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Cyber Physical Systems: A Brief Survey and an Application of a MIR (Mobile Industrial Robot) for Inspection

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Abstract: This work refers to the realization of a Cyber Physical System (CPS), i.e. modeling, analysis, and integration of a MIR (Mobile Industrial Robot) platform with an industrial robot, in order to test its operating conditions. MIRs, although usually employed in industrial environment, can be used in sectors such as inspection, assistance, defense, production, remote exploration as well as search and rescue. In addition of being programmable, thanks to the provision of sensors and navigation systems, they can adapt in real time to various environmental contexts and purposes of use. The objective of the paper is to create a CPS of a MIR that can basically perform two fundamental actions. The first one is to carry out movements in predominantly external environments and therefore with various types of terrain. The second fundamental action is the pick and place operations, i.e. the robot must be able to carry out the manipulation of objects.

Keywords: Cyber Physical Systems (CPS), Mobile Industrial Robot (MIR), Simulation, Inspection.

1. INTRODUCTION

The inspection of critical infrastructures has become of prior interest in the latest years. Due to the enormous work to be done, classical methods based on visual inspection relying on specialized personnel, are starting to be combined with newest techniques and technological solutions. As a matter of fact, the use of Robotics and Digital Technology is consolidated in the industrial sectors for production and quality assessment (Aleotti *et al.*, 2021; Leão *et al.*, 2012), and lean maintenance for decision support systems (Antosz *et al.*, 2021). However, in recent decades, their utility has expanded beyond conventional uses. Robots are now used in fields such as service (Sprenger and Mettler, 2015), agriculture (Acaccia *et al.*, 2003), search and rescue (Habibian *et al.*, 2021), remote exploration (Bellingham *et al.*, 2007), entertainment (SkyCam, 2024), manufacturing (Jefrin and Rodchua, 2022), and inspection and monitoring of structures and historical sites (Rea *et al.*, 2017; Ottaviano *et al.,* 2014). Leveraging the growing sophistication of intelligent systems is of great interest, aiming to simplify daily activities and enhance security, resilience, and reliability in various applications. The anticipation is for a significant increment in the use of robotics across multiple sectors in the near future. A noteworthy trend is the on-site application of automation and robotics for inspection, aligning with the concept of smart buildings, smart sensors, and cyber-physical systems. The future sees substantial growth in the use of robotics, particularly for inspection purposes. The integration of robotic maintenance is poised to make a remarkable impact, potentially reducing energy consumption and carbon dioxide emissions by up to 95%. For instance, the replacement of helicopters with suspended robots for inspecting transmission lines is one such development (Nagarajan *et al.*, 2019).

In this paper we consider the integration of a MIR (Mobile Industrial Robot) platform with an industrial robot in order to be used for inspection and further maintenance, including manipulation issues for the survey and possible restoration of sites of interest. To accomplish this task, the Cyber Physical System (CPS) of the complete robot has been designed and simulated to test the engineering significance and feasibility in overpassing obstacles and picking objects.

2. MIR (MOBILE INDUSTRIAL ROBOT)

In the 1970s, Automated Guided Vehicles (AGVs) appeared as a solution for the autonomous transportation of materials within a manufacturing environment. This type of mobile robot is equipped with sensors, mainly magnetic or laser, which allowed navigation. The innovation brought by AGVs was essentially of being able to follow predefined paths within a production plant. This has allowed companies to automate the handling of materials, increasing the efficiency and safety of each operational phase. With the advancement of technology and the introduction of artificial intelligence, Autonomous Mobile Robots (AMR) platforms were

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introduced (Alexovic et al., 2021). AMRs differ from AGVs in that they can navigate autonomously in the environment without the need for predefined path, i.e. they are able to interpret and understand the environment around them and carry out movements without the supervision of a human operator (MIR website, 2024). They use advanced sensors such as cameras, lidar (light detection and ranging) and 3D scanners to perceive the surrounding environment and make decisions in real time. AMRs are able to avoid obstacles, adapt to changes in the environment and autonomously plan routes to reach desired destinations. AMRs have led to a dramatic increase in efficiency and flexibility in internal handling operations, allowing companies to quickly adapt to changing production needs. These are in fact characterized by greater simplicity of insertion within the production cycle and can be easily reused in different applications or contexts when this need arises. Thanks to the safety features introduced in modern AMRs, they can be used into environments where the workspace is shared with humans and carry out activities in a synergistic manner with the staff, making processes and workflows more efficient and productive.

