

Open Platform Based Mobile Robot Control for Automation in Manufacturing Logistics^{*}

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Abstract: In this paper, we present the control of a robotic system for automation in manufacturing logistics based on the Open Platform for Innovations in Logistics (OPIL). OPIL is developed in the scope of the European H2020 project *Smart logistics for manufacturing SMEs* (L4MS), which aims to contend with the ubiquitous challenges in logistics for flexible manufacturing small and medium enterprises (SMEs). We developed the sensing and perception software module as part of OPIL, and a custom navigation module integrated with OPIL. We also developed a novel omnidirectional automated guided vehicle (AGV) suited for transporting the Euro-pallets with the payload of up to 400 kg. We use MURAPLAST d.o.o., the leading producer of Polyethylene (PE) blown film in Croatia, as a case study which demonstrates the effectiveness of the developed system in manufacturing logistics.

Keywords: logistics automation, intelligent manufacturing systems, industrial robots, automated guided vehicles, industrial control

1. INTRODUCTION

Some of the most prevalent modern manufacturing challenges lie in logistics for flexible manufacturing small and medium enterprises (SMEs). According to Gamberi et al. (2009), the logistics accounts for up to 50% of the total manufacturing cost of an item. Tompkins et al. (2010) estimate that in a typical factory transport of parts and components accounts for 25% of employees, 55% of all factory space and 87% of the production time. Automation is seen as a paramount component of reducing the logistics part in the total manufacturing costs. However, while the large manufacturers aggressively invest in logistics automation, SMEs have struggled to benefit from the automation technology due to the inflexibility of solutions, lack of in-house knowledge and large initial investment costs. Aside from the productivity challenges, shorter production cycles and the accentuated product customization require a high degree of flexibility leaving the conventional linear chain production. Modern technology can provide fully automated, modular equipment that achieves both high output and a consistently high quality, with a high degree of decisional autonomy to self-organize the production. However, the lack of standardization and the unavailability of low-cost equipment represent critical constraints for SMEs to adopt this paradigm.

Moreover, the transformation process of a conventional factory into a Smart Factory, embracing the so-called Industry 4.0 (Barreto et al., 2017), requires establishing the right organizational design and enterprise architecture that embraces the convergence of technologies such as robotics, operational technology and IT (Rückmann et al., 2015). This necessarily implies strategic thinking, planning, and re-skilling, thus involving the kind of competences and knowledge that is scarce in the manufacturing SMEs. Innovation always relies upon the combination of technical knowledge and access to finance. In a global competition, companies must invest continuously not only in innovative products but also in innovative production processes. The adoption of robots and IT infrastructure for logistics automation demands significant financial resources, which is a greater concern for SMEs than for larger enterprises (Bonini et al., 2015).

To contend with these challenges, the Open Platform for Innovations in Logistics (OPIL) is currently under development in the scope of the European H2020 project *Smart logistics for manufacturing SMEs* (L4MS). This paper presents the control of a robotic system for automation in manufacturing logistics based on OPIL. Our main contributions to the system are:

- (i) a new omnidirectional automated guided vehicle (AGV) for up to 400 kg payload suited for transporting the Euro-pallets;
- (ii) development of the sensing and perception software module as part of OPIL;

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(iii) development of the navigation module for the developed AGV, which is integrated with OPIL.

An example SME that could benefit from OPIL integration is MURAPLAST d.o.o., the leading producer of a Polyethylene (PE) blown film in Croatia and the South-eastern European region. MURAPLAST needs to optimize the process of taking the products (rolls of PE film) from the production lines, weighting them and transporting them to the storage area. This automation would boost productivity, reduce human error factor in weighting and reduce the manual labor needed to manipulate the products. We use MURAPLAST as a case study for the OPIL platform and demonstrate successful implementation of the sensing, perception and navigation modules on a new omnidirectional AGV that we developed.

