Mobile Agricultural Robot Swarms (MARS)

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Final Report

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Section 1: Executive summary

- What was the goal of the project?
  The experiment aims on small and stream-lined mobile agricultural robot units, which cooperate as a group similar to swarm principles to put seeds in the ground of an agricultural field.

- Why was the solution to the problem was important?
  MARS intends to fuel a paradigm shift in farming practices. The concept addresses looming challenges of today's large and constantly growing tractor-implement combinations with mainly three aspects. First: the need for optimized, plant specific Precision Farming to reduce input (seeds, fertilizer, pesticides) and increase yields. Second: reduction of soil compaction as well as energy consumption of heavy machinery. Third: meet increasing demand for flexible use, highly automated and simple to operate systems anticipating challenges arising from climate change as well as shortage of skilled labour.

- What was proposed as a solution?
  The robots will cooperate as a group, similar to swarm principles. MARS will focus on the seeding process for corn performed by two robots as an example. The key strategy of this approach is on the one hand the radical reduction of weight and size compared to conventional farming equipment, which also allows for a fundamental simplification of safety tasks. On the other hand it is the essential simplification compared to known agricultural robot prototypes, especially by minimized use of on-board sensors. This will be realized by transferring control algorithms, process optimizing and supervising intelligence to cloud services and utilizing precise GPS-RTK technology. All these measures are intended to lead to a significant cost reduction of the overall system paving the way towards robots as a true alternative in the agricultural domain.

- What was proposed as an impact of your solution?
  - Simplified, rugged hardware: physical robot units (with all components)
  - Cloud-based control algorithm (OptiVisor) to manage the group of robots
  - Small size seeding unit for robotic vehicle platform purpose
  - Human-machine interface to the system (monitoring, interaction possible if needed)
  - Degree of protection suitable for agricultural purpose: IP69 targeted
  - Cost focus for hardware development

- What is the final impact at the end of the project and what are the deviations in achieving the impact?
  - MARS robots with integrated seeding unit and guidance system available.
  - Unique small-sized seeding unit using highly energy efficient punch seeding.
  - Cloud based algorithm (User management, Database) available.
  - OptiVisor algorithm available.
  - HMI (Tablet UI) for planning and monitoring of seeding process available.
  - IP65 instead of IP69 (target) reached.
  - Development of small-sized seed singulation not successful. Integration of conventional seed singulation in seeding unit.

The now available MARS system stands for an integrated process of automated seeding using a flexible number of robots. The 2 currently available robots enable testing of the overall process on a real field. As soon as further robots are available in a suitable number, the overall performance of the MARS approach can be evaluated in comparison to conventional, established methods of seeding.
Robotic seeding, which was the focus of this project, serves as basis for an overall scenario where further agricultural processes can be affiliated. Managing the position of each planted seed is one of the most important concepts of the MARS approach and stands for its simplicity because it prevents the need to reconstruct process relevant information later.

For example, this enables:

- Monitoring the growth of plants
- Precise fertilization and weed control

The potential of the MARS experiment to serve as an enabler for the development and extension of further agricultural tasks can be considered very high.

Section 1.1: Milestone overview

#	Description	status
M1	Concept defined	Achieved
M2	OptiVisor Algorithm developed	Achieved
M3	System available	Achieved
M4	System validated (TRL5)	Achieved

Section 1.2: Deliverable overview

#	Description	status
D1.1	Concept Sketch	submitted
SB	Story Board	submitted
D2	OptiVisor (simulation and report)	submitted
D3	Robot Prototype + technical description	submitted
MMR	Multi-Media Report*	Deviated

*will be submitted after the final review.

Section 1.3: Technical KPIs

#	Description	status
1	OptiVisor algorithm	Achieved
2	HMI on handheld device	Achieved
3	Seeding unit	Achieved
4	Energy Consumption	Achieved

Section 1.4: Impact KPIs*

#	Description	status
1	**Simplification and Cost Reduction**	Achieved
1.1	Reduction of invest compared to a tractor-implement combination (Farmer)	Achieved
1.2	Reduction of invest for production equipment, quicker ROI (OEM)	Achieved
2	**Scalability**	Achieved
2.1	Composability of software (HSU service robotics): transfer to end user (university to business), transfer from researcher to operator (user level)	Achieved
2.2	Potential to be applicable to other agricultural tasks (spraying, fertilizing)	Achieved
3	**Improvement of Crop Production**	Achieved

3.1	Yield increase by optimized seed patterns	Achieved
3.2	Potential reduction of fertilizers and pesticides through precise application	Achieved
3.3	Fewer operators needed: addressing expected shortage of skilled human labor	Achieved
3.4	Freeing machinery capacity: allowing parallel operations of robot & tractor	Achieved
4	**Increased Safety**	Achieved
4.1	No/less large, heavyweight tractors needed: reduced accidents with interacting humans; no more injuries from rollovers on slopes etc. (no cab/ no operator)	Achieved
4.2	No high pressure oil, no high temperature components, no open mechanical power transmission, no heavy weight components	Achieved
5	**Environmental impact and sustainability**	Achieved
5.1	Significant CO2 reduction through less required process energy	Achieved
5.2	Reduced soil compaction (invers law of growth)	Achieved
5.3	Less material use (e.g. in tons of steel for equipment)	Achieved
5.4	Less environmental pollution (reduction of fertilizers and pesticides)	Achieved
5.5	No danger of an oil or fuel spillage on the field (battery-electric drive)	Achieved
5.6	Less noise (especially for nightshift operations close to residential areas)	Achieved
6	**Simplified service principles**	Achieved
6.1	Robot maintenance and repair can be done by one person on a desk	Achieved
6.2	Remote software updates and diagnosis possible	Achieved
7	**Increased reliability compared to conventional equipment**	Achieved
7.1	Impact of single unit breakdown compensable by other robot units	Achieved
7.2	Less mechanical complexity, fewer drives and no operator misuse	Achieved
8	**Possible cross domain transfer (proposed ideas)****	Not Achieved
8.1	OptiVisor algorithm for logistic tasks (“physical internet”)**	Not Achieved
8.2	RTK controlled system for navigation in production plants**	Not Achieved
9	**New cost structure; robots replacing conventional equipment**	Achieved
9.1	Costs for sophisticated conventional seeding implement	Achieved
9.2	Freed up capacity (driver and tractor available for other tasks) ads on to the benefit. Quantification of this is related to many inputs like type of conventional equipment and local labor cost	Achieved
9.3	Similar example from other domain: Manual lawn mower (Bosch Rotak 40: 250€ MSRP) vs. lawn mower robot (Bosch Indego: 1500 € MSRP)	Achieved
10	**Promotion of new agricultural processes**	Achieved

*for more details see deliverable “KPI Impact Report”

**proposed ideas: no implementation.

Section 1.5: Dissemination KPIs

#	Description	status
1	First press release (kick-off)	Achieved
2	Microsite online	Achieved
3	Teaser online	Achieved
4	Midterm press release	Achieved
5	Fair appearance	Achieved
6	Journal article	Achieved
7	Final press release*	Deviated

*will be submitted after the final review.

Section 1.6: Additional (unplanned) achievements

- Invitation to Start-Up Event "Bits&Pretzels 2016" with first live demo of MARS robot.

Section 2: Detailed description

Section 2.1: Scientific and technological progress

Overview of available MARS components and their functions

- Robots
    - Simple and robust design
    - Electric wheel drive
    - Seeding unit to plant seeds
    - RTK GPS
    - Software to realize robot functions (driving, seeding, communication, ...)
- Cloud Infrastructure
    - User Management
    - Data Management
        - Field shapes
        - Documentation of seeding process (position of planted seeds, …)
- Tablet App
    - User interface for the farmer
    - Selection of field, adjust seed parameters, …
    - Visualization of relevant process data (robot position, …)
    - Human intervention (start, stop, to CLU)
- OptiVisor Algorithm (Central entity to manage the seeding process)
    - Offline Task Planning
        - Path planning
        - Workload assignment
    - Online Process Supervision and Optimization
        - Continuous interaction with robots and cloud
        - Reaction according to current system status
        - Replanning if necessary (e.g. robot failure)

Task MARS.1 – Concept and Architecture

MARS.1.1: Definition of overall system

Figure 1: MARS Concept.

- **Logistic Unit:** The logistic unit takes care of transport, seed supply, battery charge and highly precise navigation of the robots.
- **Robot:** Each robot has its own integrated planting unit and is driven electrically. Communication with the Logistic Unit is done via the Cloud.
- **Tablet:** Task planning, live monitoring and administration of seed data can be done, for example, with a tablet from any location.
- **Satellites:** The satellite-based navigation facilitates autonomous operation and accurate geo-referenced documentation of the planting data.
- **Cloud/OptiVisor:** The OptiVisor algorithm optimizes (optimizer), and supervises (supervisor) the planting operation constantly. Intervention is possible at any time, independent of location. The cloud infrastructure hosts the OptiVisor and provides user and data management (e.g. documentation of seed positions).
- **Farmer:** The tasks of the farmer are limited to seed planning (via app) and managing the transport logistics of robot fleet.

MARS.1.2: Definition of mechanical and electronic robot concept

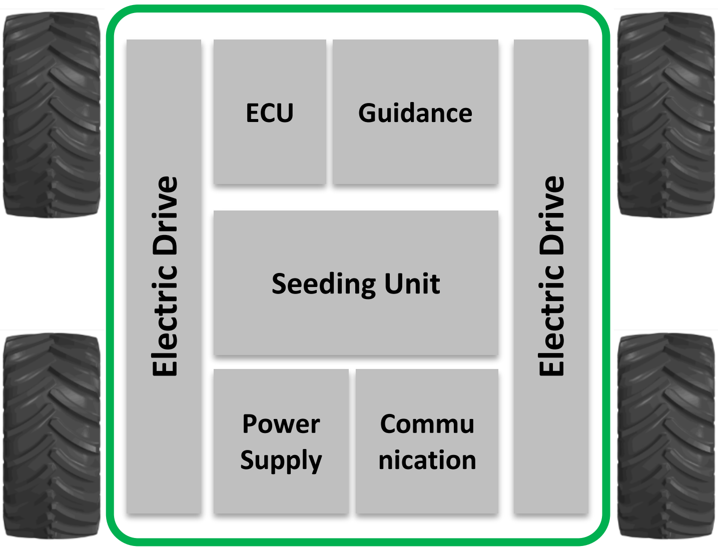


Figure 2: Robot Concept.

- **ECU:** The ECU controls the electric drive and the seeding unit. It communicates with the guidance unit and the communication device.
- **Guidance:** The guidance unit receives position signals and computes the precise position of the robot. It also computes the necessary action of the steering system according to the next waypoint.
- **Seeding Unit:** This is the mechanical core component of the robot. It puts the seed in the ground and is capable of recording the precise position of the planted seed.
- **Electric Drive:** The electric motors power the wheels of the robot.
- **Communication:** The communication device connects the robot to the outside world. It sends and receives data from the Cloud/OptiVisor.
- **Power Supply:** The power supply provides energy for all electric components. It consists of a high-performance rechargeable battery pack, implemented in a quick-change system.

MARS.1.3: Definition of software architecture (robot: traction drive, seeding unit control, communication; CLU: navigation support, e.g. RTK; system: cloud and HMI)

Figure 3 shows the global system architecture, which is divided into 3 parts. The robots (3) execute the seeding process, which is pre-planned and supervised by OptiVisor (2). The Cloud (1) provides the data and user management functionality, which is accessible via the User Interface, running on different devices (e.g. Tablet or PC).