In recent years, a new type of industrial robots known as Cobots, or collaborative robots, has emerged. Unlike traditional robots, Cobots are designed to work closely with humans and are often paired with robotic manipulators (Kumar et al., 2023). These robots are equipped with advanced safety sensors, such as force and contact sensing systems, which allow them to slow down or stop moving when they detect the presence of a person in their surroundings. Cobots are designed for being easy to install, programmed and used, allowing operators to work safely and synergistically in assembly, packaging and material handling tasks. This collaboration between humans and robots opens new possibilities in industrial automation, allowing for greater flexibility and better use of human and robotic capabilities.

It is in this context the MIR platforms fit in. Mobile robots for industrial uses are part of the Wheeled Mobile Robot (WMR) and Autonomous Mobile Robot (AMR) categories as well as that of collaborative robots. They are generally realized by a steel or aluminum chassis for guaranteeing a good combination of strength and lightness, which is combined with a driving platform that can use traction wheels with omnidirectional wheels. The wheels can be individually powered and controlled to allow the robotic system a more precise level of maneuverability. The motors are always electric and can be mounted directly on the wheels or on a transmission system that converts the engine power into torque available on the wheels.

Driverless platforms are equipped with devices such as cameras, lasers, and depth sensors with the function of improving the precision of navigation. Navigation of MIRs is possible thanks to the real-time generation of a map of the surrounding environment, by means of a combination of sensors and mapping software. The simulated map is used by the robot to calculate the most efficient route and the one with the lowest risk. MIRs are usually equipped with remote control systems that allow operators to monitor and verify their movements in real time. Alternatively, they can be remotely operated. Driverless mobile robots, also called Unmanned Ground Vehicle (UGV), can be used to perform a wide range of tasks, from delivering materials to production lines, to distributing goods within a warehouse, to logistics. As regards safety, however, MIRs are equipped with advanced sensors such as contact sensors and cameras, which allow them to avoid obstacles and detect any objects or people nearby in the industrial environment.

3. CYBER PHYSICAL SYSTEMS

Within the context of Industry 4.0, the fusion of the virtual and physical realms becomes achievable through the realization of Cyber-Physical Systems (CPS), which play the role as the fundamental building blocks for advancements in industrial automation, incorporating newest technologies such as, but not limited to, the Internet of Things, artificial intelligence computing, and big data (Cheng *et al.,* 2018). Coined by Helen Gill at the National Science Foundation of the United States in the early 2000s, the term CPS highlights the often-overlooked connection between the physical and virtual worlds, especially in a landscape dominated by applications running on personal computers.

CPS can be conceptualized as the seamless integration of computational and physical processes (Zheng *et al.*, 2018). Nevertheless, CPS extend beyond mere networked systems, as they involve the integration and utilization of data from the physical world within the digital (cyber) realm. This integration establishes sustainable feedback loops, wherein computed decisions in the cyber world may influence the physical world and vice versa (Sanislav and Miclea, 2012).

4. AN APPLICATION OF AMMR FOR INSPECTION

The MIR platform falls under the category of AMMR (Autonomous Mobile Manipulation Robot). These are robots that combine the autonomous navigation capabilities typical of AMRs with the ability to manipulate the environment around them using a robotic arm. They are typically composed of AMRs that include a collaborative robotic arm and specific equipment for the tasks for which they are used. The AMMR analyzed and simulated in this work (Figure 1) is composed by three macro-components. Locomotion will be guaranteed by a wheeled mobile robot proposed in (Rea *et al.,* 2022); on which a Universal Robots UR5e collaborative manipulator will be mounted. The robotic arm will be secured to the AMR through a steel plate, which will be sensorized by including four load cells placed at the contact points between the plate and the robot. An end-effector from the Robotiq manufacturer will be provided on the wrist of the UR5e, specifically a 2F-140 model gripper, although solutions have been explored to perform flexible manipulation, as reported in (Figliolini and Rea, 2006, Figliolini and Rea, 2007). The objective of the project is to create a CPS of the AMMR platform that can basically perform two fundamental actions. The first one is to carry out movements in outdoor environments and therefore with types of terrain that may present discontinuities. The second fundamental action is of pick and place, i.e. the robot must be able to manipulate objects, as picking, transporting, and placing them from a starting position to a final position.

