inside modules, and that these modules do not require any modifications when re-configuring the robot. Changing the robots size is a matter of cutting aluminum tubes into the appropriate length for a given application, and then clamping the modules to these tubes. Rewiring is not necessary, and excessive cables can be stored inside the modules.

The paper is organized as follows: In Section 2 we present a concept overview where the robotic system is described. This is followed by a more detailed description of the different robot modules in Section 3. In Section 4 we argue for the practical need for the presented system by looking at different applications in different environment which the robot has been and will be working in. Finally we conclude the paper in Section 5.

2. CONCEPT OVERVIEW

The robotic system presented uses a re-configurable aluminum frame and different modules to create robots of different sizes and with different properties. Rebuilding the robot is quick and easy, and can in many cases be done in matter of minutes.

The standard configuration of the robot has four-wheel drive and four-wheel steering with passive suspension to ensure good traction in rough terrain. It has a track width of 1.5 meters, a mass of <200 kg and a low center of gravity. The robot has a large internal workspace that can be used to mount different tools for different applications and it can carry a payload of 200 kg. The standard version of the robot is shown in Fig. 1. Other versions include (but is not limited to) two motor differential drive versions with caster wheels for support, versions with or without suspension modules, versions with different track widths, tall versions that can drive over fully grown cereal crops, three-wheel versions with one-wheel drive/steering and passive support wheels, and extra wide versions with 6 or more wheels.

The system is overall designed to enable light-weight, low-cost, high quality robots for any application. The modules

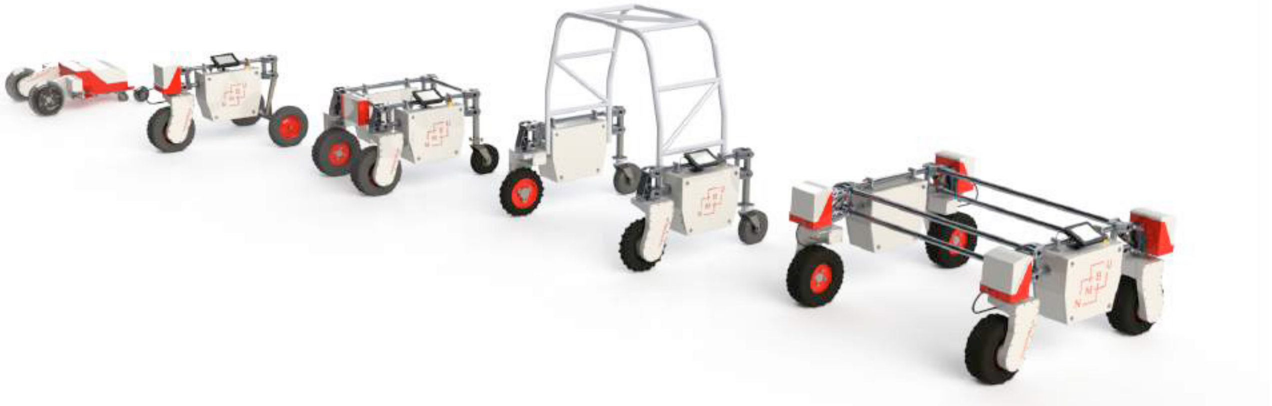


Fig. 2. A handful of the robots that can be built using the Thorvald modules. From the left: A low, narrow version for greenhouses, a three-wheeled version, a differential drive version, a tall phenotyping version, a standard version.

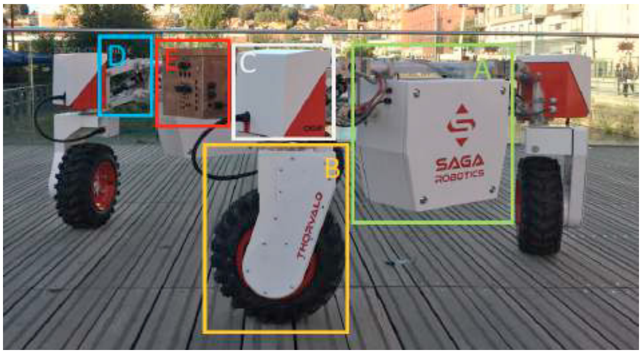


Fig. 3. Robot modules: A: Battery enclosure, B: Drive module, C: Steering module, D: Suspension module, E: Sensor interface module prototype.

make it possible to tailor the robot for a given set of task, omitting unnecessary costly parts.