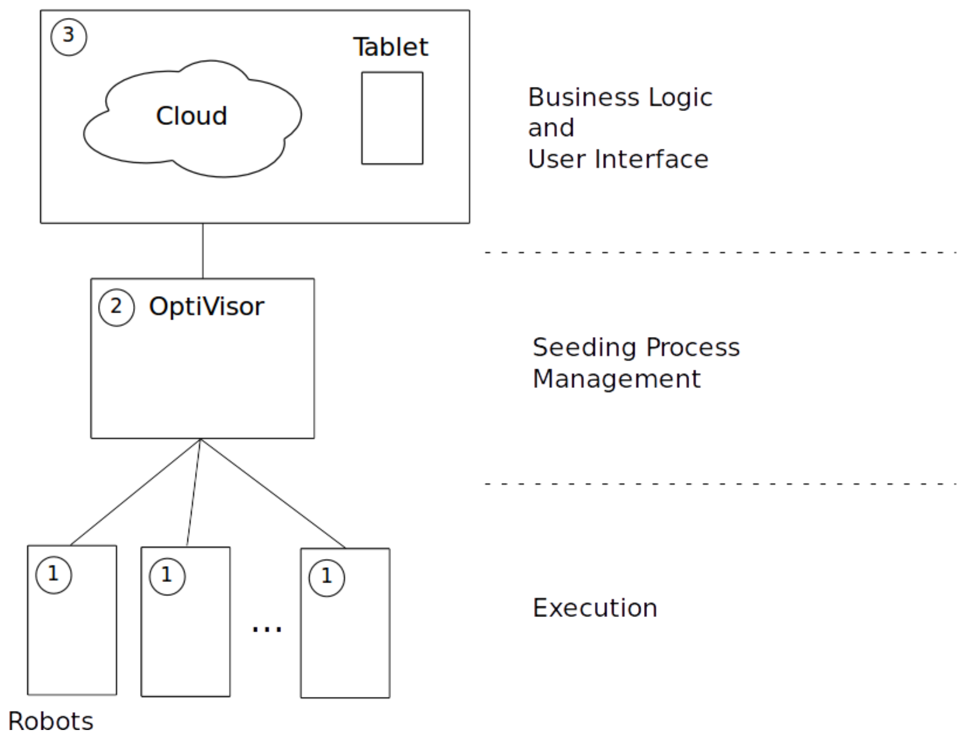


Figure 3: Global system architecture.

- Robot software architecture (traction drive, seeding unit, communication)

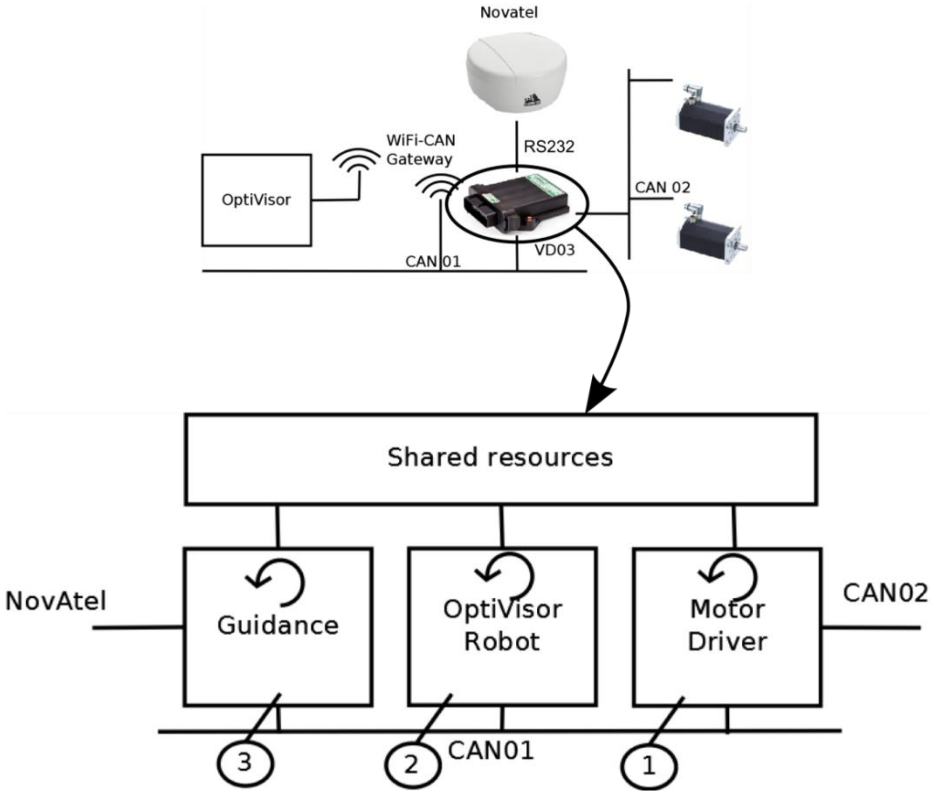


Figure 4: MARS Communication Structure.

The communication with OptiVisor is established through a WiFi-CAN Gateway. The central ECU (Electronic Control Unit) is the "VD03" (see **Figure 4**), which manages the communication between all entities. RTK is provided by the GNSS receiver ("Novatel") and the ECU ("VD03"). The motors (seeding unit, traction drive) are powered by the "Motor Driver", which is controlled by the ECU. For more details see deliverable D3 "Technical Report".

- OptiVisor architecture

The OptiVisor was implemented in a modular way using the SmartSoft approach, which provides a robotics component model, model-driven tooling and according middleware mappings. It supports the design, development, implementation and deployment of component-based robotics software systems. OptiVisor consists of a Planning and a Control component which realizes the functions of the Planning and Working Mode, a component to communicate with a real robot and components to simulate a robot. The interface between simulated and real robots is exactly the same, thus allowing the execution of the seeding process with either an arbitrary number of simulated robots or with the real ones without changing the OptiVisor implementation. The OptiVisor communicates with the Cloud Server to receive instructions and to forward status reports. These are used to visualize the current robot information on the tablet and to document the running seeding process.

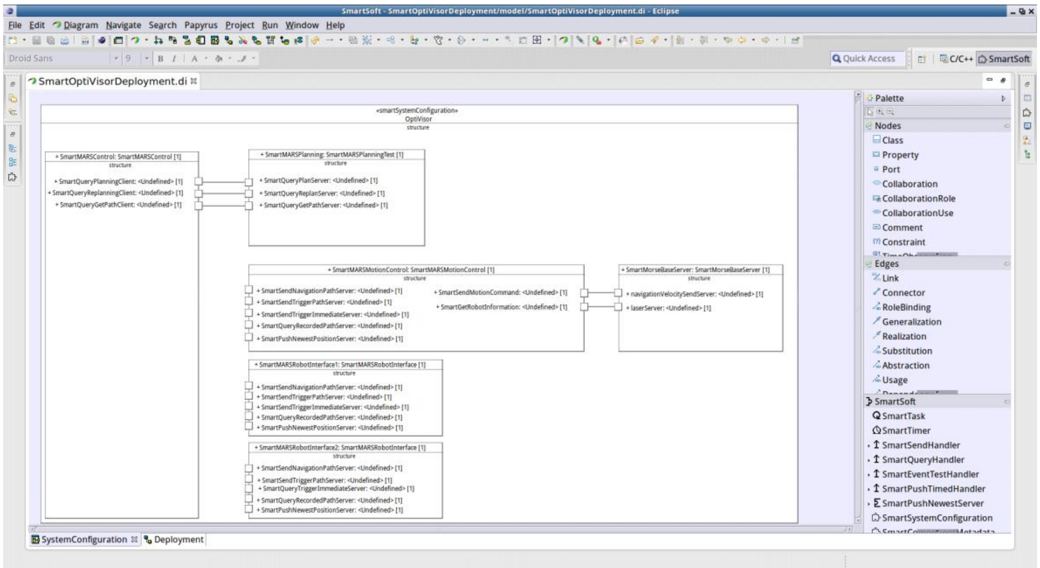


Figure 5: Deployment View in the SmartSoft MDSD Toolchain showing OptiVisor components (Control, Planning). Components to simulate robots and components for real robot communication can be composed with OptiVisor.

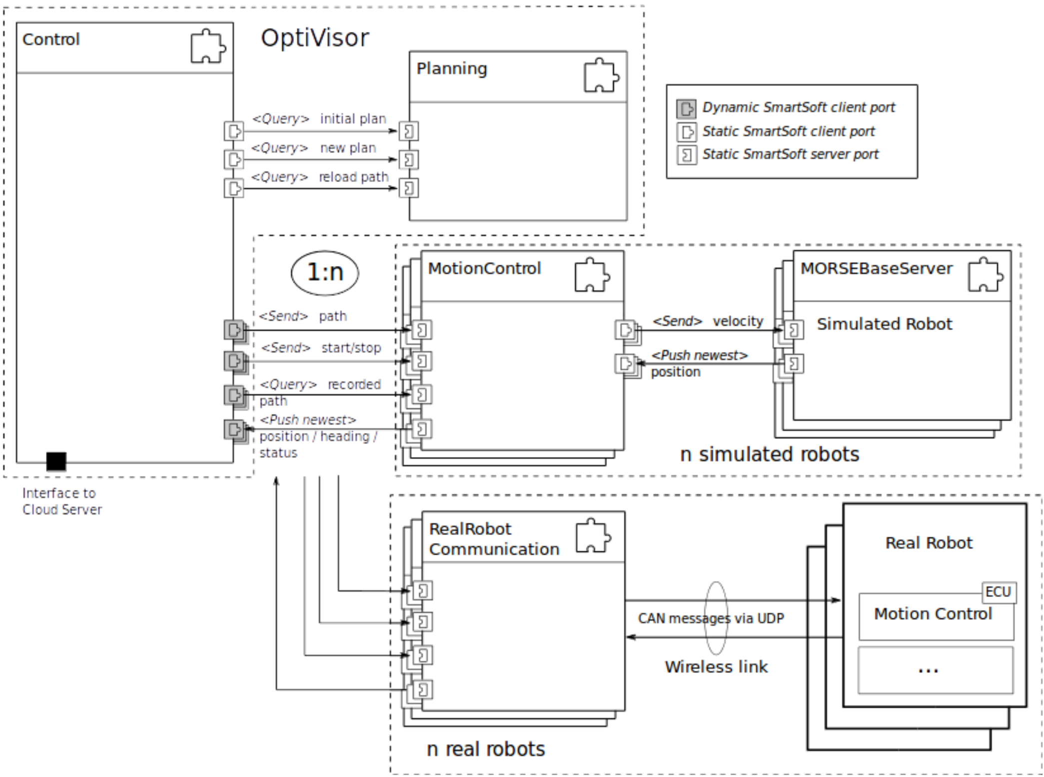


Figure 6: A desired number of robot components (simulated, real) can be composed to OptiVisor depending on the selected number of robots.