2. OPEN PLATFORM FOR INNOVATIONS IN LOGISTICS

2.1 Problem statements

A logistics automation in SMEs is one of the most common problems known. Fast-growing companies are putting the production process as the highest priority while ignoring the logistics. So far, there exists no platform that would enable complete virtualization of the intrafactory logistics automation and afterwards enable fast integration of various sensors, AGVs, mobile robots, and human operators for the planned logistics automation. The idea of OPIL is to provide such functionality. OPIL is an open and modular IoT platform that acts as a container of well-known software modules such as SLAM or navigation, but also allowing a custom made solution for a specific robotic system. It provides an easily deployable set of applications for rapid development of complete logistics solutions, including the components for task planning, process optimization, and visualization of the logistics process with human-machine interfaces. OPIL also provides a ready integration with Visual Components, a state of the art 3D factory simulator, allowing the complete development and testing of logistics solutions virtually, and presenting them to factories before actual implementation. OPIL's open architecture supports the usage of open-source frameworks such as Robot Operating System (ROS) for development of new components such as perception, navigation, and mobile manipulation, and FIWARE Orion Context Broker (OCB) for components interoperability. The challenge lies in the connection of these techniques and modules, i.e., to provide interfaces that will allow easy connection of modules and equipment of various vendors.

The OPIL architecture is depicted in Fig. 1 and in the following subsections we briefly describe its modules.

2.2 Layer 1 - IoT Nodes

Agent nodes of the Layer 1 are the architecture components that interact with the physical world – the Layer 0. They can interact by sensing (Sensor Agent Node), by acting (Robotic Agent Nodes) or by interfacing with humans (Human Agent Nodes).

Robotic Agent Node (RAN) This OPIL component provides the capability to deal with the physical actors of a

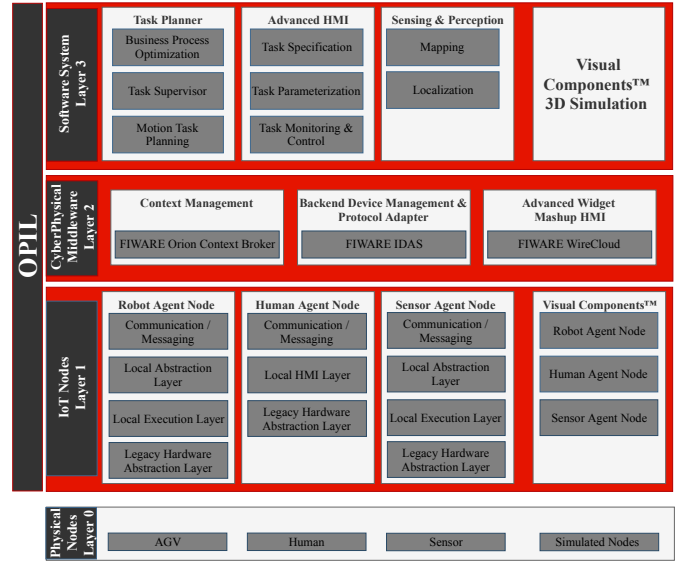


Fig. 1. OPIL architecture.

logistics domain. According to the OPIL framework, robot agents have two basic capabilities: (i) transportation of products inside the production plant; (ii) manipulation required for loading and unloading products from the plant to the AGV and vice versa. RAN has a submodule for Communication and Messaging which handles the translation from the internal agent communication infrastructure and the OPIL middleware. RAN also features the Local Abstraction Layer which enables system configurability and provides an abstract description of the Robot Agent node. It provides information dependent on the agent's need to execute a manipulation or a transport task. The Local Execution Layer enables the robot agent to execute assigned tasks. Finally, the Legacy Hardware Abstraction Layer abstracts the actual kinematics or dynamics and provides the linear/angular velocity set-points interface for a mobile robot or an AGV to the Local Execution Layer.