The simplest robots that can be made using these modules are differential drive versions and three-wheel versions. Both types of robots only require two motors (as opposed to eight motors for the standard 4WD/4WS configuration). This reduces the cost of each robot, which makes them well suited for swarm applications with limited requirements for pulling power (differential drive version should in general be able to generate more pulling force than the three-wheel version, but will be more costly). If the swarm application turns out to require robots with greater pulling capabilities, the robots can be reconfigured with more drive modules.

The robot is fully electric and runs on 48 VDC lithium-ion batteries. The robot main computer resides inside one of the robots battery enclosures. One or more additional computer can be connected to the robots local Ethernet network. The on-board computer, motor controllers and batteries are all connected to a CANopen network, and the on-board computer runs ROS (Robot Operating System) on Linux Ubuntu. Because of the modular nature of ROS, the majority of the code can be made to work with all the different versions of the robot. To further increase this modularity, effort has been put into making configuration files as new versions of the robot are tested. Version-specific parameters are then loaded from the configuration files into the ROS parameter server where they are available for all processes running in the ROS network. Re-configuring the physical parts of the robot into a completely new configuration should therefore not require extensive amounts of coding.

3. ROBOT MODULES

The robot modules can be combined in different ways to form robots with different properties. Active drive modules and passive wheel modules can be combined to create robots with different kinematic properties, and battery enclosures can be added to extend the robot's battery life. A handful possible configurations are shown in Fig. 2.

The modules are described in the following subsections.

3.1 Battery Enclosure

The battery enclosure is made of aluminum and holds the main computer, a wireless access point with a built in switch, electronics and batteries. It clamps to the robot frame, and provides power and communication to other modules. Only one such enclosure is required to run the robot, but more can be added to increase the amount of batteries the robot can carry. Optionally, the module can be fitted with a weatherproof touch screen that connects to the on-board computer through a waterproof all-in-one connector.

The battery enclosure is shown in Fig. 3 A.

3.2 Drive Module

The drive module contains a motor and transmission connected to a wheel, and it is what propels the robot. The module can be connected to the output shaft of a steering module (see Section 3.3), which allows the module to rotate relative to the frame of the robot (around the vertical axis through the center of the wheel). In this case, the motor is driven by a two channel motor controller mounted on the steering module. For a differential drive robot the modules connect directly on the robot's frame. The motor is then driven by a separate motor controller module.

The drive module has a 500 W propulsion motor with synchronous belt and planetary in-wheel reduction gear which gives it a nominal speed of 1.5 m/s. Depending on the robot configuration, the robot will be fitted with one or more drive modules.

The drive module is shown in Fig. 3 B.

3.3 Steering Module

Some robot configurations require one or more drive modules to rotate around a vertical axis to be able to control the robots heading, or to improve manouverability. This is achieved by connecting drive modules to steering modules. A steering module can be connected to the robot's frame directly, or optionally to a suspension module which in turn is connected to the frame. The module is self-contained with a brushless DC motor, transmission and a two channel motor controller, and only requires one power cable and one communication cable from the outside world. The motor controller drives both the steering motor and the motor of the connected drive module. The design allows for $> 360°$ rotation of the drive module relative to the steering module. This gives the robot good maneuverability. E.g a standard 4WD/4WS robot may drive sideways and still have almost the same mobility as when driving in the forward direction.

The steering module is shown in Fig. 3 C.