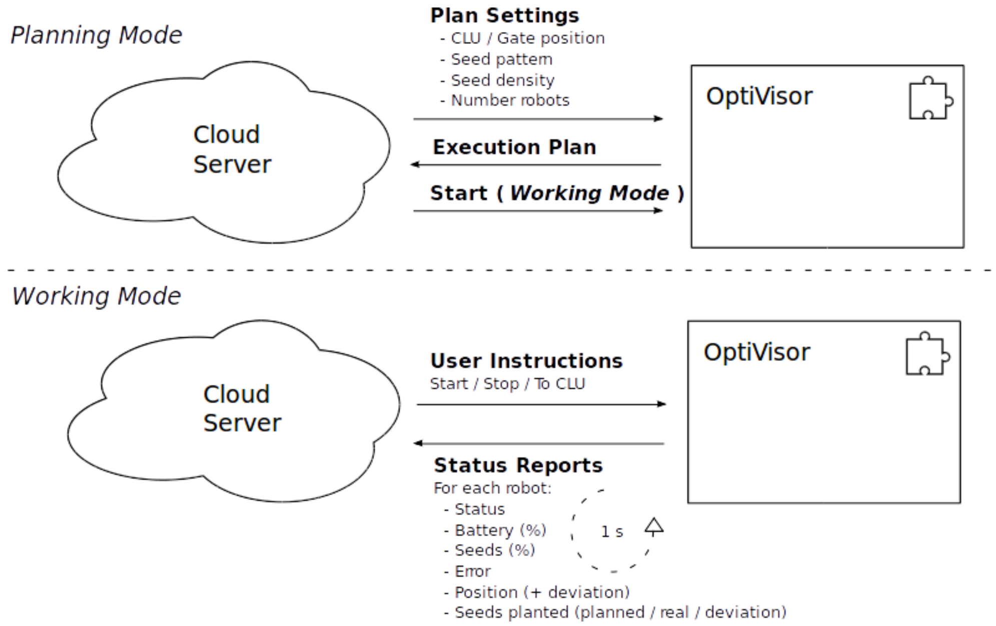


Figure 7: Protocol between Cloud Server and OptiVisor for Planning and Working Mode.

- Cloud Server and Tablet

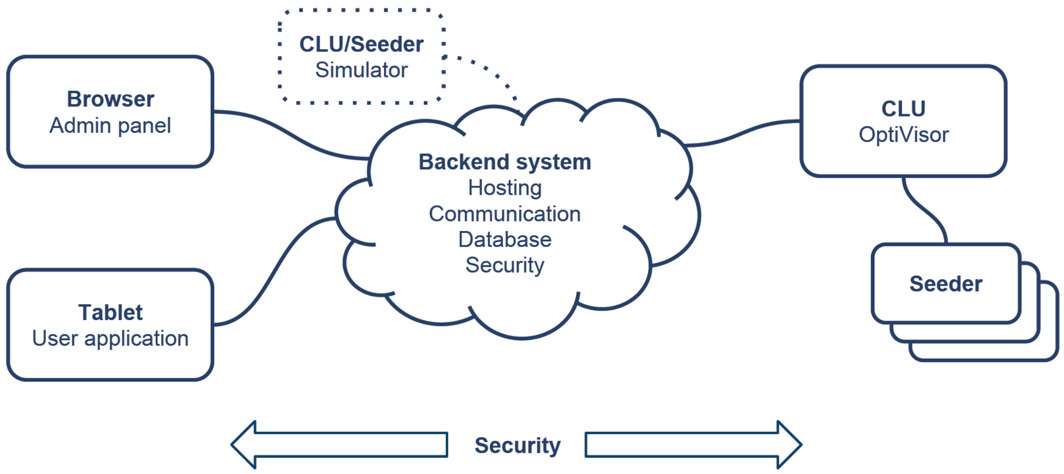
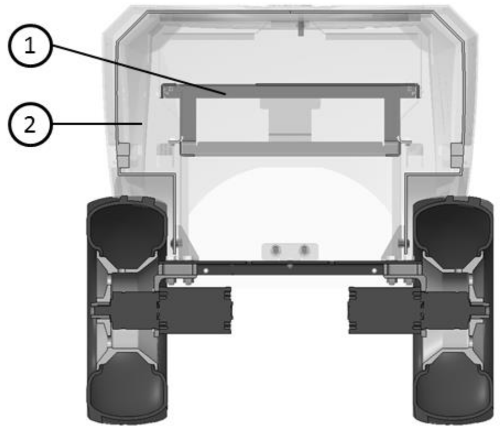
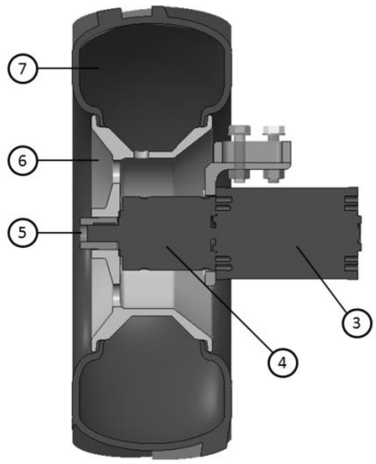


Figure 8: Cloud Server Infrastructure (Tablet App = User application).

Task MARS.2 – Hardware Development

MARS.2.1+2.2: Design of robot chassis/robot drivetrain

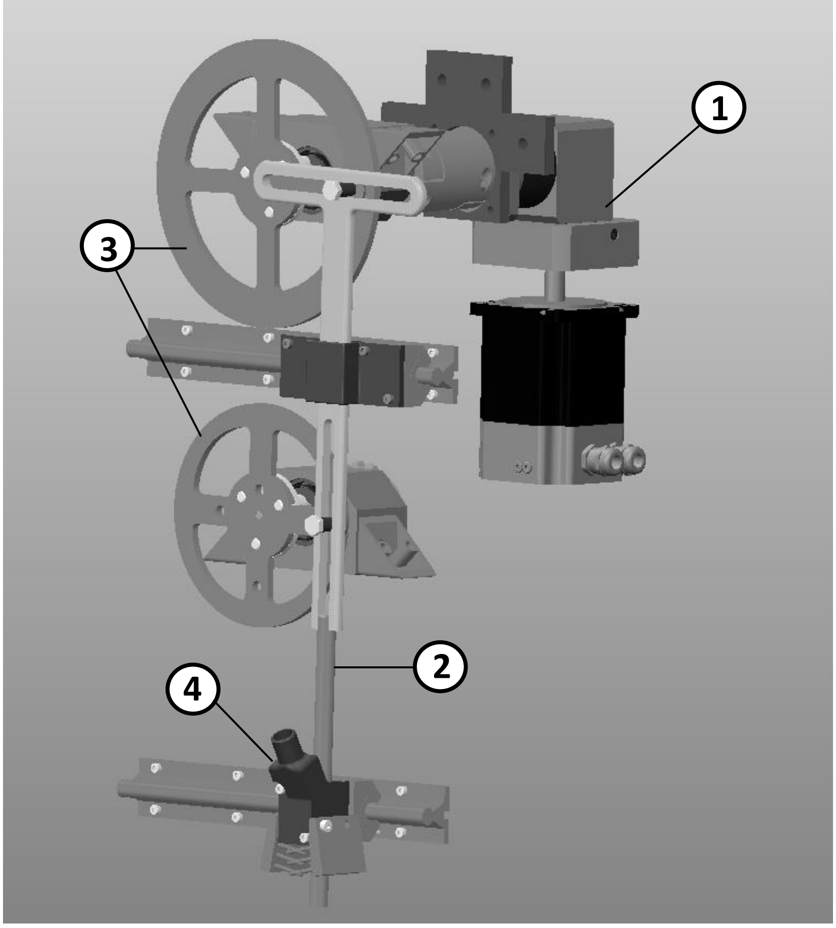




Position	Description	Details
1	Chassis	Sheet metal design
2	Body	Composite
3	Motor	Dunkermotoren BG 65x25, 92.2 W at 24 V, nominal rpm: 3100
4	Gear	Planetary gear Dunkermotoren PLG 52, i = 50
5	Clamping set	
6	Rim	Diameter: 6” (151 mm), rim width: 3” (73 mm)
7	Tire	Width: 110 mm, diameter: 325 mm, rim size: 6”

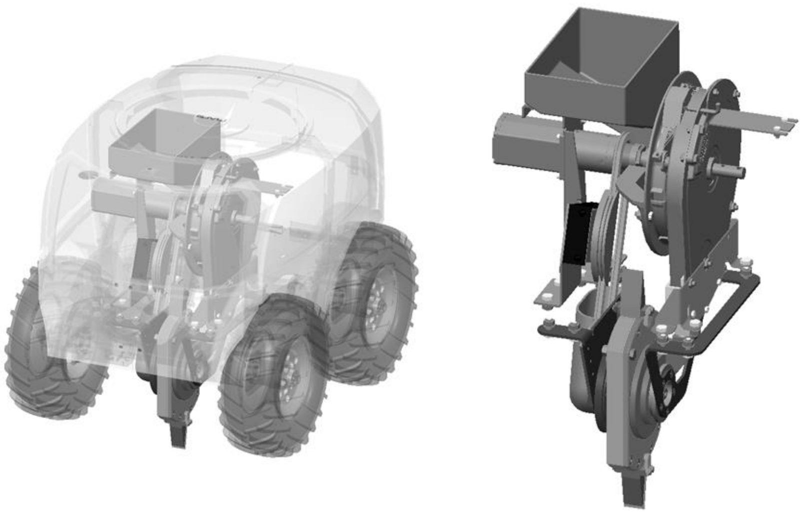
MARS.2.3: Design of seeding unit

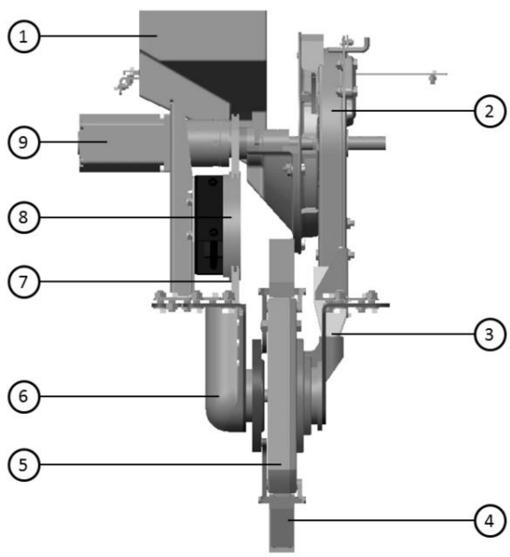
- Design of seeding unit #1 (cycloidal stamping)



Position	Description	Details
1	Motor	Nanotec 24 V motor with angular gear
2	Stamp	Stamp for pushing seeds in the soil
3	Cam discs	Cam discs for stamping (upper disc) and compensation of robot movement (lower disc)
4	Supply system	Seed channel for handover between fixed and moving parts

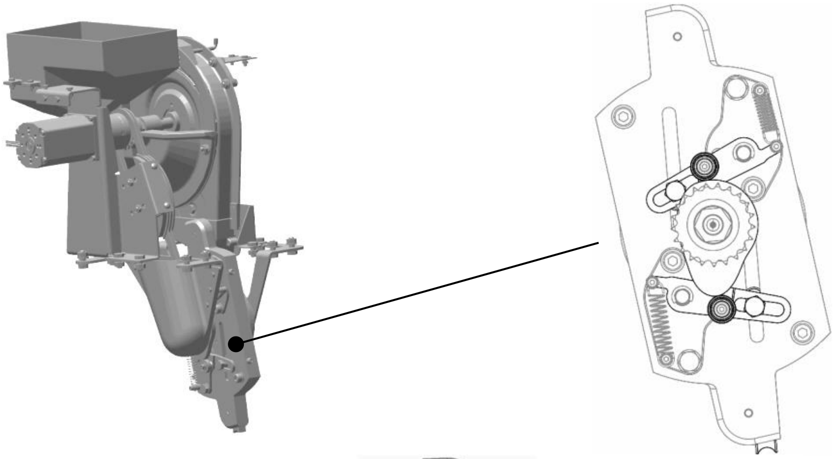
- Design of seeding unit #2 (rolling mechanism with flaps)

