A modular control architecture for safe and robust robot operation and inspection in steep slope vineyards[1]

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Abstract: In fall line cultivation of vineyards, the vines are planted vertically to the hill's slope. Therefore, steep slope vineyards require a high amount of manual labor, doubling production costs. Working in such environments is exhausting and laborious. Therefore, autonomous robots should assist humans in reducing costs and increasing safety. However, current state-of-the-art robotic systems and control architectures are not designed to work in such harsh environments with extreme terrains. Therefore, this work proposes and modular control architecture for safe and robust autonomous working in steep slope environments. Tests in an authentic vineyard near the Moselle river in Germany prove the approach's feasibility and robustness.

Keywords: Off-Road Robotics, Steep Slope, Agricultural Robots, Behavior-Based Control, Control Architectures

1 Introduction

A vineyard's layout is typically in fall line cultivation. In this kind of cultivation, the vines are planted vertically to the hill's slope. The authors of [SML21] highlight that extremely steep slope vineyards suffer from the disadvantage of higher manual labor, resulting in more than twice the labor costs per hectare considered over one working year. However, there is a cultural desire to preserve the cultivation of these steep slopes, which have a decisive influence on the appearance of wine-growing regions such as the Moselle or Ahr valleys in Germany. From an ergonomic point of view, working an entire day in such an environment is exhausting and laborious for a person. Therefore, there is a particular need to automate this steep slope work. According to a Geisenheim University survey of 500 self-marketing wineries with steep slopes [SML21], the median winery has an area of 2.5 ha of steep slope vineyards. This small amount often does not justify purchasing a crewed steep slope vehicle, whose acquisition costs with attachments and associated trailer can reach a lower six-figure amount, depending on the manufacturer. Therefore, an objective is offering a crewless vehicle that is affordable in its acquisition costs even for smaller wine estates and saves additional labor costs through autonomous work.

[1] This work was founded by the Federal Ministry of Food and Agriculture, Germany (BMEL) and is part of the project *experimental field southwest* (`https://ef-sw.de`).

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A particular challenge for autonomous working in steep slopes is the extreme environmental conditions. Typical state-of-the-art algorithms regarding off-road navigation and working consider moderate terrains, e.g., [Br13], [Ga19]. Accordingly, navigation planning and perception need to consider the terrain-based challenges in addition. However, a vineyard is typically clearly structured. Therefore, some assumptions regarding the surroundings can apply, which reduces complexity. Therefore, this work presents a modularized control framework that considers steep slope vineyards' specialties for autonomous traveling and inspection.

This paper introduces configurable, modular control framework for safe and robust inspection of steep slope vineyards. Therefore, Sect. 2 presents related work to autonomous working in vineyard applications and related control architectures. Details on the demonstrator robot are available in Sect. 3. Sect. 4 provides an overview to the integrated behavior-based control architecture iB2C, which is fundamental for designing a robust, fault-tolerant off-road control concept. Sect. 5 presents details of control architecture. There was a special focus on properties as extensibility, robustness, maintainability, and a lightweight implementation. Finally, Sect. 6 provides experiments and Sect. 7 summarizes and concludes.

2 Related Work

There is an enormous variety of agricultural vehicles. The authors of [KFP17] illustrate that machines that work on an agricultural terrain with a slope of more than 60% require a winch to prevent accidents. Therefore, the relevant category for steep slope viticulture vehicles have such a device, and the following focuses on such systems in more detail.

Established viticulture vehicle systems usually consist of two subsystems: A transport platform that moves on public roads, typically a trailer or sometimes a self-propelled tool. The second component is the working vehicle itself driving between the trellis. A person sitting on top controls the vehicle and manually works and switches on or off the corresponding device. Most of these vehicles are crawlers because of their excellent ground contact and the low center of gravity[3]. The drawback of tracked vehicles is the height, weight, and ground erosion caused by the weight.

Existing control technology in agriculture which could be beneficial for the use cases in viticulture, are primarily developed for flat terrain. The authors of [Ad17] show an approach of a teleoperated agricultural robot that applies a spraying agent to the plants. [Sa18] shows the path planning for a robot used in vineyards for crop monitoring. The automated task of dispersion of pheromone dispenser is explained in [Ro18]. There are few crewless, autonomously operating vehicles for steep slope viticulture as Geisi [SBK12], [Br17], or Slopehelper [Ba21].