Human Agent Node (HAN) This OPIL node provides the capability for a human operator to communicate with the system. HAN can give inputs for the system and also receive information via this node. Similarly to RAN, HAN has a submodule for Communication and Messaging, which is in charge of handling the translation from the internal agent communication infrastructure and the OPIL middleware. The second submodule, the Local HMI Layer, provides multimodal, multichannel interaction capabilities to allow warehouse operators communication with OPIL in an easy and intuitive manner.

Sensor Agent Node (SAN) SAN allows collecting relevant information from production and the warehouse for OPIL components such as Task Planner and RAN. Sensors are directly connected to the SAN's Legacy Hardware Abstraction Layer. This submodule allows the sensor data reading and sending the data to the Local Execution Layer which then translates the sensor readings to a usable form. The Local Abstraction Layer enables system configurability and monitoring the real-time values from connected sensors. The Communication and Messaging handle the connection and translation from SAN to the OPIL middleware.

2.3 Layer 2 - Cyber Physical Middleware

The Cyber Physical Middleware (Layer 2) has a twofold role; it decouples the world interacting components from the pure software components and it allows for components interoperability. It enables the communication between the IoT nodes at Layer 1 and other components of the OPIL. This communication is supported by specific sub-modules of this layer such as the Pub/Sub Context Broker through the network infrastructure. For example, in the case of Layer 1, Communication/Messaging submodules are tasked with translating toward the Layer 2 Pub/Sub Context Broker which has the goal of dispatching information to other OPIL actors involved by the specific scenario.

2.4 Layer 3 - Software Systems

The Software Systems (Layer 3) represents the highest level of OPIL containing all the services that this platform provides to the end users. This level is made of three main modules: the Task Planner, the Advanced HMI, and the Sensing and Perception module.

The Task Planner module is in charge of: (i) deciding and optimizing the tasks to be dispatched to the different agents in the OPIL architecture by means of a Business Process Optimization submodule; (ii) planning the motion tasks for the robot agents in the OPIL architecture by means of the Motion Task Planning submodule; (iii) monitoring the execution of the task dispatched to the agents by means of the Task Supervisor submodule.

The Advanced HMI OPIL node consists of three different submodules. The Task Monitoring and Control submodule has two key functionalities: the subscription and visualisation of information available in OPIL and the controllability of the operations, tasks and other actions planned by OPIL and human actors. The Task Parameterization submodule collects and parameterizes data collected from Enterprise Applications. The Task Specification submodule formulates a task based on the task related information received from Task Monitoring and Control submodule, and task specific parameters received from the Task Parameterization submodule.

The Sensing and Perception component allows OPIL to provide information suitable for safe and accurate motion planning to the actors of OPIL system, i.e. the RAN. The Localization submodule provides 2D or 3D pose estimates for RAN, while the Mapping submodule provides information about the structure of the manufacturing shop-floor for the components involved in navigation. One of our contributions to the OPIL system lies in the development of this module and we discuss implementation details in the following section.

3. ROBOTIC SYSTEM FOR AUTOMATION IN MANUFACTURING LOGISTICS

3.1 Hardware setup: Robot and Sensors

We designed and built a novel automated guided vehicle (AGV), dubbed Anda. The Anda AGV is shown in Fig. 2. Anda is built from the mechanical and electrical parts

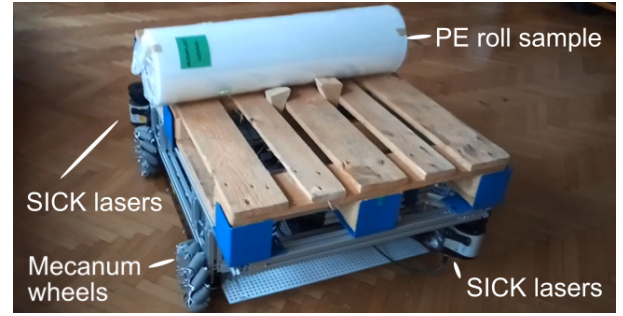


Fig. 2. The developed AGV Anda.