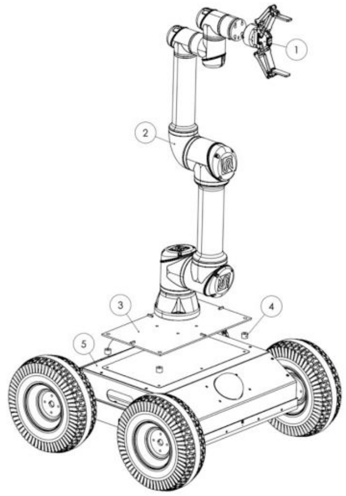


Figure 1. The designed CPS of the AMMR composed by 1) the gripper, 2) Cobot Universal Robots UR5e.; 3) Mounting platform; 4) load sensors; 5) the 4- wheeled robot.

5. SIMULATION TESTS

5.1 Stepfield pallets

The evaluation of the robot's mobility will be carried out through repeatable terrain modeling named as stepfield pallets. The stepfield pallets were developed to support designers of mobile robots and represent complex terrains in an easily reproducible and repeatable way with the aim of acquiring statistically significant data on their performance (Jacoff *et al.,* 2003; Jacoff *et al.,* 2008).

Figure 2 shows the modelled stepfield pallet to simulate the AMMR negotiating with the terrain and picking, grasping during the movement, and releasing the object.

In detail, the tasks envisaged have been divided into three main macro-phases:

1. Picking up an object placed frontally along the direction of advancement.

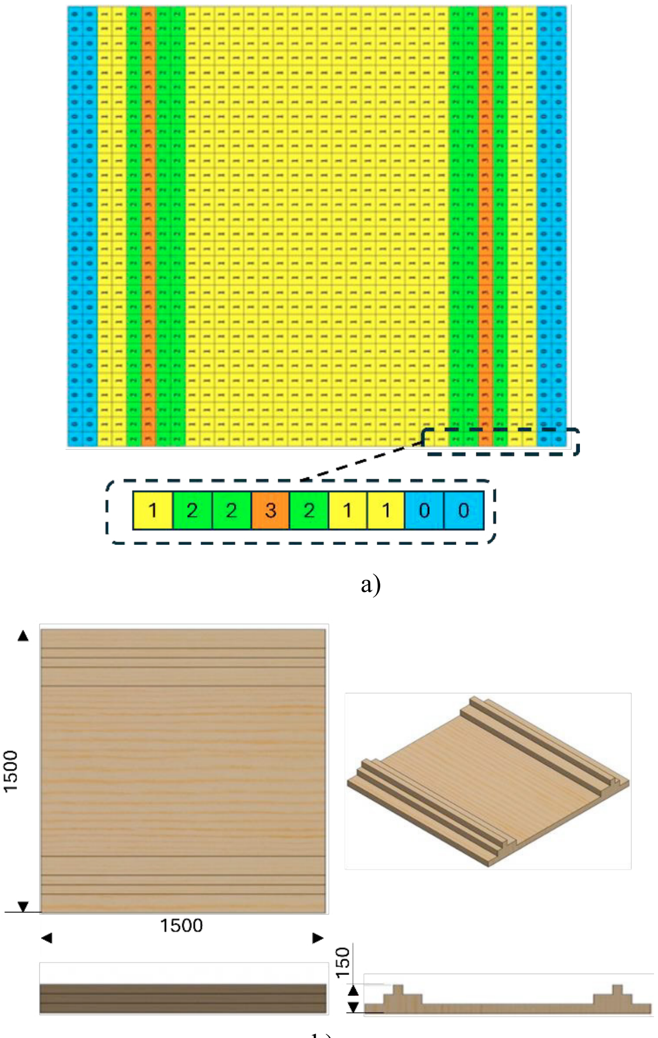
2. Transport of the object from the initial position to the final position following a path in which a discontinuity in the terrain has been foreseen.