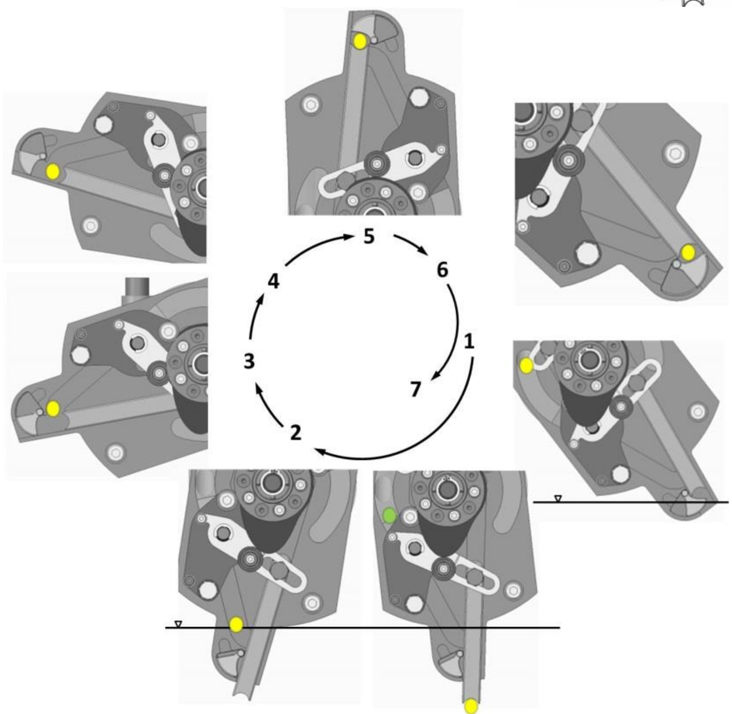




Position	Description	Details
1	Seed reservoir	Approx. 3 liters
2	Seed singulation	Precision Planting Finger meter for seed singulation
3	Supply system	Seed channel for handover between fixed and rotating parts.
4	Shovels	Shovels for punch seeding
5	Seeding unit	Seeding unit with internal seed channels Speed: 3 seeds per second (typical: 0.11 ha/h)
6	Chain guard	
7	Chain	Drive system for seeding unit
8	Chain tensioner	
9	Motor	Dunkermotoren BG 65x25, 92.2 W at 24 V, nominal rpm: 3100 with planetary gear PLG 52. (See chapter 1 «drive train»)

- Design of seeding unit #3 (rolling mechanism with stamps)

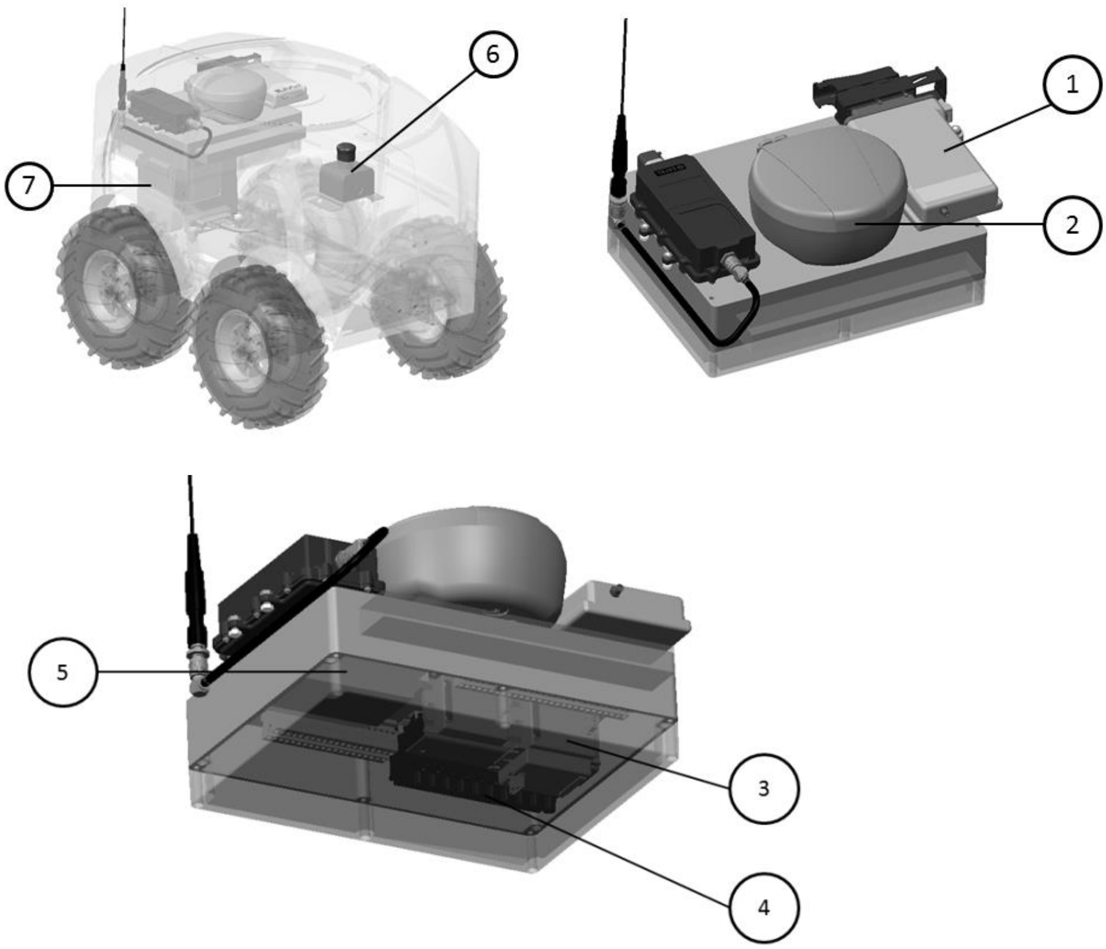




Position	Description	Details
1	Handover	Seed enters the seeding unit (moving) from supply system (fixed).
2	Forwarding	Seed is pushed towards the stamp channel by gravity and centrifugal forces.
3	Entry	Seed enters the stamp channel in front of the stamp.
4	Closing	Stamp closes the seed supply channel (controlled by cam disc).
5+6	Lock	Stamp holds the seed close to the sealing cap of stamping channel.
7	Placement	Seed is placed in the soil through stamping motion.

MARS.2.4: Design of peripheral components (seed/fertilizer tank, mounting of electric/electronic components)

- seed tank: see MARS 2.3
- mounting of electric/electronic components
  - electric motors: see MARS 2.2 and MARS 2.3
  - peripheral electric/electronic components:



Position	Description	Details
1	Robot ECU	STW VD03 (IMU, 2x CAN-BUS (250 kBaud/s), GSM Modem)
2	GPS antenna	Smart antenna (Novatel SMART6-L with RTK)
3	Motor controller	miControl B60, max. current: 15 A (5x)
4	Fuse Box	
5	Wifi-CAN Gateway	Gateway for OptiVisor – Robot Communication (PEAK Systems)
6	Emergency stop	
7	Battery	Lithium iron phosphate battery, 240 Wh, 24 V

MARS.2.5: Selection of electric components (e.g. electric drives)

- Electric motors: Dunkermotoren BG 65x25, 92.2 W at 24 V, nominal rpm: 3100 with planetary gear PLG 52.
- Motor controller: miControl B60, max. current: 15 A (5x)
- Battery: Lithium iron phosphate battery, 240 Wh, 24 V

Task MARS.3 – Electronics and Software Development

MARS.3.1: Selection of robot ECU

Robot ECU: STW VD03 (IMU, 2x CAN-BUS (250 kBaud/s), GSM Modem)

MARS.3.2: Development of OptiVisor and cloud algorithms (e.g. logging of seed position)

The OptiVisor algorithm has an offline and online part to realize its functionality.

- Planning Mode (Offline)
  - Determines the initial execution plan taking into account the user specified plan settings. The initial execution plan contains (for reach robot):
    - A navigation path the robot must follow to cover the field
    - A trigger path indicating positions where the robot should place seeds (depending on seed pattern and seed density parameters)
    - Suitable refill points leading the robot back to CLU to refill corn tank and energy
      - Optimization strategies:
        - Reduce overall number of refill phases
        - Reduce overall distance to drive
- Working Mode (Online)
  - Managing the running seeding process:
    - Sending of navigation and trigger path segments to each robot depending on their current position
    - Handling robot failures
      - Reassignment of work
      - Replanning of refill points
    - Collision avoidance
    - Handling user instructions (start / stop / to CLU)
    - Process relevant data (e.g. position of planted seeds, …) and forward to Cloud Server

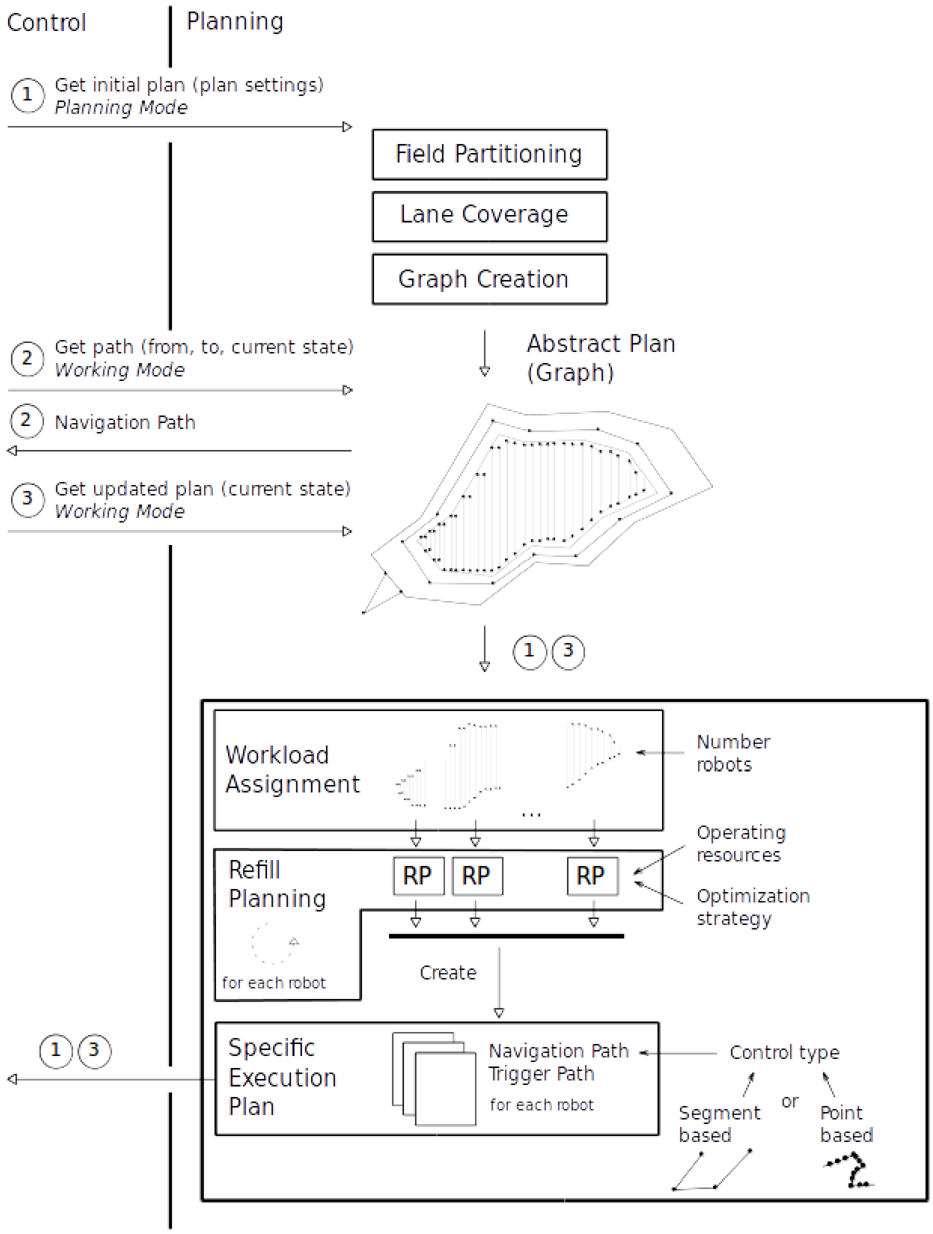


Figure 9: Steps of the planning algorithm and interaction possibilities between Control and Planning component. The initial execution plan is provided in Planning Mode. In Working Mode, the Control component can request an updated plan based on the current state (e.g. if a robot failed)