of AndyMark, Inc.: four Mecanum wheels powered by four brushed DC motors, VEX microcontroller with a designated PID controller for each wheel implemented in the EasyC V4 Cortex Programming Kit (Rivera et al., 1986), and two 12 V, 18 A/h sealed lead acid batteries. The Mecanum wheels allow Anda to support bearing a heavy load and to move in any direction; in-place rotation, forward-backward, left-right, simultaneously rotating and translating in an arbitrary direction. Each wheel has a payload of up to 100 kg, while all four wheels put together can bear almost four times more. The aluminium construction is built to carry two SICK laser sensors placed diagonally for sensing the surrounding obstacles in the environment and for ensuring safety on the software level. Dimensions of the aluminium construction correspond to the dimensions of the Euro-pallet (0.8 m \times 1.3 m), which is placed on top of Anda and enables carrying the payload. The weight of the Anda robot without a pallet is 30 kg. Anda carries an onboard computer which contains RAN software IoT module. It is connected to the wheel encoders and the SICK lasers. RAN also sends the calculated velocity commands to the robot's motors.

Besides Anda, the system consists of an industrial PC - Revolution PI. This industrial PC contains the SAN software IoT module to which two buttons are connected to. These buttons are necessary for simulating the end of processes for loading and unloading of the PE roll. An additional PC is the OPIL server, containing the Cyber Physical Middleware Layer 2 and also parts of the Software System Layer 3: Task Planner and HMI. The Task Planner is a simplified state machine, which monitors the state of the process and sets the task to the AGV or worker, e.g., sends the AGV to the loading area; informs the worker that the AGV is ready for loading/unloading; etc. The whole sequence of states is started through the HMI. The HMI can be visualized in a web browser on any PC or tablet.

3.2 Software setup: Sensing, Perception and Navigation

The initial step is to develop a ROS-based robot, i.e. developing the Hardware Abstraction Layer of the RAN. We developed a module that reads the encoder signals and converts them to the ROS messages for kinematics and dynamics and velocity set-points interface. After this step, all communication between the modules in the Software System Layer 1 is through ROS.

The purpose of the Localization submodule is to answer where is the robot/AGV positioned related to its built world. The Localization submodule enables high precision

localization of the robot/AGV, and also influences on the precision of the robot/AGV's built world, which is continuously developing within the Mapping submodule. The pose information that is produced by the Localization submodule influences on the quality of the robot/AGV's motion control. The quality of the result depends on the used sensors and data processing from various sensors. For localization in a known environment, we use the Adaptive Monte Carlo Localization (Dellaert et al., 1999) as AMCL package under the Robot Operating System (ROS) (Quigley et al., 2009).

The purpose of the Mapping submodule is to give a representation of the world where the platform or more platforms are operating. This submodule is closely related to the Localization submodule and the precision of the built map influences on the pose estimation precision provided by the Localization submodule. The map is continuously developed as the platform is moving through the environment, but it can start from the a priori model (e.g. CAD model of the environment). A map can be represented in various formats (e.g. vector, raster, feature map, topological map). A topological representation is used in the Software System Layer 3 of OPIL for multi AGV route planning by the Task Planner, which is currently out of the scope of this paper.

The algorithm which runs on the computer is the OPIL module RAN, which executes navigation processes necessary to move the robot from the arbitrary point A to another point B. Since the robot can not move without knowing its pose, the local instance of Sensing and Perception is placed next to the RAN on the AGV computer. A custom navigation is used instead of the one inside the RAN, which proves the OPIL modularity. We used fast and convergent navigation of anyshape holonomic mobile robots in dynamic environments proposed by Seder et al. (2013). This navigation algorithm is based on D* (Stentz, 1997) and employs the receding horizon principle (Goodwin et al., 2006) to handle dynamic environments. Based on these, a continuous motion generation approach generates smooth motions that are fast to compute. If an obstacle appears on the way it is efficiently avoided sometimes even without slowing down.

