Multi-layer cyber-physical low-level control solution for mobile robots

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Abstract. Self-driving vehicles and mobile robots are used more and more in public transportation and industrial companies. Multiple experimental platforms, which can be operated in an urban or industrial environment have been developed recently. The key development for robust and safe control of the robot’s operation is relying on the low-level cyber-physical system (CPS). CPS is composed of a collection of tightly integrated computational (cyber) units which are communicating with the physical world. CPS integrates computation and communication aspects with control and monitoring techniques. In this paper, the scientific goals underscore the analysis of the existing state of the art solutions to increase security, safety, and reliability of the multiple experimental platforms.

1. Introduction
Digitalization and robotization is a constant challenge for the industry to make production more effective, robust, and reliable. The fourth industrial revolution, called Industry 4.0 puts smart technology into the focus where robots, production units, and services are interconnected. Despite the interconnection of hardware, the integration of the robots with the manufacturing engineering systems should be developed and tested [1]. Thus, the standard automated guided vehicles (AGV) cannot fulfill more complex tasks and must be upgraded to more flexible mobile robots that can reroute on-demand and intercommunicate with other machines. Several types of research already investigated how to integrate autonomous vehicles into the industry 4.0 environment [2]. The modularization in mobile robotics is essential to offer flexible reconfiguration, efficient design, and reduce the development and implementation time. The proper architecture and modular concept must be considered already in the early design stage and proper methodologies are proposed for mechatronic system design. Christophe et. al. proposes OPAS [3] to synthesize conceptual design solutions in early design stages [4]. Early design and simulation toolkit for mobile robot platforms [5] relying on these methodologies helps to design modular universal mobile robots for the industrial logistic environment, inside the manufacturing area. From the development and later implementation side, the inside manufacturing area is adding additional limitation parameters for the development stage like (communication limitations, localization, shorter distances and space, limitations of safety, etc.).

The lower-level cyber-physical solution shown in figure 1 is a critical part of controlling modular mobile robots using modules that interact with the physical world. These modules are divided mainly into sensors, actuators, and computation units. Also, inside cyber-physical solutions, the modules are usually distributed, and therefore communication is an important part of the system. The separate
constituent parts (sensors, actuators, software, etc.) of the cyber-physical solution collaborate to create some global behavior [6]. Nowadays it is very important to get real-time data from the production area and from the mobile robot to make real-time analysis and management tasks [7].

![Cyber-Physical System Diagram]

**Figure 1. Cyber-Physical system**

Mobile cyber-physical systems have significant computational resources to maintain localization, obstacle detection, safety functions, and path following. Computational resources can be divided into two different categories like artificial intelligence (AI) based on high-level decision-making and lower-level control logic. AI and high-level decision making based on some special computer to run robotic operating systems (ROS). In many cases, it is a regular PC. The low-level control logic is near or inside actuator or sensor modules. It handles a regulation for actuators and makes the first information processing for information received from sensors. Also, it controls and forwards information between the modules.

The communication inside the mobile cyber-physical solutions is usually based on the CAN (Controller Area Network) and the Ethernet networks [8]. CAN is an existing multi-master broadcast serial bus communication protocol for connecting electronic control units (ECU) in automotive applications. However, several vulnerabilities such as the lack of authentication and the lack of data encryption have been pointed out by several authors, which may ultimately render vehicles unsafe [9]. Security and safety-critical applications in the automotive industry require a new protocol to transfer the data at a higher speed than the existing CAN protocol allows. FlexRay is a newly introduced communication protocol for an automotive control system developed to fulfill the increasing demands for higher safety and data rate [10]. Also, multiple wireless communication mechanisms, such as WiFi, 4G, EDGE, Bluetooth used to interconnect several devices, to connect robots or connect robots to the internet. Right now, new developments are going to use and test 5G in similar conditions.

A mobile cyber-physical system may have multiple sensory input devices. The most common sensors for vision and 3D imaging systems are lidars, radars, and cameras [11]. There may be sensors for localization, for example, GPS and inertial sensors, also sensors that can detect the presence of nearby objects without any physical contact. Such sensors are ultrasound or infrared distance sensors. Different sensors may measure internal parameters. For example, battery current and motor speed.
actuators are propulsion and steering systems for wheeled robots. There may be lifting mechanisms for cargo, robot arms, and other moving devices. Some robots have legs with electrical or hydraulic drive mechanisms. All these modules are interconnected over a communication network and controlled computational resources. In this paper, the focus is on a practical approach and implementation of a cyber-physical system on mobile robots and autonomous vehicles.

2. Overview of similar projects
Public transportation and logistics inside industrial companies include different types of robots, drones, and autonomous vehicles. Smaller robots that can be used inside the warehouses and factory floors are under the consideration. Different robots are brought out in Table 1, according to the producer, and are selected to analyze the onboard cyber-physical system development. Robots are chosen based on the sort of lifting or goods carrying mechanism, which allows them to move the payload from one location to another. These robots usually have good navigation capabilities inside the rooms, which are crucial in narrow corridors and cases where limited space is available.