3.4 Motor Controller Module

The motor controller module provides a weatherproof housing for a two channel motor controller and is used in place of the steering module for controlling two drive modules when steering motors are not required, e.g. on a differential drive robot. The modules clamps to the robot's frame and requires connection to power and communication in the same way as the steering module.

The motor controller module is shown on the front of the narrow differential drive robot in Fig. 2.

3.5 Passive Wheel Modules

For differential drive robots, caster wheels can be used to support the frame. For three-wheel versions, two supporting wheels are needed. These modules connect to the robot in the same way as drive modules, but is far less complex internally. Replacing drive modules for passive wheel modules will therefore reduce the overall cost of the robot, but it will of course also lower the robots pulling capabilities and maneuverability.

3.6 Suspension Module

The suspension module is optional and is not required for the robot to work. However, it will improve the robot's traction capabilities by keeping all wheels in contact with the ground even in extremely uneven terrain. It will also absorb shocks if the robot is moving fast over rough surfaces. The module connects between the drive module and the robot's frame. It allows the drive module vertical travel so that the robot may adapt to the terrain. The module is fitted with an adjustable passive air shock absorber that, if needed, can be locked in any position.

The suspension module is shown in Fig. 3 D.

3.7 Sensor Interface Module

As different research projects may require different sensors, it is important to make the process of mounting sensors on the robot as simple as possible. To achieve this, a sensor interface module can be installed. The module clamps to the robot's frame and ensures quick and easy sensor connectivity. It contains a computer connected to the robot's local Ethernet network. The computer is also connected to a powered USB hub. The module provides 12 VDC and 5 VDC sensor power, but can easily be modified to provide additional power at other voltages. Connectivity for CANopen devices and 48 VDC power for motors or other high power devices is also included in the module. Waterproof USB connectors, waterproof Ethernet connectors and cable glands protects the content of the module against the environment.

The first prototype of the sensor interface module is shown in Fig. 3 E.

3.8 Sensor Mounting Module

The sensor mounting module clamps to the frame and is designed to carry sensors and antennas. The module consists of aluminum profiles that act like mounting rails for sensors. A sensor can therefore slide to any position before it is locked securely in place. Transverse aluminum profiles can slide up or down to easily customize the module for a given application. On the prototype, a few "work horse" devices have more permanent mounting brackets that have been precisely located in the module's frame using a total station. These devices include a Velodyne VPL-16 3D LIDAR, a Xsenns MTi-G-710 GNSS/INS, and 5/8" screws for antennas or prisms. The sensor mounting module prototype fits outside the sensor interface module prototype, but they can also be mounted independently.

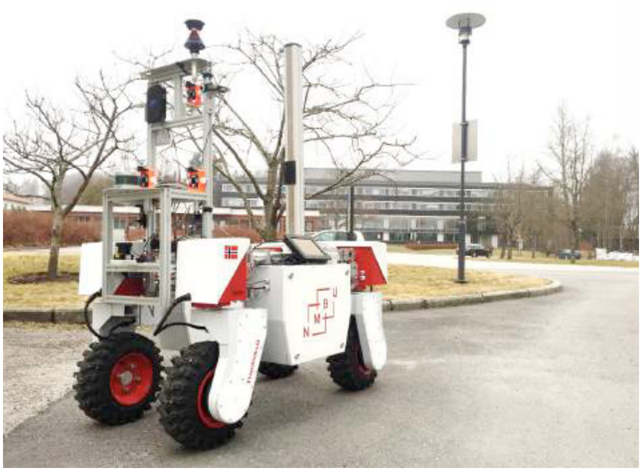


Fig. 4. Narrow Thorvald II robot for use in strawberry tunnels. The sensor mounting module prototype is clamped to the front of the robot.

The first prototype of the sensor mounting module is shown in Fig. 4.

3.9 Robot Frame

The robot's modules clamps to a frame comprising of 40 mm tubes. For the standard robot configuration these are plain, straight aluminum tubes arranged in two rectangle, one 15 cm over the other (center to center). Additional diagonal members can be clamped on to increase stiffness.