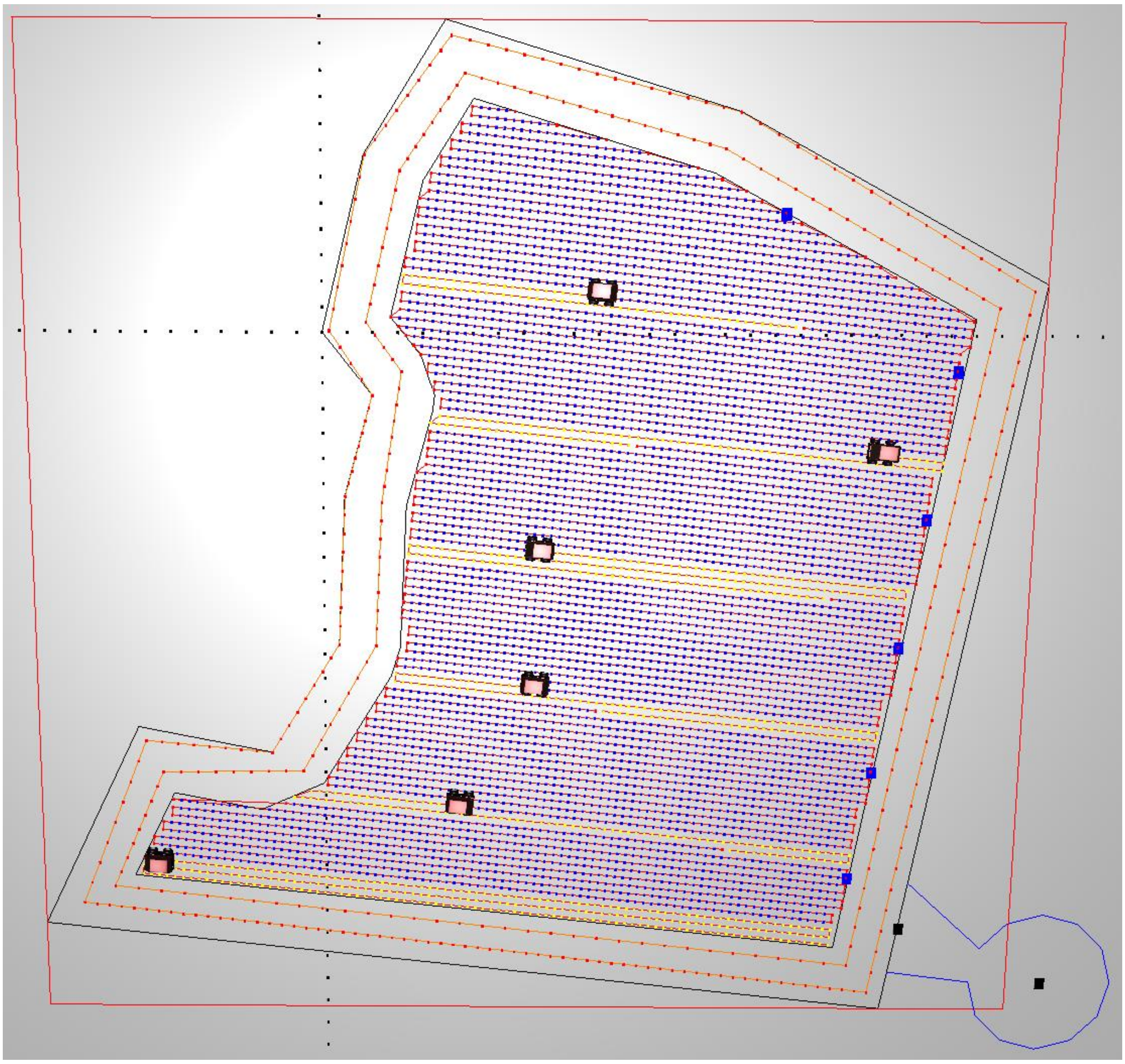


Figure 10: OptiVisor in Working Mode managing a simulated robot swarm.

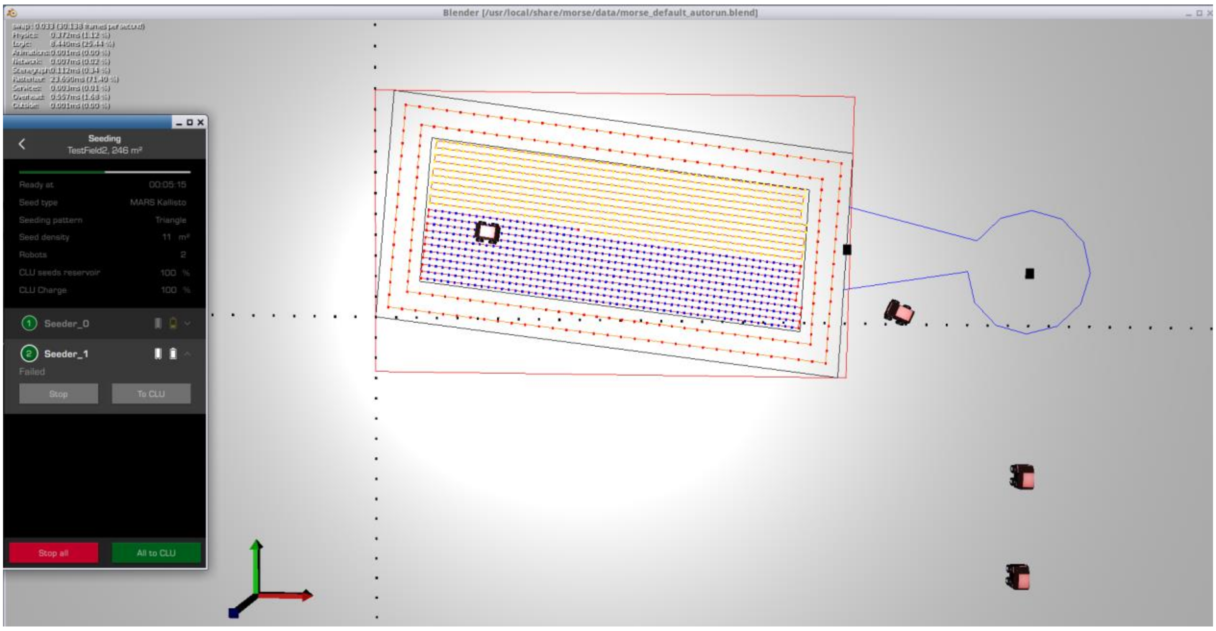


Figure 11: Robot 2 failed during Working Mode. OptiVisor reassigns the remaining work to robot 1 to finish the planned task.

More details about the OptiVisor algorithm can be found in [1]. A demonstration of the OptiVisor algorithm together with a simulated robot swarm can be found under [2].

MARS.3.3: development of robot algorithms (e.g. for traction drive, seeding unit, communication):

- The OptiVisor task (running on robot ECU) is in charge of the communication between OptiVisor and Robot. The communication flow is shown in **Figure 12**.

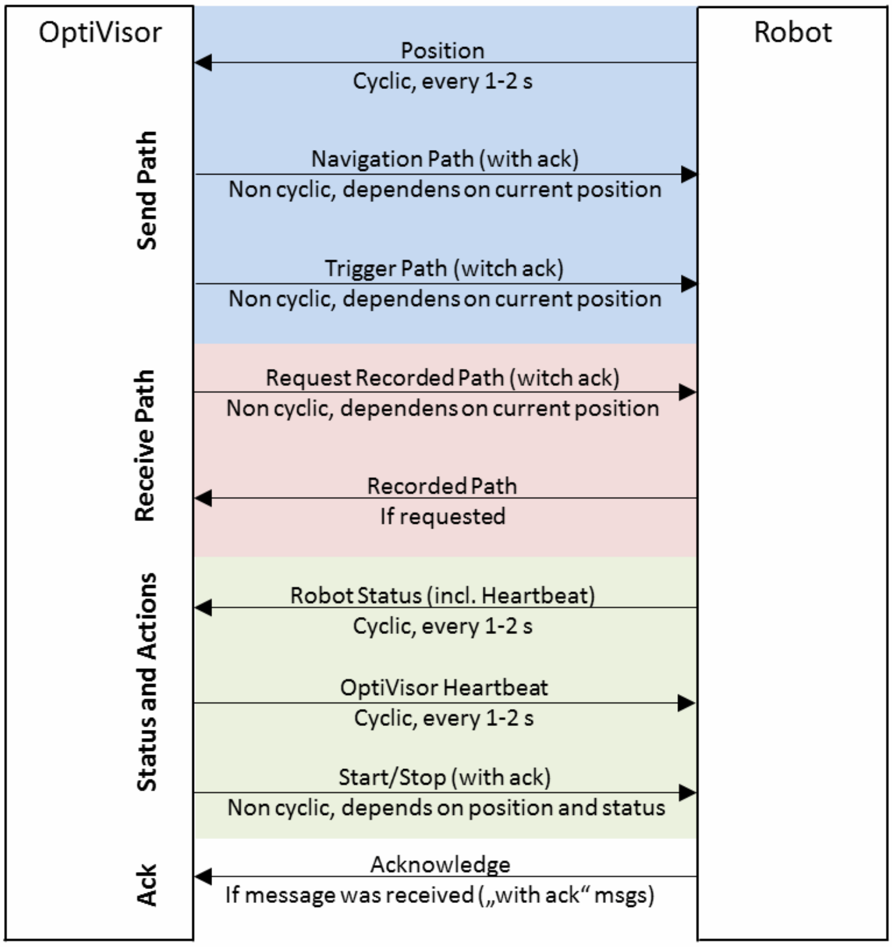


Figure 12: OptiVisor-Robot Communication

- The Guidance task (running on robot ECU) receives the state of the GNSS receiver and of the navigation system. It also communicates with the OptiVisor-Robot task (see above) to process the start/stop commands as well as the navigation path to be able to compute the steering control signal. The flowchart of the Guidance task is shown in **Figure 13**.