3. Placing the object in the assigned point which is in a perpendicular position with respect to the direction of advancement.

The three phases that compose the complete test, two of manipulation and one of locomotion, were designed and simulated to verify whether the system is able to operate as expected. In particular, the following data was considered, stepfield pallet data: overall dimensions: 1500x1500 mm; grid: 30x30 mesh dim. 50x50 mm; cubic elements: 50 mm; max. height obstacle:150 mm. object material: aluminum; dimensions: 97.4x97.4 mm; mass: 2.49 kg.

5.2 Simulations

Several simulations were carried out with the designed AMMR, displayed in Figures 3 and 4, using a specific stepfield pallet reported in Figure 2. In particular, numbers in Figure 2a) identify different heights of the obstacles, i.e. 0 is 0 mm that increases by 50 mm for each increasing number up to 150 mm. The AMMR system behavior has been simulated, as reported in Figures 3 and 4, in negotiating obstacles according to the scenario given in Figure 2. Simulation results give information about the designed mechanical systems but also on the mechatronic development by verifying the actuation and the manipulation of the object in grasp. Figure 5a) shows the velocity of the Center of Mass (CoM) in overpassing the obstacle reported in Figure 2. The above-mentioned results are related to one of the simulations that have been run at different conditions. The maximum value for distance of the AMMR in the negotiation with the stepfield pallet is approx. 3700 mm, as reported in Figure 5a). The max value of velocity of the AMMR experienced during the simulation was approx. 220 mm/s, as reported in Figure 5b). Similar considerations can be obtained for the gripper position and velocity, as reported in Figures 5 c) and d). The simulation results reported in Figure 7 are related to the load cell (labelled 4) in Figure 1) placed between the lower mobile robot and the upper arm (labelled 2 - Cobot Universal Robots UR5e). They are given in Figs 7 a) and b).



a)

b)

Figure 2. Stepfield pallet used for the tests: a) a scheme; b) model and dimensions.