[3] Exemplary systems exist here `https://www.geier.it/de/modelle/ueberblick/`

There are two main drawbacks regarding the existing robots: massive construction and limited autonomy skills. In particular, SLOPEHELPER[4] is a large robot with a weight of nearly two tons and a width of 160 cm. Accordingly, the vehicle is too large to safely operate within the narrow vineyard conditions addressed by this contribution. Also, the soil corrosion and ground compaction are too extensive. In general, the autonomy skills of these robots are minimal (e.g., tactile driving to keep the lane). However, there is a demand for automated mapping and documentation through robots to support winemakers and allow intelligent farm management. Accordingly, the robot requires mapping plants, detecting diseases, and estimating harvest failures. Therefore, this work proposes a modular architecture beyond low-level vineyard navigation.

3 Steep Slope Vineyard Inspection Robot

Fundamental design considerations of the applied steep slope inspection robot provides [KGB21]. The robot is a lightweight carrier system with a low center of gravity and can equip various attachments as sprayers (see also Fig. 1). Accordingly, there is a separation of concerns between driving and working subsystems. The robot secures through a steel cable, which controls the longitudinal motion through a winch and prevents falling. Tab. 1 shows the most important driving relevant properties. They define the configuration of the low-level safety systems as stop distance, rollover prediction, or trajectory correction.

Tab. 1: Hardware and kinematic specification of the demonstration robot.

Property	Value	Property	Value
Wheel Base	1.18 m	Max. Velocity	$1.50\,\mathrm{m\,s^{-1}}$
Track Base	0.69 m	Max. Curvature	$0.84\,\mathrm{m^{-1}}$
Vehicle Length	1.71 m	Min. Turning Radius	1.18 m
Vehicle Width	0.76 m	Min. Turning Cycle	2.36 m
Vehicle Height	0.75 m	Max. Ground Clearance	0.26 m
Tire Radius	0.28 m	Tilt Angle*	32.80°
Length KC To Front	0.31 m	Max. Fwd Incl. Angle*	00.00°
Length KC To Back	1.40 m	Max. Bwd Incl. Angle*	46.00°

* under the assumption of a mounted sprayer attachement and higher center of gravity

The driving kinematics of the robot is a non-standard differential drive. Three primary criteria affect navigation planning:

controllable winch the winch secures the robot in steep slopes through a steel cable. Additionally, the cable supports the robot's longitudinal motion and aids the localization systems. The winch is located in front of the robot. Therefore, the robot reverses the inclination and drives forward during upwards climbing.

[4] https://slopehelper.com/parameters

kinematic center The robot has four wheels, but only the (larger) front-facing (to the winch) tires are actively controllable. The rear-facing wheels are passive. Therefore, the kinematic center locates at the front axle on the ground.

active front tires The robot's front tires actively control and correct the motion. During descending the slope, the primary motion vector defines through the surface. Therefore, the motion adjustment occurs only through the front tires.

The inspection robot has a symmetrical sensor layout with four stereo cameras covering each side of the vehicle. Additionally, localization sensors exist. Fig. 1 and Tab. 2 illustrate the sensor setup. For cost reduction, the setup avoids deploying laser sensors. However, with an expected price reduction in the future, this constraint may change.

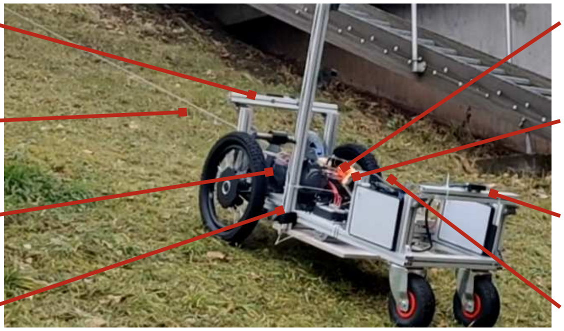

Fig. 1: Early prototype of vineyard inspection robot with the proposed sensor layout during steep slope trials. The robot is secured by a steel cable and controls the inclination climb (here approximately 35°) through a winch. The tires actively correct the robot's motion.

Tab. 2: Corresponding sensor setup. Sensor poses are relative to the kinematic center of the vehicle. (f/ l/ r/ b) indicates a front, left, right, or back mounting. The winch directs to the front.