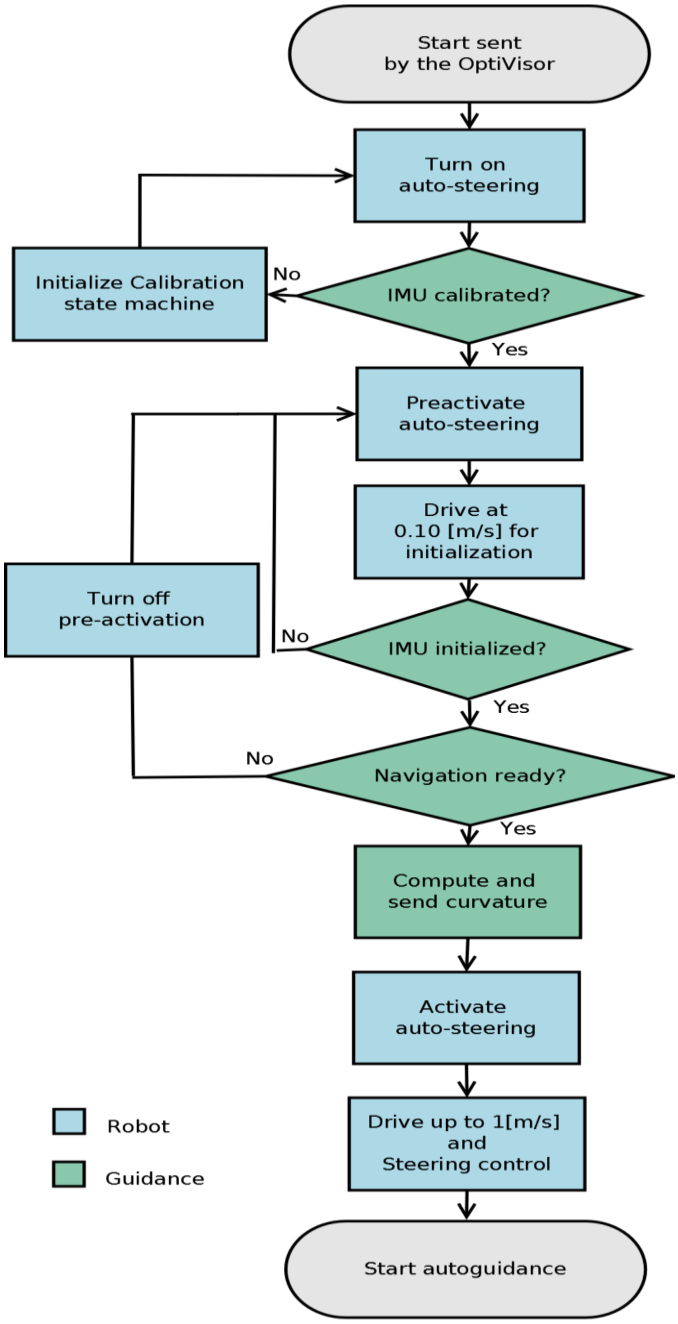


Figure 13: Auto-Steering flow chart.

- Traction Drive and Seeding Unit algorithms: The set value of each engine speed (traction drive) is calculated by the Steering Control (see above) according to the desired turning radius (skid steering) and transmitted to the Motor Controller over CAN-BUS. The set value of the seeding motor is calculated based on the current speed over ground and the distance to the next desired seeding position.

MARS.3.4: Development of HMI (e.g. monitoring app)

The MARS App (**Figure 14**) serves as HMI for planning and monitoring the seeding task. It can be installed either on a desktop PC or a tablet and is connected to the cloud (database, user management) and to OptiVisor (seeding paramters). After selecting a field the user can change the following paramters: seed density, seed type, seeding pattern, name of CLU, position of CLU, available robots. After pressing the “continue” button all parameters are sent to OptiVisor which immediately starts planning the seeding task (e.g. calculation of robot paths).

When the CLU was placed at the predefined location near the filed, the seeding task is started by pressing the “engage” button. This also enables the monitoring mode of the MARS App, showing the current status and location of each robot and the overall status of the seeding task.

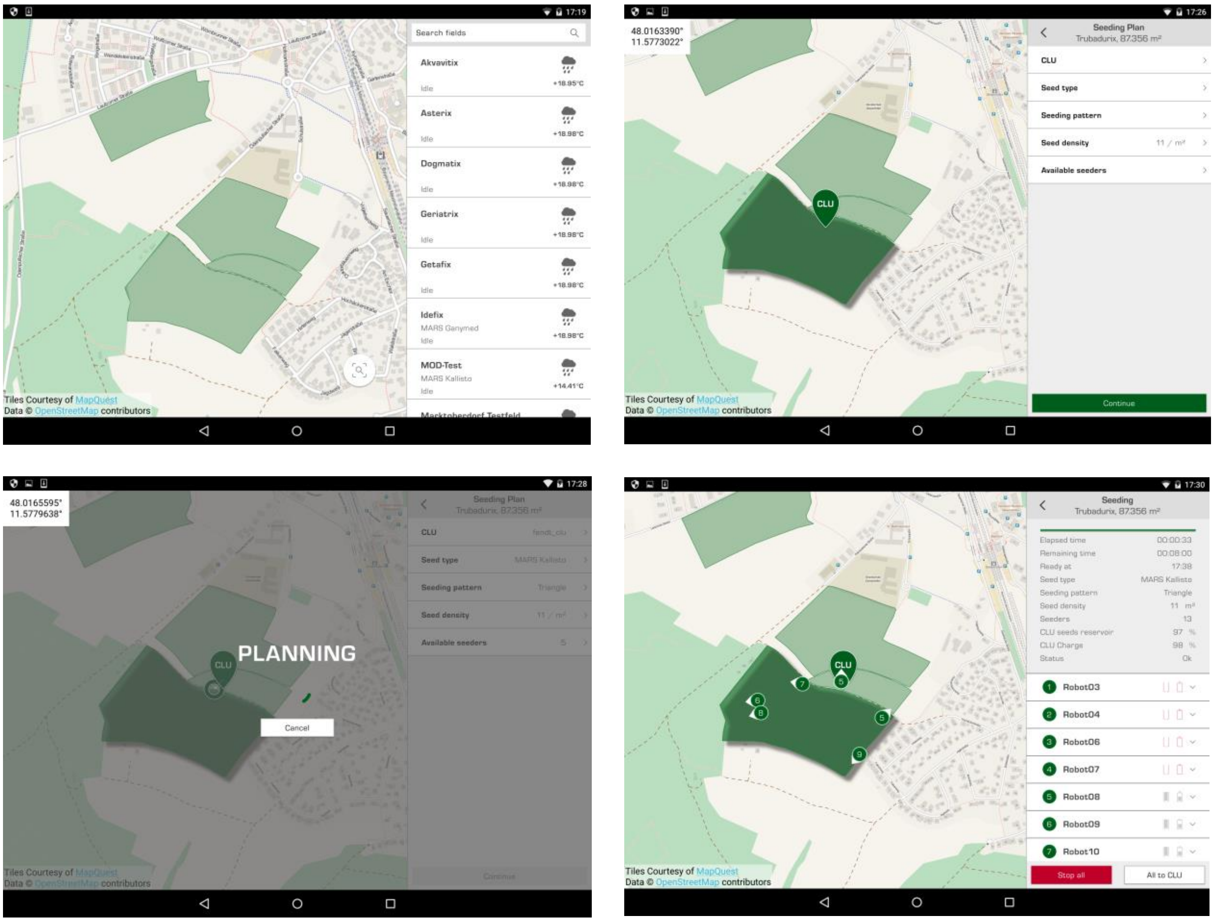


Figure 14: HMI (MARS App) for planning and live monitoring of the seeding task.

Task MARS.4 – System Integration

MARS.4.1: Sensor integration

- Position sensor: GNSS Antenna (Novatel) for RTK-GNSS support for autonomous driving.
- Engine speed sensor: BLDC motor with integrated hall sensors for speed control of traction drives and seeding unit.

MARS.4.2: Integration of algorithms within system architecture

- HMI: Android-App for Tablet. Internet connection to Cloud via Wifi/4G.
- Cloud: Server Application running on Amazon-Cloud. Connection to HMI and OptiVisor/CLU via websockets.
- OptiVisor: Application running on Linux-PC. Connection to Cloud via Wifi/4G. Connection to robots via Wifi.
- Robots: Communication Task implemented on robot ECU (Linux). Connection to OptiVisor via WiFi.

MARS.4.3: Integration of tethered (e.g. robot ECU to seeding unit) and wireless communication (e.g. robot to cloud server)

- Tethered communication:
  Robot-ECU to electric motors (traction drive, seeding unit): CAN-BUS
- Wireless communication:
  CLU/OptiVisor to Robot: WiFi communication
  CLU/OptiVisor to Cloud: Cellular (4G) communication
  Tablet to Cloud: WiFi/4G communication

Task MARS.5 – Implementation and Assembly

MARS.5.1: Assembly of robot chassis and hardware components

Figure 15: Different stages of robot assembly.

MARS.5.2: Assembly of electronic components and wiring

Figure 16: Electronic box with fuses, Wifi-to-CAN Gateway and Motor Controllers.

Figure 17: Electric Motors and wiring.

MARS.5.3: Software implementation on relevant hardware (robot ECU, cloud server, handheld device)

- Implementation of Cloud algorithms on Amazon Cloud: Web-Interface for Data- and User-Management. After the login the user can upload the field boundaries via kml-files. These fields can be selected in the MARS App for seeding. The logged positions of each planted corn are stored in a database, which can be accessed via the MARS App or by the Web-Interface.

- Implementation of guidance algorithm on robot ECU:

  The guidance algorithm relies on the position and heading calculated based on the information from GNSS Antenna and IMU. It controls the speed of the four wheels so the robot follows the predetermined path by OptiVisor, which is sent to the robot via WiFi.

- Implementation of seeding and traction drive controller on robot ECU:

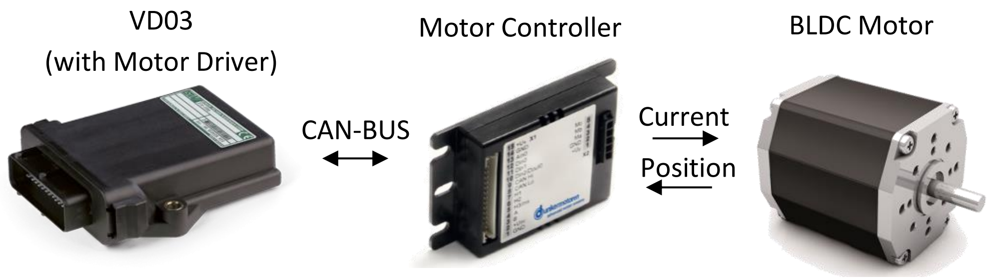


Figure 18: Physical communication layer.

  Figure 18 shows the physical communication layer between Robot ECU (VD03), Motor Controller (MC) and motor. Each MC is connected to one motor and has a unique address. The MC matches the actual motor speed with the received set point speed from the Motor Driver (MD). It also transmits the actual phase current, voltage, temperature of the power electronics, speed and position to the MD via CAN-BUS. This enables a precise control of the driving, turning and seeding speed of the robot.

- Implementation of HMI on handheld device: The MARS App is implemented as Android App on a Tablet, but could be also used on any desktop PC running Windows or Linux. See MARS.3.4.

Task MARS.6 – System Test and Validation

MARS.6.1: Test of seeding unit in laboratory and relevant environment (TRL 4 and 5)

- Test of seeding unit #1 (TRL 4):

Figure 19: Laboratory and field tests of first seeding unit.

- Laboratory test of seeding unit #3 (TRL 4, **Figure 20**)

Figure 20: Laboratory test of seeding unit.

- Test of modified seed singulation.
- Test and calibration of seed handover between fixed and rotating parts.
- Test of seed channel and seed handover (towards stamp) inside of rotating seeding unit.
- Test of stamping mechanism.
- Test of closing mechanism (sealing of stamp channel).
- Validation through high speed movies (**Figure 21**).

Figure 21: Still frame taken from high speed recording of seeding unit during laboratory test.

- Field test of seeding unit #2 and #3 (TRL 5, **Figure 22**)
  - Validation of laboratory tests in real environment conditions.
  - Test of soil influence on stamping mechanism (increase of friction, clogging through sticky soil).
  - Validation of appropriate seed placement and seed treatment (right depth, right pressure, coverage with soil).
  - Endurance test.
  - Validation of different closing mechanism (sealing of stamp channel).

Figure 22: Field test of seeding unit #2 and #3.

MARS.6.2 + 6.3: Test of components (drivetrain, communication devices) and robots in laboratory and relevant environment (TRL 4 and 5).