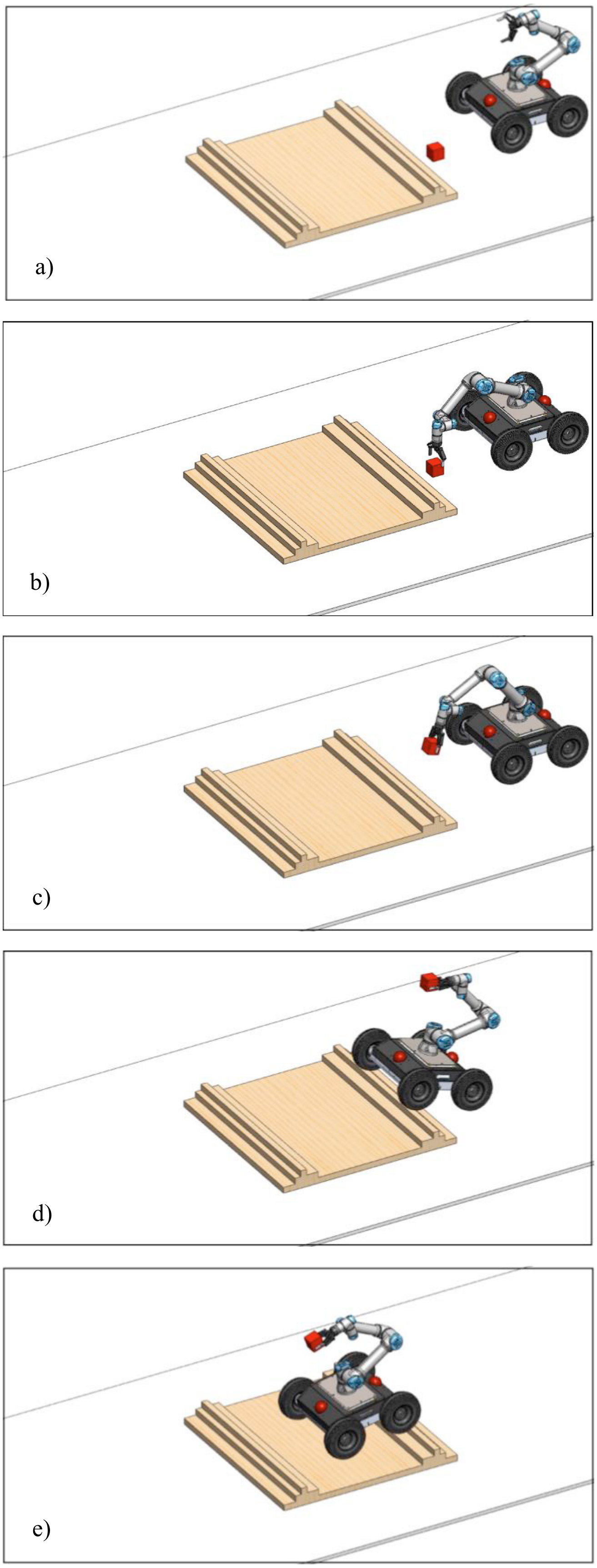


Figure 3. Snapshots of the AMMR negotiating the stepfield pallet in Figure 2); a) t = 0 s; b) t = 12 s; c) t = 21 s; d) t = 39 s; e) t = 45 s.