Sensor	x [m]	y [m]	z [m]	Φ [°]	ψ [°]	φ [°]
ZED2i (f)	1.26	0.00	0.60	0.00°	0.00°	0.00°
ZED2i (b)	-0.32	0.00	0.60	0.00°	0.00°	180.00°
Realsense D435 (l)	0.50	0.34	0.60	0.00°	0.00°	90.00°
Realsense D435 (r)	0.50	-0.34	0.60	0.00°	0.00°	-90.00°
MS 3DM-GX5-25	0.00	0.00	0.60	0.00°	0.00°	0.00°
u-blox NEO7P	0.00	0.00	0.80	0.00°	0.00°	0.00°

4 Integrated Behavior-Based Control

Behavior-based systems have been well known since the 1980s for robots' reactive and robust control. Brook's subsumption architecture changed design of control systems fundamentally [Br86] and many behavior-based robots followed over time, e.g., [Ar98], [Ma90], [Jo04].

A more recent behavior-motivated approach, inspired from the gaming industry and in particular the popular game Halo 2 [Is05], are behavior trees [Io20]. They allow for dynamically reacting to unstructured environments due to the high modularity and reactivity.

The integrated behavior-based control (iB2C) architecture [RWB17], developed at the Robotics Research Lab of the TU Kaiserslautern, provides a behavior-based framework that decouples control and data flows. It includes a partial activity of behavior nodes. Accordingly, it can represent non-discrete states. Therefore, a BBS has a unique way of system arbitration which creates robustness and flexibility. It consists of highly distributed and parallel units with overlapping functionality. The resulting behavior emerges from the direct interaction of those components. Also, iB2C explicitly focuses on modeling behavior-based perception systems.

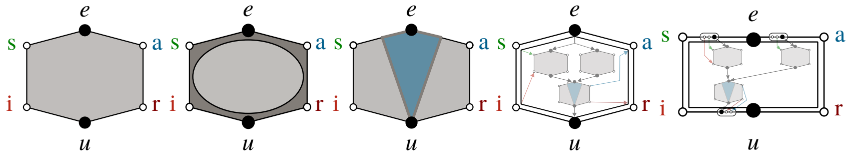

Fig. 2: The different components of the iB2C architecture [Wo21]: Module, Percept, Fusion, Group, Layer.

An important concept of iB2C is modularization, abstraction, and interaction of different components (Fig. 2). Therefore, an iB2C behavior network has multiple (simple) behaviors that interact. Accordingly, a behavior network shows the control and data flows in a graph-like appearance similar to the execution order. A module is the standard unit for control context and percepts tailored towards perception systems. Fusion behaviors resolve conflicts, which arise from parallelism and overlapping functionality. Behavior systems tend to grow large through modularity. Therefore, groups and layers provide encapsulation to avoid arbitrary connections between subnetworks. Therefore, a group acts as a single behavior within the network and denotes a strict encapsulation. Layers encapsulate softly concerning the semantical meaning. Therefore, they provide additional layer interfaces which provide access to selected behaviors encapsulated by the layer.

Each behavior offers a standardized interface for system arbitration using an *Activity Function* $f_a e \in 0,1$. Additionally, data processing uses a specialized interface with the *Transfer Function* Fe that computes output data u based on inputs e. It can be *stimulated* by another behavior's activity via the stimulation input s and *inhibited* via the inhibition input i. The behavior's internal *potential* $\phi = \min\left(s, 1 - i\right) \in 0,1$ describes the effective relevance of a behavior in the network. It limits the behavior's *activity* $a = \min\left(\iota, f_a e\right) \in 0,1$ which represents the amount of influence in the current system state. The *target rating* $r = f_a e \in 0,1$ resembles the behavior's contentment with the current system state. While the so called *meta-signals* s, i, a, r are strictly defined in- and outputs, the vectors e and u can carry arbitrary sensor and control data.

An example for a rollover prevention safety system shows Fig. 3. Data flow connections show black, stimulation links green, and inhibitions red. The network monitors the roll and pitch angles of the robot stops if a critical value is exceeded.