Table 1. Listed robots are used in the logistic task.

| Developer (Robot name) | Software | Sensors |
|------------------------|----------|---------|
| Amazon Robotics (Drive Unit) | Proprietary agent-based software running on the robots. | Downward-facing camera, upward-facing camera, infrared sensors, and collision-detection bumpers. |
| Fetch Robotics (Freight) | ROS + custom navigation packages | Two Intel RealSense 3D cameras, SICK TIM lidar |
| Locus Robotics (LocusBot) | Proprietary | Lidar |
| Vecna Robotics (RC20 Conveyor) | Proprietary Pivot.al (multi-agent AI-based orchestration engine) | NA |
| InVia Robotics (Picker Robot) | Proprietary inVia Robot Management System (RMS) | Industrial-grade global shutter cameras |
| Robotnik Automation (RB-2 BASE) | ROS | 2x Lidar, RGBD devices for the detection of obstacles |
| MiR - Mobile Industrial Robots (MiR100) | ROS | 2x SICK microScan3 safety system, 2x 3D camera |
| HOMAG Group (TRANSBOT) | NA | 2x Lidar |
| TalTech (BoxBot) | ROS + Autoware | 4x Lidar, cameras |

The robots brought out in Table 1 have quite different software, sensors, and control systems. There is a trend to use open-source solutions for different kinds of mobile robot control software. A popular choice is a Robot Operating System (ROS) with a specific software stack or add-on modules [12]. There are few such robots, for example, BoxBot, Robotnik, MiR, and Freight. Others are using proprietary software, which may be a disadvantage, because it may be difficult to add new functionality on an ongoing basis of changing tasks. High-quality sensors like 3D lidar (light detection and ranging) are not very common. Most robots use 2D lidars, cameras, and ultrasound sensors. This set and functionality of sensors may limit the robot's performance in new or more complex environments and in the manufacturing environments where the changes are very often taking place.

The long-term goal is to create a situation, where multiple robots work together for one specific task or serve the manufacturing process. For example, logistics robots serve the production stations by supplying the raw material and bringing production results into the warehouse. This kind of multi-robot
3. Concept of multi-layer cyber-physical architecture

Tallinn University of Technology (TalTech) developed a low-level control architecture of the CPS first for a self-driving last-mile bus called iseAuto [15, 16]. Then based on the same architecture, a new small-scale logistic robot (BoxBot) has been developed to move boxes in rather tight spaces. During the tests, it was determined that the robot is capable of transporting packages without human interference. It is not trivial to implement robot-based logistics as many specific issues need to be solved and addressed. Corridors and transportation spaces are usually designed for humans and the robot must navigate between obstacles that may change at any time. The tasks of the robot may also change.

The iseAuto has been designed to be a minibus that is going to operate primarily on the territory of the university campus, therefore the speed of the vehicle was limited to 20 km/h. The architecture of the vehicle’s CPS is divided into layers as described in figure 2. The AI and high-level decision-making layer make autonomous driving decisions based on the sensor’s input layer. The vehicle speed and direction commands are sent to the actuators layer that has a mission-critical functionality to take care of the vehicle’s actual control. Control logic is divided into two layers – the master controller layer and the drive controller layer. The main task of the master controller is to act as a central gateway between all the nodes. The most sophisticated low-level functionality is integrated into the drive controller which controls the vehicle movement and steering. For safety reasons, a separate safety controller has been developed to stop the vehicle, when some fault is detected. The communication layer runs on separate CAN networks and Ethernet.

![Figure 2. Low-level control solution for TalTech iseAuto](image)

Small scale logistic robot BoxBot is developed to operate inside warehouses and to transport materials from and to the production units and empty boxes between washing stations and production units. The control architecture of the logistic robot is like iseAuto and is divided into the same layers as described in figure 3. Also, it is adapted to fit a much smaller space. The upper layer provides input to the ROS high-level control system. The AI & drive algorithm layer is based on the NVIDIA Jetson AGX Xavier developer kit. The logistic robot commands are sent to the low-level control layer that has a mission-critical functionality to take care of the robot’s movement control. The central unit for this layer
is the master controller. The difference is that the drive controller which is originally meant to control the iseAuto OEM platform and steering is not needed and replaced with a simpler motor controller for two-wheel hub motors. For lifting mechanism and other system dedicated controllers included.

![Diagram of the control solution for TalTech BoxBot](image)

**Figure 3.** Low-level control solution for TalTech BoxBot

Both CPSs have three layers of control. High-level running AI and drive algorithms, mid-level master controller mediating and prioritizing the messages, and low-level control for actuators. The proposed unified concept includes an automatic connection level for all sensor and actuator modules. Plug and play modules are listed and information is sent to the upper level. The modules start automatically when they are connected to the communication network. A separate safety controller has been developed for the iseAuto platform, but it is not suitable for other applications, therefore new safety functions are built-in to the system and tightly integrated with all layers of CPS.

4. Discussion and future work

The first objective is to establish a multi-model cyber-physical architecture for a new industrial mobile robot BoxBot 2 which can be used later to build different types of smaller or bigger scale autonomous robots. The long-term goal is to create a situation where multiple robots work together for one specific task or serve the manufacturing process. More common and not platform-specific real-time tracking and monitoring systems should be further developed.

5. Conclusion

The paper analyzes the existing state of the art solutions of cyber-physical systems of mobile robots and concludes that many existing mobile robot platforms are non-modular and not compatible with extensions. Previously developed low-level control architecture of the CPS of a self-driving last-mile bus called iseAuto and mobile industrial robot BoxBot is analyzed in more detail and compared. By using the same architecture as a full-scale self-driving vehicle, a new small-scale logistic robot BoxBot 2 was developed for industrial indoor logistics. The target is to move materials in rather tight spaces in industrial areas and corridors. The concept derived from self-driving vehicles is converted to a multi-model cyber-physical architecture for an industrial autonomous mobile robot where the long-term goal is to create a situation where multiple robots work together for one specific task or serve the manufacturing process.
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