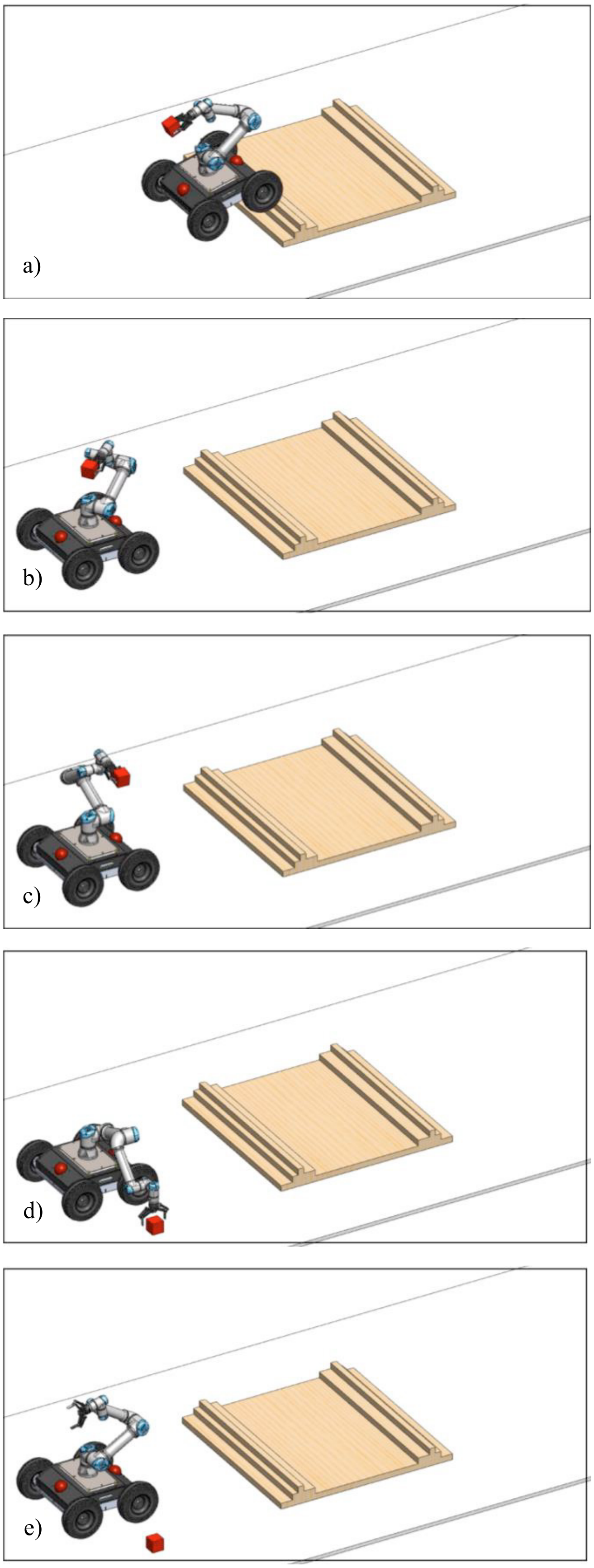


Figure 4. Snapshots of the AMMR negotiating the stepfield pallet in Figure 2); a) t = 51 s; b) t = 60 s; c) t = 65 s; d) t = 83 s; e) t = 95 s.

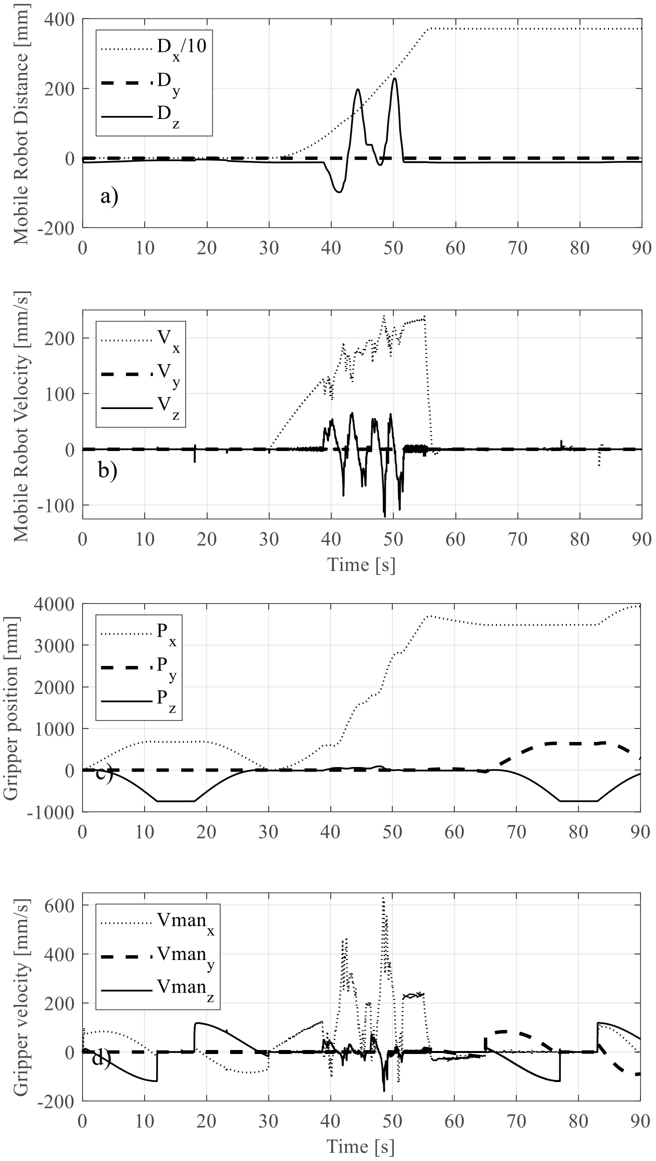


Figure 5. Numerical results of the simulation in Figures 3 and 4: a) trajectory and b) velocity of the CoM of the robot; c) position of the center of the gripper; d) gripper velocity.

Finally, it was tested the overturning ability. The presence of the Cobot may improve the ability of the AMMR to overpass an obstacle increasing the overturning resistance. Figure 8 shows a simplified scheme for the system at the instant when it starts overturning considering only the rear wheels able to exert the driving force. According to the scheme in Figure 8 it is possible to consider

$$-W(\mathrm{x}\cos\vartheta - y\sin\vartheta) + N_f(\mathrm{p} + r_R\sin\vartheta) = I_C\dot{\omega} \qquad (1)$$

The vehicle overturning will be avoided if $\dot{\omega} \leq 0$. It may be possible if and only if $(\mathrm{x}\cos\vartheta - y\sin\vartheta) > 0$, that is

$$\tan\vartheta < \frac{x}{y} \qquad (2)$$

Therefore, the condition in Eq. (2) for x, y values can drastically influence the ability to overcome obstacles.