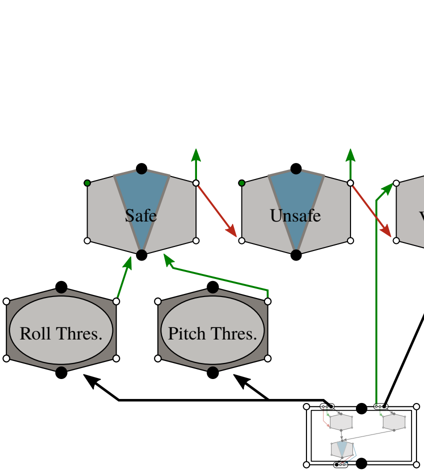

Fig. 3: Example behavior network for rollover prevention in steep slope environments. The robot is default unsafe and inhibits the control velocity. Percept behaviors monitor the safety-relevant inclination thresholds of the robot. If the inclination is within the safety margins, the network actively suppresses the unsafe state. Accordingly, the robot is allowed to set the control velocity. The conflict between stopping and driving resolves the velocity fusion.

5 Modular Robot Control Architecture for Steep Slope Driving

The architecture follows an action-/perception-oriented design [SPB08] and realizes through the behavior-based architecture iB2C. Important properties are

Modularity, extensibility, and maintainability The framework consists of modular control and perception nodes that structure in semantically corresponding layers. The communication realizes by clearly defined interfaces between the layers. This modularity allows for the easy exchange of methods and software components. Accordingly, the system is easily maintainable since the separation of concerns and encapsulation prevent side effects on the remaining software concept. The action-/perception-oriented design further decouples perception and control by exchanging so-called virtual sensors. Therefore, the architecture is also easily extensible since the application requires adding novel hardware for specific tasks to the robot, such as spraying or inspection devices. The corresponding software units must also be easy to integrate, based on the plug-and-play principle.

Robustness The robot operates in a semi-structured environment, but the environmental conditions are still demanding. As the name already indicates, a steep slope vineyard has extreme inclinations, which the robot must consider during driving to avoid damages or accidents. Therefore, the system must behave robustly to environmental disturbances as the weather, illumination changes, and season-related appearance changes. Further, smaller vegetation such as grass, which is no actual obstacle, is not allowed to affect the robot's control and navigation abilities negatively.

Real-time performance The robot must safely navigate the steep slope environment. Therefore, the control systems require to react in real-time (e.g., 20 ms) to avoid collisions or rollover based on the environment. A particular challenge is the detection of negative obstacles. It is only possible to close the gap due to obstructions, and therefore short-term safety must secure the robot.

Light weight implementation A particular aim is cost reduction for the base robot, primarily a carrier system for attachments or personnel. Therefore, fewer computational resources are available, demanding careful management of resources and, thus, algorithms.

An architecture that features many of these properties is REACTiON [Wo18], tailored towards robust off-road navigation in cluttered environments. However, the default architecture requires high computational resources since semantic scene interpretation, and terrain-based navigation planning is done [Wo20].

In contrast, the terrain where the robot operates is semi-structured, and therefore simplifications regarding scene interpretation are possible. A vineyard contains multiple, clearly structured rows. The general structure of a vineyard is somewhat similar compared to other locations, and the vine lines define the track for navigation, and the robots navigate between them. The steep slope vineyards have their trellis scaffolding and vines aligned with the slope. Therefore, the inclination and the plants define the main driving direction. The robot must follow the primary structures and avoid colliding with them or object within the vineyard.

The proposed control architecture (Fig. 4) focuses on the described properties. It consists of an hardware abstraction layer (blue), perception (yellow), control (red) and user interface (gray). An important property of the layered design are the interface definitions. Accordingly, each layer has a clear role within the framework and implementation are exchangeable.