- Joint tests of components (drivetrain, communication, electric/electronic periphery).
- Test and validation of drivetrain:
  - Driving on hard surface (paved road): Steering, Acceleration, Breaking, Zero-Turn-Behavior.
  - Driving on soft soil (field): Steering, Acceleration, Breaking, Zero-Turn-Behavior.
  - Increase of max. available torque through passive cooling of motor controllers.
- Test and validation of communication devices:
  - Manual steering of robot through WiFi connection between robot and tablet.
  - Sending and receiving of navigation path and seed positions.
- Test and validation of electric/electronic periphery:
  - Validation of battery runtime.
  - Validation of overall electric architecture and robustness in rough field conditions.

MARS.6.4: System test and validation in relevant environment (TRL 5)

Figure 23: First system tests.

Figure 24: System test in relevant environment (field test).

Test of overall system including Tablet, OptiVisor, Cloud and Robots (see also deliverable MMR):

1. Cloud: Upload of kml-file (generated through GoogleEarth) with field boundaries. (**Figure 25**)
2. Tablet: Planning of seeding task with MARS App (Selecting field, entering seeding parameters, positioning of CLU). (**Figure 26**)
3. OptiVisor: Receiving of user input (parameters from MARS App). Task and path planning for each robot.
4. Tablet: Start of seeding task by pressing “Engage” button. (**Figure 27**)
5. Robots: Receiving navigation path and seed positions. Sending of current status and position. Executing of seeding task. (**Figure 28**)
6. OptiVisor: Entering supervision mode. Supervising current robot status and position.
7. Tablet: Monitoring of current system status and robot position. Possibility to interact with robots by pressing “stop” or “back to CLU”. (**Figure 29**)
8. Cloud: Documentation of seed positions. (**Figure 30**)

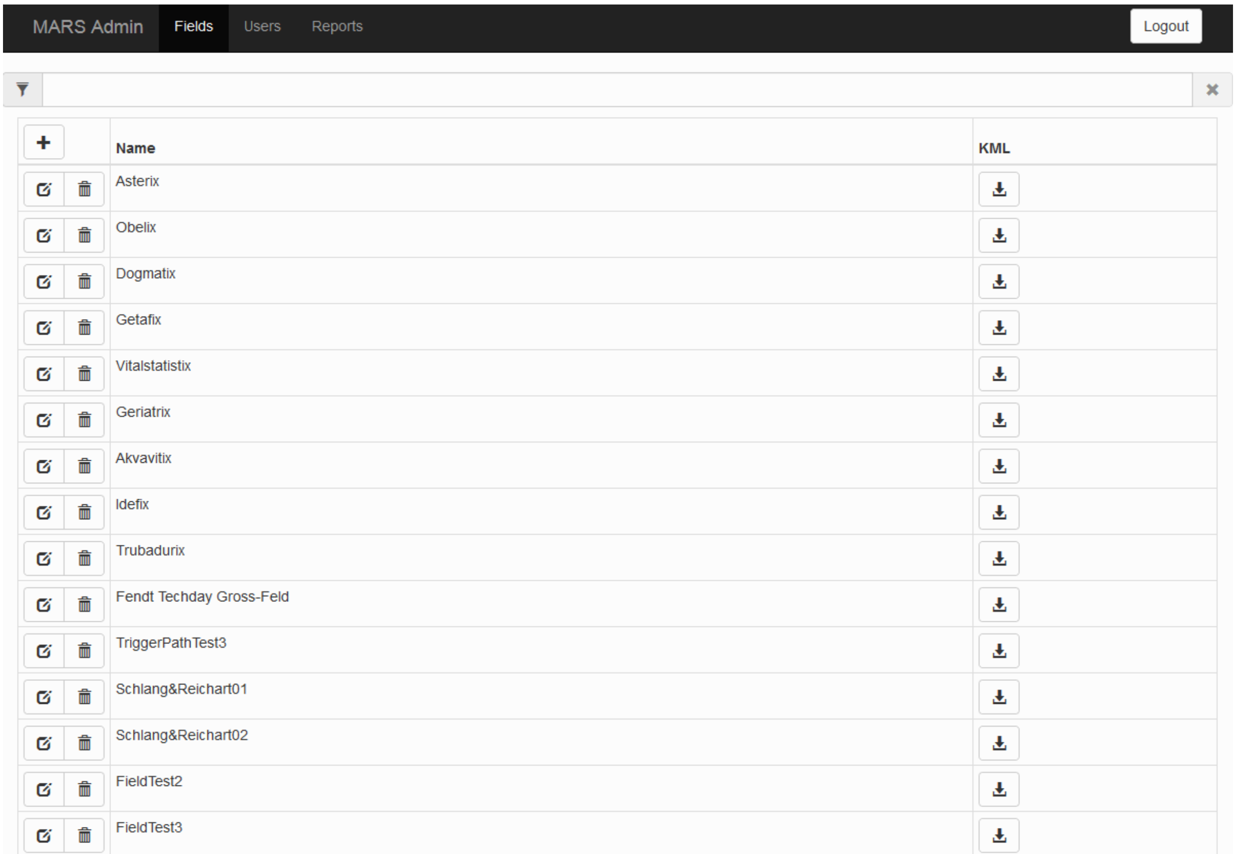


Figure 25: Upload of field boundaries (KML files, web interface).

Figure 26: Planning of seeding task (field selection, parameter adjustment).

Figure 27: Starting the seeding task.

Figure 28: Robots executing the seeding task.

Figure 29: Monitoring of current system status and process.

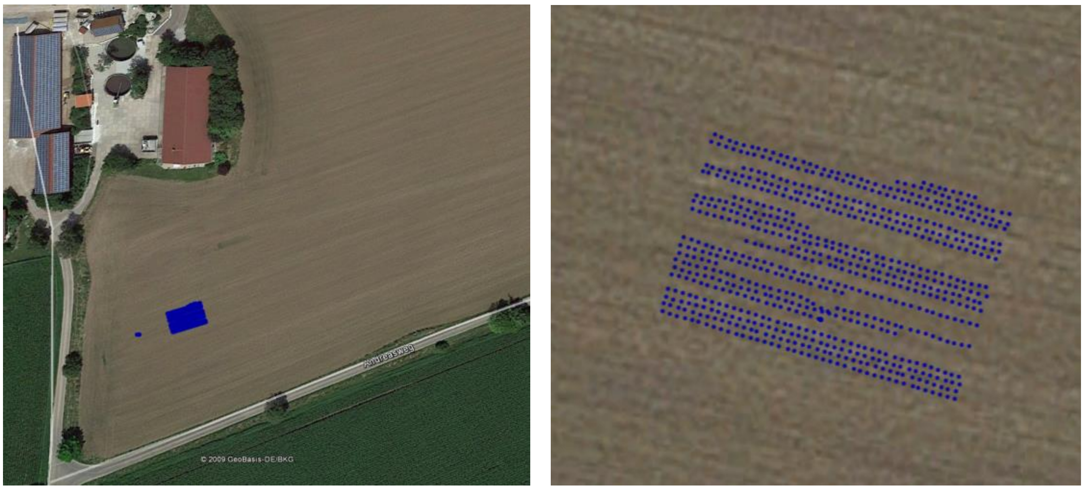


Figure 30: Documented seed positions (KML file downloaded from Cloud via web interface). Snapshot taken during execution of seeding task.

Section 2.2: Scientific and technological achievements

- Patents: 5 patents pending (1 for MARS concept, 4 for seeding unit).
- TRL: TRL 5 (Validation in relevant environment) reached. See reports and deliverables.
- Technical KPIs:
  - OptiVisor Algorithm (Deliverable D2)
    https://www.youtube.com/watch?v=dgksZDH1JN8
  - HMI on handheld device
    See MARS.3.4 (chapter 2.1).
  - Seeding Unit
    See MARS.2.3 and MARS.6.1 (chatper 2.2).
    Development of new seeding unit suitable for small robots from scratch. No suitable device available on the market. Core device of MARS robot and enabler for future seeding robots.
  - Energy consumption (KPI Impact Report)
    75 % reduction of CO_2 emission, exceeding the goal of 20 % CO_2 reduction by 2020.

Section 2.3: Socio-economic achievements

Major impact related KPIs (for detailed description see KPI Impact Report):

- Simplification and Cost Reduction
  - MARS vs. conventional equipment
    MARS equipment: appr. 15 % cost reduction compared to conventional equipment.
  - No tractor for planting needed: Freed-up resources (tractor, operator) for other tasks.
  - Reduction of labor costs: No driver needed during the planting process (10.01 €/h → 1 k€/year).
  - No special tools or heavy workshop equipment needed: Robots are small, lightweight and easy to repair.
  - Easier transportation. No need for big industrial trucks.

- Scalability
  - MARS robot for other tasks (spraying, fertilizing). Only one third of the available installation space of a MARS robot is used for basic components. The remaining space can be used for installing tools.
  - The SmartMDSD Toolchain of Hochschule Ulm supports scalable system composition from previously developed software components and the distributed development of new components. Thanks to this approach, components that were developed prior to MARS (e.g. the SmartMorseBaseServer and SmartCdlServer) have been re-used in MARS. Other components that are developed within MARS (e.g. OptiVisor, SmartMARSMotionControl, SmartMARSRobotInterface) can be used to compose new systems beyond MARS.

The service-oriented and component-based approach of SmartSoft allows for exchanging individual components without altering the system architecture. Using this approach, the MARS scenario can be run in simulation or real-world by solely exchanging respective components. While in real-world only 2 robots are available for testing, the scalability of the MARS approach has been demonstrated in simulation with a large number of robots (up to the computational limits of the platform running the OptiVisor). This significantly reduced the testing effort and allowed for an evaluation in all kinds of different settings covering a huge bandwidth of scenarios. Performing the simulation with a flexible number of robots is a helpful method to gain important knowledge about the procedure like the optimal number of robots that should be used for specific fields.

While the SmartMDSD Toolchain was not developed within MARS, its application in the MARS project has led to the identification of new requirements considering robot fleets and swarm robotics that are not yet covered within the SmartMDSD Toolchain. These are currently taken up to consolidate and extend the SmartMDSD Toolchain. The step from single robots to robot fleets will have impact way beyond the MARS project.

MARS contributed in bringing the SmartMDSD Toolchain closer to the end user since, thanks to MARS, the toolchain has been "demonstrated in operational environments" (technology readiness level 6 according to [3]). The insights of applying the toolchain in MARS and other projects were reported in a user-study in [4].

- Improvement of Crop Production
  - Yield increase by optimized seed pattern: 5 % [5]
  - Reduction of fertilizer by applying site-specific nitrogen fertilizing: 2 to 8 % [5]
  - Reduction of pesticides: up to 50 % [5]
  - Fewer operators, farmer can focus on other duties.
  - Freeing of machinery capacity: No tractor needed for seeding process.

- Increased Safety
  - Robots are lightweight: Total weight < 50 kg
  - Robots have low-power motors: Max. power < 960 W (short-term, total).
  - Robots operate at low speed: Driving speed < 4 kph.
  - No interaction with moving robots
  - No high pressure oil, no high temperature components.

- Environmental impact and sustainability
  - 75 % reduction of CO_2
  - Reduced soil compaction: Robot ground pressure appr. 0.1 bar vs tractor ground pressure appr. 0.8 bar.
  - Less material use: Robot fleet = 400 kg, Planter = 2345 kg (with fertilizer tank)
  - Less environmental pollution: up to 50 % reduction of chemicals [5]

  - No danger of oil spillage, less noise (20 dB lower)

- Simplified service principles
  - Robot maintenance can be done by one person on a desk.
  - Remote software updates through cloud and OptiVisor.

- Increased reliability compared to conventional equipment
  - Impact of single unit breakdown compensable by other robot units
  - Less mechanical complexity, fewer drives and no operator misuse

- Possible cross domain transfer (proposed ideas)
  - OptiVisor algorithm for logistic tasks
  - RTK controlled system for navigation in production plants

- New cost structure; robots replacing conventional equipment (see “simplification and cost reduction”)

- Promotion of new agricultural processes
  - MARS supports modern tillage approaches (e.g. no-tillage, strip-tillage).
  - MARS enables new approaches for subsequent tasks (e.g. fertilizing, plant protection) through storing the exact location of each seed.