4. APPLICATION EXPERIMENT

4.1 Experiment description

In this application experiment a small factory model of the MURAPLAST production area is built. The small factory has the model of the machine with the ready PE roll that needs to be weighted and transported and the model of the packing station. The experiment features the developed omnidirectional mobile robot Anda with a mounted Euro-pallet for holding the roll. The robot autonomously navigates to the location in the laboratory representing the machine that produces the PE film roll and waits for the roll to be placed on top of the robot. In this application experiment, placing the roll is done by a human, but MURAPLAST is considering installing a mechanism that would remove the shaft from the roll and put the roll on the robot. After loading the roll, the human operator needs to press the button to confirm that the roll

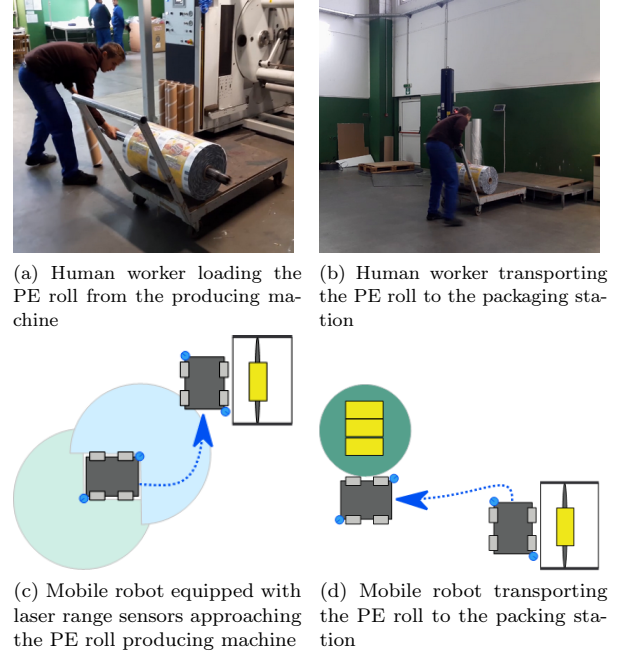


Fig. 3. Human worker participating in the PE roll production process and illustration of the robot doing equivalent tasks

is loaded on the robot. As a future improvement of the pilot experiment, the aluminium construction will also feature an infrared sensor for detection that the roll is mounted on the robot. Subsequently, the robot navigates to the location in the laboratory representing the packing station, where the roll is unloaded. In this application experiment, the unloading operation is also done by a human, but at MURAPLAST the robot needs to drive to the forklift which has a tool for picking up the Euro-pallet. By pressing the button connected to the Revolution PI industrial PC, the system is aware if the roll has successfully been dropped off. Afterwards, the robot returns to the location representing the PE roll producing machine and the whole process is repeated.

Since the space in MURAPLAST is very tight and crowded, there is no a static route where the robot needs to transport the roll. This is also simulated in the experiment by adding randomly placed obstacles to the environment and a human walking around, thus testing the robot's ability to autonomously find its way to the target machine while avoiding dynamic obstacles. For obstacle avoidance, the two Anda's laser scanners placed on the corners of the aluminium construction are used. For future improvement, the laser scanners which possess a safety certificate are employed. Photos of a human worker participating in the PE roll production process are shown in Fig. 3a and Fig. 3b, while an illustration of the robot doing equivalent tasks is depicted in Fig. 3c and Fig. 3d.

4.2 Logistics workflow

The logistics workflow consists of precisely defined sequential operations. After successful execution, the whole process is repeated. The logistics workflow was defined as follows:

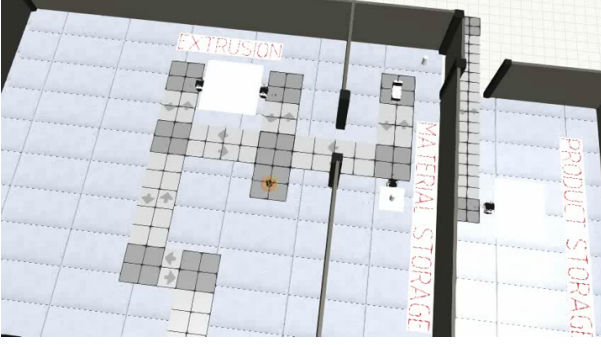


Fig. 4. Muraplast digital twin in Visual components. This environment can also be seen in the accompanying video ¹.