Hardware Interface (blue) The hardware interface encapsulates the physical hardware, either the robot, a simulation, or data playback of recorded data. Accordingly, the interface provides similar data with similar quality. Therefore, the behavior framework, which accesses the hardware interface, cannot distinguish between real, recorded, and simulation data. This modeling allows for testing the control framework under various conditions. E.g., the simulation allows for testing safety-critical situations, which otherwise would destroy the robot or its surroundings. Therefore, the overall probability of the system causing fatal

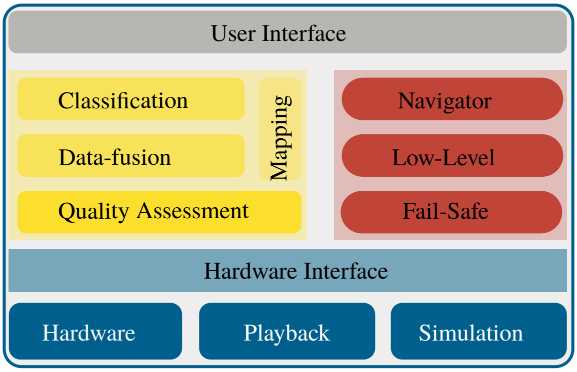

Fig. 4: Overview on the modularized architecture. Each component refers to an iB2C layer and allows a separation of concerns for a high extensibility and maintainability.

damage to the environment or robot reduces. The interface contains the robot's motion data: velocity, curvature, and the steel cable's length. The sensor data streams (camera image, point cloud, IMU, GNSS) are also available.

Perception (yellow) The perception system has different central components: quality assessment, data fusion, classification, and mapping. Initially, the data quality of each sensor system evaluates for disturbances and filters low-quality information [RWB17], [WB21]. Then, data fusion combines different data streams to higher-level information. Examples are point cloud merging and localization filters. Subsequently, an evaluation of data follows. The surrounding categorizes into drivable and non-drivable regions. These segmentation data maps into local grid representations. With this, maps act as short-term memories for sensor data and guide navigation planning.

Control (red) The primary control units are the navigator, low-level, and fail-safe. The navigation planning system is relatively simple due to the structuredness of the vineyard. Nonetheless, a user can advise the robot to navigate to a specific plant or a desired coordinate within the row. A low-level controller monitors the robot's safety by considering obstacles and adjusting the steering to drive collision-free within a row. A fail-safe system avoids falling over (see also Sect. 4).

6 Experiments

Field tests were made in Zell (Moselle), Germany, one of the biggest wine-growing centers in the Moselle wine region. A flat terrain was chosen for initial tests because of the facilitated working conditions. The distance between the vine rows, which is the tramline, is

Fig. 5: Data recording for validation of the control and perception concepts. The sensor setup used on the robot is mounted to an experimental design to check the sensing quality. The Velodyne HDL32E laser serves as the ground truth for the stereo cameras.

Fig. 6: Stereo camera views (front, left, right). The front camera records the steel cable. The sideward facing cameras scan the vine.

equally 2.20 m. In the trellis itself, the vines are planted with a distance of 1.10 m. The first experiments for the sensor setup are done with a frame pulled through a vineyard on a skid (see Fig. 5). Between the first and the second row, the skid was placed and pulled along the row by a winch. On October 22nd 2021, one day before the grape harvest, records were made to receive images of the foliage wall under vintage conditions.

The setup used an additional 3D lidar for reference and ground truth purposes. Otherwise, the sensors matched Sect. 3: The front-facing ZED2i stereo camera served for path planning and the recognition of the vines. The sensor skid contained a RealSense D435 camera on each flank, directed at the foliage wall or the vine. A GPS and IMU sensor was mounted at

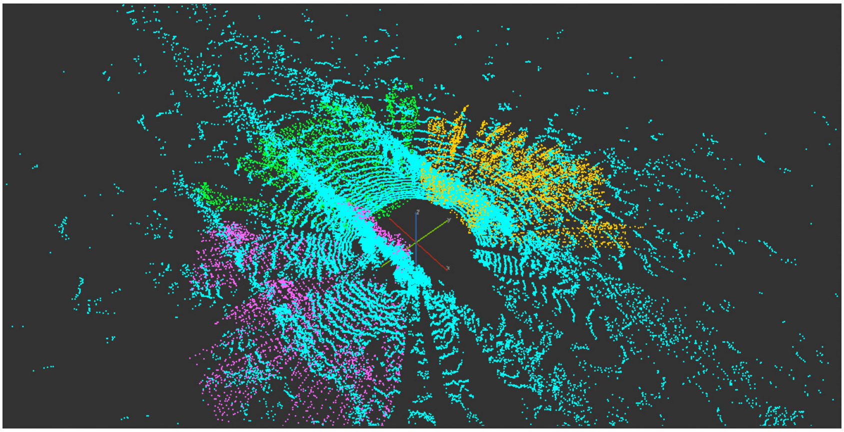

Fig. 7: The combined stereo point cloud. The laser-based reference point cloud is depicted in turquoise. The stereo cameras visualize in green, pink, and yellow.