As all electronic components are contained within the robot's modules, it is easy to design custom frames. Tubes can be bent or welded to create more complex frames. The phenotyping arc described in section 4.2 and depicted in Fig. 5 is one example of a custom frame.

Drive modules or passive wheel modules typically connects at the robot's corners, but they can also be clamped to the middle of the frame to add extra support for high load versions. An example is shown in Fig. 6.

4. APPLICATIONS

Thorvald robots are currently being used in research projects by the Norwegian University of Life Sciences (Norway) and the University of Lincoln (UK). As the purpose of the robotic system is to make modular robots that can be adapted to work in a wide range of agricultural environments, the robot will be used in several vastly different projects. Some current and future applications are described in brief below.

4.1 Open field

The open farm field can make use of several different versions of the Thorvald robot. The standard 4WD/4WS

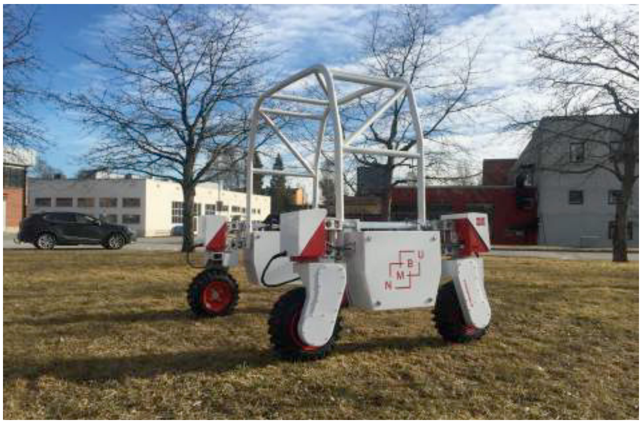


Fig. 5. A Thorvald II robot for cereal phenotyping. The high transverse arc allows it to drive over fully grown crops without damaging the plants.

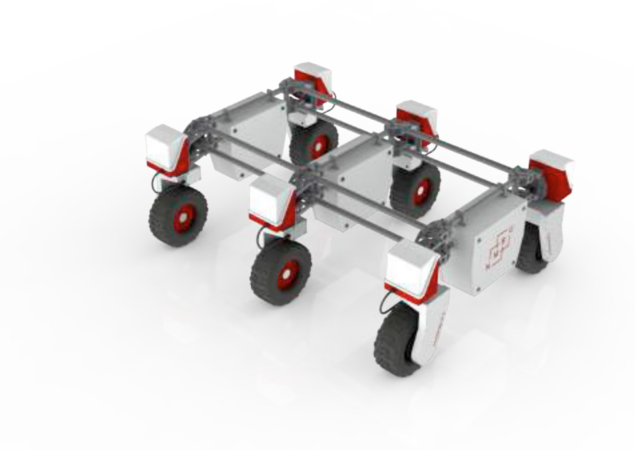


Fig. 6. A wide, six wheeled Thorvald II robot

is suited for applications which require high load or pulling capability, while differential drive versions or wide three-wheel versions may be better for monitoring and other applications with lower requirements to power.

The Thorvald II robot is not intended to be used for heavy work like plowing. However, the first prototype of the robot has been used in tests of robotic tillage. In the test the robot had a track width of 1.5 m and it was stripped of its suspension modules. During the test, the robot was driving sideways successfully pulling two small tines across the field at a depth of approx. 15 cm. The setup is shown in Fig. 7.

Test were performed in both dry and wet conditions. For the test in wet conditions, the field was in such a state that tractors would not be able to operate on it. Still the robot was able to perform its task without getting stuck, and the tracks where the robot had been driving were barely visible. The fact that robots can still operate in wet conditions, when conventional tractors must stay clear of the field, really demonstrates the huge potential of light-weight agricultural robots.