- (1) HMI announces that the roll is ready and the worker presses the button on the HMI to start the task. This creates a request to send the AGV to the loading station.
- (2) The Task Planner sends the movement task to the RAN where the RAN converts it to the AGV specific commands.
- (3) The AGV starts moving and informs the Task Planner when the goal is reached.
- (4) The Task Planner informs the worker that the roll is ready to be loaded through the HMI.
- (5) The worker loads the roll on the AGV and pushes the button A for acknowledgment.
- (6) Once the button A is pressed, the SAN sends this event towards the Task Planner via the Layer 2.
- (7) The Task Planner, after receiving this event, creates and sends a new movement task to the AGV to transport the roll to the unloading station.
- (8) The AGV, controlled by the RAN, moves to the unloading station and at the goal informs the Task Planner that the task is completed.
- (9) Through the HMI, the Task Planner informs the worker that the roll needs to be unloaded.
- (10) The worker unloads the roll and pushes the button B.
- (11) The button B triggers the new task from the Task Planner in which the AGV is sent to the waiting area.

4.3 Digital twin

In the first part of the application experiment, a virtual factory (digital twin) is developed in Visual Components software (Kuts et al., 2019). The base for the virtual factory is the current MURAPLAST manufacturing ground comprising machines for extrusion, printing machine and cutting machine. The digital twin allows decision-making and optimization without disturbing the actual production before actually investing in developing it (Macchi et al., 2018). Experience and knowledge acquired from the execution of the first part enable the appropriate identification, focusing and shaping in the second part of the experiment with the factory mock-up that serves as a real-life verification of the proposed solution. A part of the MURAPLAST digital twin setup is shown in Fig. 4.

¹ youtube.com/watch?v=uIv1hgTLOW

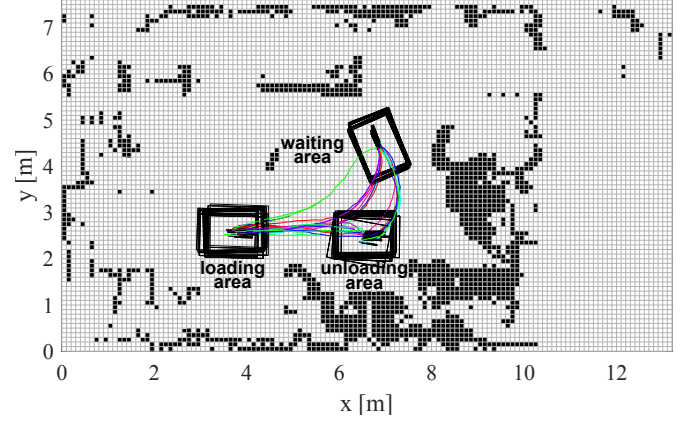


Fig. 5. Long run of the experiment between loading, unloading and waiting areas.