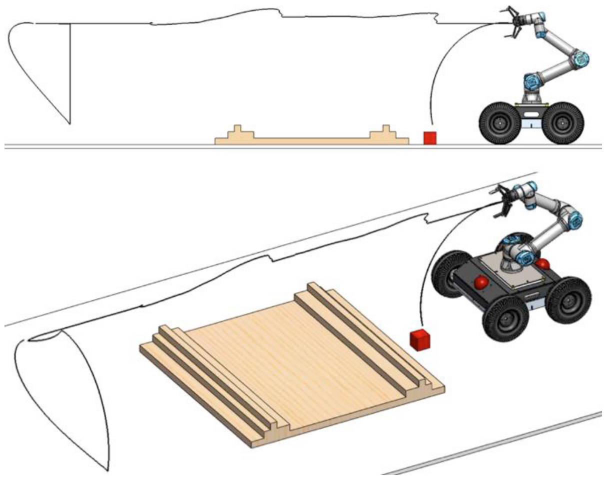


Figure 6. Snapshots of the AMMR gripper trajectory during the pick and place operation: a) side view; b) 3D view.

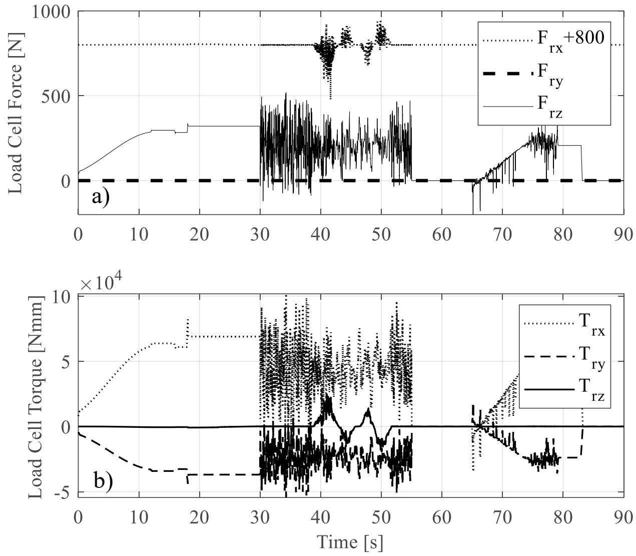


Figure 7. Numerical results of the simulation in Figure 6: a) load cell force; b) load cell torque.

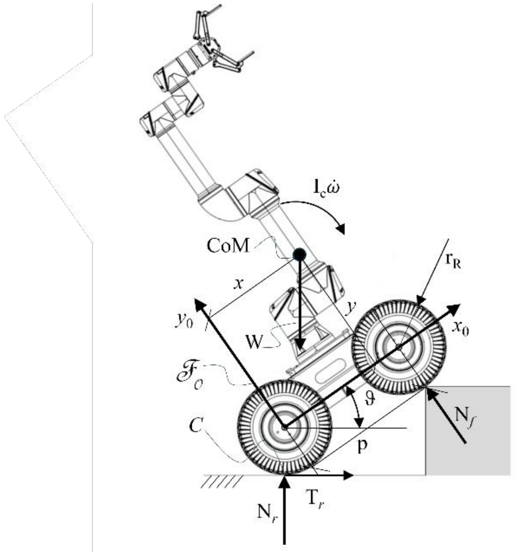


Figure 8. Planar scheme for overturning verification.

6. CONCLUSIONS

In this paper, a CPS of an AMMR platform has been realized for a possible application of inspection and monitoring. It is composed by three main parts: a mobile robot, specifically an Inspection Robotic System; a collaborative manipulator from Universal Robots; and an end-effector. Simulation tests have been reported in order to test its feasibility in overpassing obstacles and manipulating objects. Simulation tests have been proposed relating to picking and manipulating an object and overpassing obstacles.

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