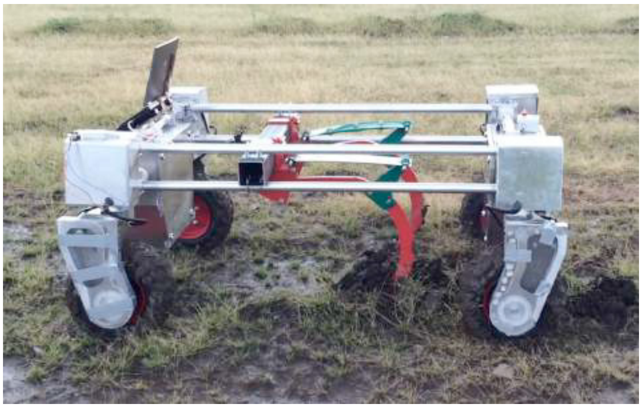


Fig. 7. Testing of robtic tillage in wet conditions during development of the initial Thorvald II prototype

4.2 Phenotyping

Thorvald I was used by researchers working with cereal phenotyping (Burud et al. (2017)). The researchers are using cameras sensitive to visual and near infrared parts of the electromagnetic spectrum to study plants. The robot had a fixed height of 59 cm which is lower than the height of fully grown plants. For this reason the robot could not be used for the whole season as it would damage the plants.

With Thorvald II, this problem is easily solved by exchanging the cross members of the frame for a tall transverse arc as shown in Fig. 5. The arc will also be used for mounting sensors relevant for phenotyping, like cameras and LIDARs.

4.3 Farm logistics

The Thorvald II robot is designed to carry 200 kg. This makes the robot well suited for tasks related to farm logistics.

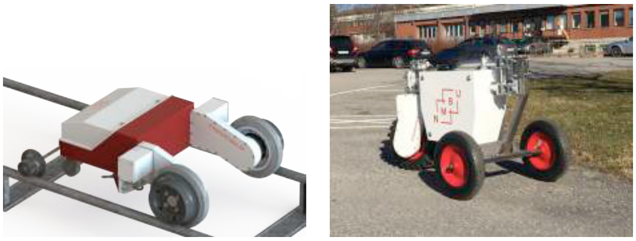
In strawberry farms pickers lose much picking time because they have to carry the strawberries to the end of the field whenever they pick a full box. At the end of the field the strawberries are weighed before they are driven to storage. One farmer the authors spoke to estimated that his pickers on average spend one third of their time carrying boxes. As the boxes of strawberries are quite heavy and are being carried manually, there has to be roads across the farm field for every 50 meters. If these roads are removed, the total area used for growing crop would increase with approx. 15%.

Adopting a fleet of low cost, high load carrying robots for transporting strawberry boxes from the pickers to the end of the field may therefore result in a great cost reduction for the farmer.

The task of carrying boxes to and from pickers should be relatively simple to solve using robots, and is an example of how mobile robots can be useful in the picking process even before they are capable of doing the actual picking in an economically viable way.

4.4 Polytunnels

Polytunnels follow the natural contours of the ground which means that a robot operating in this environment



(a) A Robot for use in greenhouses (b) A three-wheeled Thorvald II robot during development

Fig. 8. Narrow robots made from Thorvald modules

should be robust to uneven ground surfaces. If the crop is grown in the ground, it may be possible to use the same robot configurations as in the open fields. If the crop, on the other hand, is grown on table tops, the robot must either be tall enough to drive over the tables or narrow enough to fit between the tables. Both solutions can easily be achieved with the Thorvald II system.

For an experiment on table top strawberries, the second solution was chosen. The purpose of the experiment was to investigate the effect of a particular UV light frequency on mildew (fungus). For this experiment Thorvald II was configured with 4WD/4WS, without suspension and with a track width of only 57.5 cm. The robot was then narrow enough to fit between the tables, and the four-wheel steering made it easier to maneuver the robot in the tight spaces at the end of the rows. The robot is depicted in Fig. 4.