Section 2.4: Dissemination activities

Dissemination Plan

Type	Planned	Achieved
Fairs	Agritechnica	InnoRobo 2015, Lyon Hannover Fair 2016, Hannover Automatica 2016, München
Magazines, newspapers, journals, etc.	ATZ off highway Mobile Maschinen	See below list of press releases and journal articles.
Conferences	ERF (European Robotics Forum)	Robobusiness 2015, Milan (Presentation) IROS 2015, Hamburg (ECHORD++ booth) ETFA 2015 (Paper presentation) ERF 2016, Ljubljana (Networking) ETFA 2016, Berlin (Panelist) IECON 2016, Florenz (Paper presentation) Ulmer Robotertag 2016, Ulm (Presentation) Bits&Pretzels 2016, Munich (Presentation) International Agricultural Robotics Forum 2016, Toulouse (Presentation) VDI Conference LAND.TECHNIK 2016, Cologne (Presentation)
Multi-media or web based dissemination	AGCO Website	AGCO Website HS Ulm Website
Other	MARS Movie	MARS Movie (YouTube Channel Fendt-TV) YouTube Channel of Servicerobotics Ulm

Indicator	Planned	Achieved
Theses	4 Theses	3 diploma theses (2 seeding unit, drive train) 2 master theses (CLU, agronomic potential) 1 bachelor thesis (seeding unit)
Publications	1 Publication	3 Publications (see below list of journal articles and papers)
Invention	2 Patents	5 Patents (pending)

- Press:
    - First press release (kick-off) published on www.fendt.com and Facebook (Fendt Global), April/May 2015
      Title: MARS Mission in Agricultural Engineering. Cited by profi, www.profi.de
    - eilbote, www.eilbote-online.com, and B4B Schwaben, www.b4bschwaben.de
    - Press release Hochschule Ulm, 29.05.2015, http://www.hs-ulm.de/de//?open_id=4
    - MARS Report, Neu-Ulmer Zeitung, 15.07.2015
      http://www.augsburger-allgemeine.de/neu-ulm/Statt-Traktoren-sollen-bald-Roboter-ueber-die-Felder-rollen-id34793902.html
    - MARS Radio Interview, Antenne 1, 29.07.2015
    - MARS report, kompakt 01_2015, journal of Hochschule Ulm
    - Midterm press releases Südwest-Presse: Roboter säen den Mais
      http://www.swp.de/ulm/lokales/ulm_neu_ulm/Roboter-saeen-den-Mais;art4329,3708965
    - Press release MARS Website Go-Live on fendt.com
      http://www.fendt.com/int/de/news-detail.asp?p=page_3436_web_de
    - Press release MARS at Hannover Messe
      http://www.fendt.com/int/news-detail.asp?p=page_3547_web_en
    - VDI News about MARS presentation (Ulmer Robotertag)
    - Ke-NEXT.de Online Magazine (with Interview)
      https://www.ke-next.de/videos/wie-roboterschwaerme-die-landwirtschaft-veraendern-sollen-202.html
    - Fendt press conference Int. presse conference on Sep 1, 2016, 11h. First presentation of MARS Teaser. MARS Teaser available in 6 different languages: german, english, french, italian, russian, spanish.
    - Press release: „Cloud solution for location-independent robot control"
      http://www.fendt.com/int/news-detail.asp?p=page_5002_web_en
    - Press release: "Brezeln auf dem MARS"
      http://www.fendt.com/de/news-detail.asp?p=page_5606_web_de-DE

- Journal Articles and Papers
    - Timo Blender and Christian Schlegel. Motion Control for Omni-Drive Servicerobots under Kinematic Dynamic and Shape Constraints. In Proc. of the 20th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Luxembourg, September 8-11, 2015 (10.1109/ETFA.2015.7301401).
    - Benno Pichlmaier and Thiemo Buchner: MARS – Forschung im Bereich Feldrobotik, Mobile Maschinen (4/2016).
    - Paper for IEEE IECON2016: Timo Blender, Thiemo Buchner, Benjamin Fernandez, Benno Pichlmaier, Christian Schlegel. Managing a Mobile Agricultural Robot Swarm for a Seeding Task. The 42nd Annual Conference on IEEE Industrial Electronics Society Florence, Italy, October 2016

- Fairs and Conferences:
  - Robobusiness 2015 (Milan): “Project MARS – A Simplicity Approach on Agricultural Robotics”. Benno Pichlmaier, AGCO.
  - InnoRobo: Project MARS, Lyon, 01.07.2015 - 03.07.2015.
  - IROS 2015: MARS Video on display at ECHORD++ booth of IEEE/RSJ IROS 2015, Hamburg, 28.09.-02.10.2015.
  - Echord++ Review: Presentation of MARS Experiment, ECHORD++ Review, Lisbon, Portugal, 19.10.2015.
  - HS Ulm Open Labs, „Nacht schafft Wissen“: MARS poster, 03.12.2015.
  - 9. Ulmer Robotertag 2016: Presentation „MARS - Roboterschwärme auf dem Feld" (German), Thiemo Buchner, AGCO. http://www.servicerobotik-ulm.de/drupal/sites/default/files/2016-03-10_MARS_Ulmer_Robotertag_public.pdf
  - Hannover Messe 2016: MARS booth (3D model, video and tablet-UI).
  - Automatica 2016, Munich: MARS booth (3D model, video and tablet-UI).
  - Bits & Pretzels 2016: Live-Demonstration of MARS Robot.
  - IEEE IECON2016: Presentation “Managing a Mobile Agricultural Robot Swarm for a Seeding Task”, Timo Blender, HS Ulm.
  - International Agricultural Robotics Forum 2016 (Toulouse): “Project MARS – A Simplicity Approach on Agricultural Robotics”. Thiemo Buchner, AGCO.
  - 74. International VDI Conference LAND.TECHNIK 2016 (Cologne): "Einzelkorn Saateinheit für mobile Agrarroboter (Forschungsprojekt MARS)”, Johannes Utz, AGCO.

- Websites and Facebook posts:
  - MARS Website by FENDT: www.fendt.com/mars
  - MARS Website by HS Ulm: http://www.servicerobotik-ulm.de/drupal/?q=node/75
  - Facebook post from Fendt Global about MARS:
    more than 38.000 people reached, more than 1.300 clicks, more than 240 reactions

- Videos:
  - MARS Teaser: https://www.youtube.com/watch?v=Wc23f52lfX0
  - MARS Video about OptiVisor: https://www.youtube.com/watch?v=dgksZDH1JN8

Section 3: Resource usage summary

Preliminary resource summary AGCO*

Type	Usage	Details
Personnel costs	93 % of approved budget	27 APMs: Thiemo Buchner, Benjamin Fernandez, Simon Pinter
Travel	42 % of approved budget	Meetings, Fairs, Conferences
Equipment	49 % of approved budget	Workshop supplies, small generator
Consumables	179 % of approved budget	Mainly robot parts
Total	**107 % of approved budget**	

Preliminary resource summary HS Ulm*

Personnel			
M. Sc. Timo Blender		01.05.15 – 31.10.16	
M. Sc. Dennis Stampfer		01.06.16 – 31.10.16	
Traveling			
1	Kick-Off, Paris-Orsay	14.01. – 17.01.15	Schlegel
2	Project Meeting, AGCO Marktoberdorf	15.07.15	Blender, Schlegel
3	IEEE ETFA Conf., Luxemburg, Paper Presentation	07.09. – 12.09.15	Blender
4	ECHORD++ Review, Lissabon, Project Presentation	18.10. – 21.10.15	Schlegel
5	Software Test, AGCO Marktoberdorf	03.02.16	Blender
6	Software Test, AGCO Marktoberdorf	23.02.16	Blender
7	Hannover Messe Industrie, Exhibitor	26.04. – 30.04.16	Blender, Schlegel
8	Software Test, AGCO Marktoberdorf	10.06.16	Blender
9	AUTOMATICA München, Exhibitor	21.06. – 23.06.16	Blender, Schlegel
10	Software Test, AGCO Marktoberdorf	05.07.16	Blender
11	IEEE ETFA Conference, Berlin, ECHORD++ Panelist	05.09. – 09.09.16	Schlegel
12	Software Test, AGCO Marktoberdorf	15.09.16	Blender
13	Software Test, AGCO Marktoberdorf	22.09.16	Blender
14	Software Test, AGCO Marktoberdorf	29.09.16	Blender
15	Integrated Scenario Testing, AGCO	10.10. – 14.10.16	Blender
16	IEEE IECON Conference, Florenz, Paper Presentation	23.10. – 28.10.16	Blender
17	ReApp Workshop, Karlsruhe	27.10.16	Stampfer
18	Software Test, AGCO Marktoberdorf	14.11.16	Blender
19	Final Project Review, Marktoberdorf	17.11.16	Blender, Schlegel
20	WS Business Model Innovation, München	28.11 – 29.11.16	Blender
Consumables			
1	RTK GPS (Emlid) for Real-World Algorithm Testing		

* see final financial report (due end of 2016) for details.

Section 4: Deviations and mitigation

AGCO:

- Deviation in resource usage (consumables) due to higher material costs than expected.
- Deviation in resource usage (personnel costs) due to employee change. Compensation through outsourcing of certain tasks (no costs claimed).

Section 5: Future work

The further development of the MARS system, including robots, CLU, cloud algorithms and OptiVisor, is promising. Next steps include a further simplification of the seeding unit while increasing its reliability, the integration of the finger meter (seed singulation) and the design and manufacturing of a CLU prototype. The miniaturization of the seed singulation would be a major step towards the usage of small robots for seeding. Regarding a more cost-effective robot navigation system, further research and technical development need to be undertaken, as it is a key-enabler for further robotic applications in the agricultural domain. The development of more cost effective and integrated components (e.g. battery, motor, chassis, motor controller) should be adressed together with industry partners.

Section 6: Lessons learned (optional)

- Early start of seeding unit design was essential for the project’s success as the number of possible design iterations was limited due to the long manufacturing process. A simulation model could have saved some time.
- A lot of effort was put into the development of the guidance algorithms to reach a proper steering behavior of the robot units. The main reason for this is that the robot uses skid steering which causes a soil-dependent change of the instant center of rotation.
- The development of a miniaturized seed singulation device was not successful due to the complexity of handling biological materials like seeds. A standard finger meter was used instead.

Section 7: References

[1] Timo Blender, Thiemo Buchner, Benjamin Fernandez, Benno Pichlmaier and Christian Schlegel: *Managing a Mobile Agricultural Robot Swarm for a Seeding Task*, In Proc. Industrial Electronics Society, IECON 2016 - 42nd Annual Conference of the IEEE, Florence, Italy, October 24-27, 2016.

[2] YouTube-Link: *https://www.youtube.com/playlist?list=PLJxdA4EZjZiXp_uk_9d18BrkX9SCf6lAI*

[3] euRobotics aisbl: *Robotics 2020 Multi-Annual Roadmap*, Dec 2015.

[4] Dennis Stampfer, Alex Lotz, Matthias Lutz and Christian Schlegel. *The SmartMDSD Toolchain: An Integrated MDSD Workflow and Integrated Development Environment (IDE) for Robotics Software*. Special Issue on Domain-Specific Languages and Models in Robotics, Journal of Software Engineering for Robotics (JOSER), 7(1), 3-19 ISSN: 2035-3928, July 2016.

[5] C. Rösch et al.: *Precision Agriculture*. TAB Arbeitsbericht Nr.106. 12/2005.