4.4 Experiment execution results

The logistics workflow of the application experiment for MURAPLAST was executed at the ICENT premisses. After a start of the process in the HMI, the Anda mobile robot started to navigate to the loading area, then, unloading, and finally to the waiting area. A human operator was acknowledging the loading and unloading processes through SAN. Figure 5 presents the actual goal locations in the laboratory representing the waiting, loading and unloading areas, and the robot trajectory of long run of the experiment, repeating the whole logistics process roughly ten times. The tolerance for the goal reaching was set to 0.3m, meaning that the RAN will send the "goal reached" status to Task Planner if the robot reaches the circle around the goal with the predefined radius. It can be seen that the robot footprint presented at the goal locations is always at similar locations. This proves the robustness of the robotic system for a long run navigation. During the navigation, moving obstacles were introduced to test the robustness of the logistics process, which is not constrained to always take the same routes. This is shown in Fig. 6, where a sequence of transitions between waiting, loading and unloading areas is shown in static case (upper row of subfigures) and with an introduced moving obstacle (lower row of subfigures). It can be seen how Sensing and Perception module manages to localize the robot inside the mapped environment (grey), by comparing visually the position of laser readings of the front (red) and rear sensor (green) with respect to the mapped environment. Figure 6 also shows the discrete plan of the robot from the current position to the goal and the continuous trajectory that the robot currently executes. Moving obstacle test was performed when the robot was in transition between waiting and loading areas (Fig. 6 upper row of subfigures). It can be seen how Anda changes its discrete plan (route) dynamically to avoid collision with the obstacle ².

5. CONCLUSION

In this paper we presented the control of a robotic system for automation in manufacturing logistics based on OPIL. We developed the sensing and perception software module within OPIL, and a custom navigation module integrated

² youtube.com/watch?v=7koPrwFSvLc

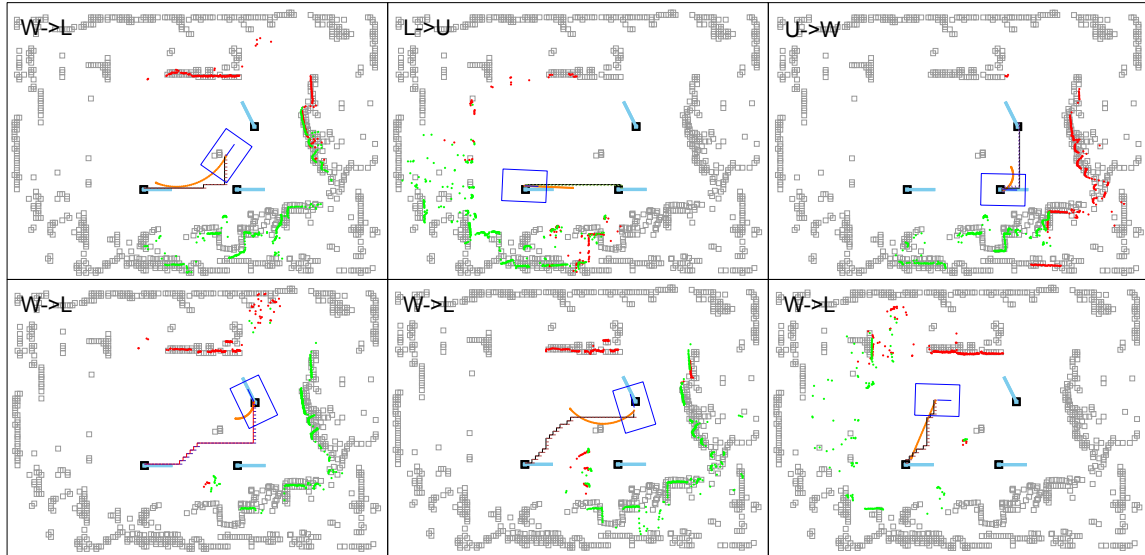


Fig. 6. Sequence of transitions between waiting (W), loading (L) and unloading (U) areas. Second row shows avoiding obstacle on the way from waiting to loading areas. Laser readings are presented with red (front laser) and green (rear laser) dots.

with OPIL. We also developed a novel omnidirectional AGV suited for transporting the Euro-pallets with the payload of up to 400 kg. We demonstrated successful implementation of the developed software modules and AGV for the OPIL based mobile robot control for automation manufacturing logistics in a case study of MURAPLAST SME, the leading producer of a Polyethylene (PE) blown film in Croatia. The results also show the main benefit of OPIL as an open platform that acts as a container, which allows deploying a custom made module designed for a specific robotic system. The future version of OPIL development goes in the direction of solving more complex logistics workflows including more AGVs, their routing and scheduling, and relevant data sharing between them.

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