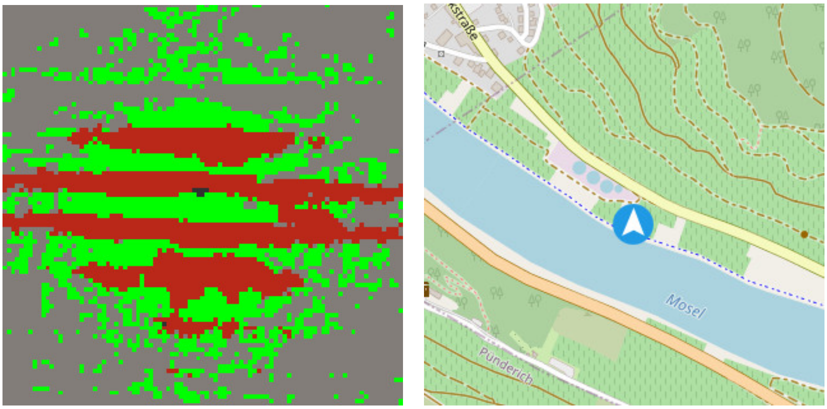

Fig. 8: Occupancy map and localization results. Traversable regions between the vine are labeled green. Plants and objects show in red.

the kinematic center of the vehicle. The ZED camera's roll angle was titled horizontally to investigate the influence of path planning and to create a map.

The skid started at the end of the row. Then, it was pulled with continuous speed along the trellis by a winch. Records of the driven path and the foilage of both sides- and the vine itself were done simultaneously. The orientation and height of the different cameras have been changed during other runs.

Figs. 6–8 visualizes the results of the vineyard tests. An initial observation is that the cameras capture all relevant parts of the vine and the track.

The stereo point clouds match accordingly and build a complete surround view, which is required to segment the vine from the ground. Also, the main structures (poles, stems) are well separated in the point data. Quality assessment filters distorted points, which are typically farther away. The stereo point clouds match accordingly and build a complete surround view, which is required to segment the vine from the ground. The lookahead distance is between 3–5 m (with a deviation of max 0.1 m), which is sufficient for path planning and feature extraction. The segmented information is stored using occupancy grids, representing free passages between the vine. The navigation systems adjust to the surrounding obstacles. Also, the localization showed a good performance since there are few obstructions in a vineyard, and the steel cable supports localization.

One additional finding was that it is sufficient to use one stereo camera in the vehicle's driving direction to generate path planning and mapping images. Thus, no laser point cloud is required from the quality aspect.

7 Conclusion

The contribution introduced a modular control architecture for autonomous inspection and working in steep slope vineyards. Maintaining the work in steep slope vineyards is a cultural desire but comes at a high cost and is labor intensive. State-of-the-art robot systems (Sect. 2) operate either in flat terrain, are heavy, or do not have a substantial amount of autonomy besides simple (sometimes tactile) lane following. Accordingly, Sect. 3 presents a concept for a steep slope robot, which is lightweight, secured by a winch, and can mount attachments. The vehicle has a sensor setup containing localization sensors and stereo cameras to perceive the conditions of the vines and autonomously operate in the vineyard. Sects. 4–5 provided an overview to behavior-based robotics, in particular iB2C, which implements the modularized robot control architecture. Essential properties are robustness, modularity, extensibility, and efficiency. The framework provides quality assessment, data fusion, classification, and mapping systems. Further, there exist navigation planning and low-level/ fail-safe safety systems. Experimentations occurred in a vineyard near the Moselle river using the described sensor setup slide (Sect. 6). There was a high performance, and the sensors proved to perceive and map the surroundings robustly. The robot successfully localized itself within the vineyard and created maps of the trellis lines.

Future work addresses additional tests with the robot in steep slope environments. Also, data sets created during different seasons should allow for automated documentation of the vineyard conditions. A further topic is the automated switching between trellis lines. The robot relies on the steel cable to secure itself from falling. However, the operation space becomes limited to a single row. Therefore, an autonomous carrier as presented in [Wo20] should move the robot automatically to the next row or vineyard, respectively.

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