4.5 Greenhouses

There is a great variation in the layouts of greenhouses, and different greenhouses may require different robot configurations. The authors are currently making preparations for a project on treating cucumber with UV lights. Here the robot will be driving on rails in narrow rows between the plants. At the end of the row the robot will drive off the rails and navigate to the next row on a concrete floor. The rails and the concrete floor are a part of the pre-existing infrastructure of the greenhouse.

For this project we are planning to flip two drive modules 90° and connect them to a simple, custom steel frame. Each drive modules is then fitted with a double set of wheels, one for driving on rails and one for driving on concrete. While driving on the rails the robot will be supported by a second set of rail wheels at the rear. When the robot is driving on concrete, it will be supported by two caster wheels. A model of the planned robot is shown in Fig. 8a.

Another robot configuration that may be useful in a greenhouse, is the narrow three-wheeled Thorvald shown in Fig. 8b. This robot is made from one battery enclosure, one drive module, one steering module and a set of passive wheels.

5. CONCLUSION

The tests and experience of using the Thorvald II robot shows great promise for the future. The robot preforms well in vastly different environments, and several robots will be built in time for the 2017 season. Minor improvements have been made to the mechanical design based on experience from operation in the field and from several rebuilds. The goal is to reduce the build time and build cost to a minimum, as this will enable low cost swarms of high quality robots. The robot is scheduled to participate in several experiments in Norway and the UK with applications such as measuring soil moisture and phenotyping tasks in open fields, UVB-treatment against mildew and in-field logistics in strawberry tunnels, and monitoring and UVB-treatment of cucumbers and tomatoes in greenhouses.

ACKNOWLEDGEMENTS

We would like to thank Øystein Sund and Marius Austad for work on the design and building the robots.

REFERENCES

Bangert, W., Kielhorn, A., Rahe, F., Albert, A., Biber, P., Grzonka, S., Haug, S., Michaels, A., Mentrup, D., Hänsel, M., et al. (2013). Field-robot-based agriculture:“remotefarming. 1” and “bonirob-apps”. In *71th conference LAND. TECHNIK-AgEng 2013*, 439–446.

Batey, T. (2009). Soil compaction and soil management–a review. *Soil use and management*, 25(4), 335–345.

Bawden, O., Ball, D., Kulk, J., Perez, T., and Russell, R. (2014). A lightweight, modular robotic vehicle for the sustainable intensification of agriculture. In *Australian Conference on Robotics and Automation (ACRA 2014)*. Australian Robotics & Automation Association ARAA, University of Melbourne, Melbourne, VIC. URL `http://eprints.qut.edu.au/82219/`.

Burud, I., Lange, G., Lillemo, M., Bleken, E., Grimstad, L., and From, P.J. (2017). Exploring robots and uavs as phenotyping tools in plant breeding. In *IFAC 2017 World Congress*.

Green, O., Schmidt, T., Pietrzkowski, R., Jensen, K., Larsen, M., Edwards, G., and Jørgensen, R. (2014). Commercial autonomous agricultural platform - kongskilde robotti. *Second International Conference on Robotics and associated High-technologies and Equipment for Agriculture and Forestry.*

Grimstad, L., Pham, C.D., Phan, H.T., and From, P.J. (2015a). On the design of a low-cost, light-weight, and highly versatile agricultural robot. In *2015 IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO 2015).*

Grimstad, L., Phan, H.N.T., Pham, C.D., Bjugstad, N., and From, P.J. (2015b). Initial feld-testing of thorvald - a versatile robotic platform for agricultural applications. In *IROS Workshop on Agri-Food Robotics: dealing with natural variability, 2015.*

Nawaz, M., Bourrié, G., and Trolard, F. (2013). Soil compaction impact and modelling. a review. *Agronomy for Sustainable Development*, 33(2), 291–309.

Oksanen, T. (2015). Accuracy and performance experiences of four wheel steered autonomous agricultural tractor in sowing operation. In L. Mejias, P. Corke, and J. Roberts (eds.), *Field and Service Robotics*, volume 105 of *Springer Tracts in Advanced Robotics*, 425–438. Springer International Publishing.