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Autonomous Vehicles and Automated Warehousing Systems for Industry 4.0

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Abstract

The rapid development of new technologies that enabled the emergence of important development segments such as the Internet of Things, Cyber Physical Systems, Information and Communication Technologies, Enterprise Architecture, and Enterprise Integration, have led to completely new manufacturing paradigms, which is called under the common name – Industry 4.0. The constantly growing use of autonomous vehicles and associated logistics solutions is among the most influential factors that foster this novel intelligent production framework. This paper describes the results of the latest research activities of the Laboratory for Robotics and Intelligent Control Systems in the Industry 4.0 domain where the focus lies on the shop floor digitalization and advanced control concepts that enable the transfer of technology and delivery of high-scalable logistic solutions.

Keywords: *Industry 4.0, shop floor digitization, autonomous vehicles, automated warehouses, logistics, technology transfer.*

1. Introduction

Since the first industrial revolution that began with the introduction of mechanical manufacturing facilities (the invention of the first mechanical weaving loom in 1784), the human society has gone through similar major changes three more times. The second industrial revolution started with the help of electricity that enabled mass production for the first time. Hundred years later, the third industrial revolution started with the help of electronics and information technology that enabled automated production.

In the literature devoted to Industry 4.0 there are many definitions of the meaning of this term [1-4]. Behind all definitions are the main technologies of Industry 4.0 that include [1,2]:

- Identification (RFID) and real-time locating systems (RTLS)
- Internet of Things (IoT) and Internet of Services (IoS),
- Cyber Physical Systems (CPS),
- Industrial automation,
- Continuous connectivity and information,
- Cybersecurity,
- Intelligent robotics,

- Product lifecycle management (PLM),
- Semantic technologies, industrial big data,
- Computational vision to improve the productivity of manufacturing industrial systems

Croatia, as a member of the European Union, has created its own strategy of smart specialization for the period 2016-2020. There one can find why everybody should do something useful for a common Croatian society goal, which is to overcome the following negative states and facts [5]:

- Croatia's innovation performance over the last decade has fallen short of expectations. The innovation system is operating below its potential.
- Croatia is significantly below the EU-average in innovation and belongs to a group of countries considered as moderate innovators.
- Croatia is performing below the EU average in most dimensions, but above the EU average in human resources.
- There are three factors that impede innovation: tax regime, lack of early stage financing and business environment. One structural problem that Croatia faces is that the volume of business R&D is low, despite the generosity of existing tax breaks.
- High-value products and services remain a negligible part of exports, and the country's skills and technological capabilities have remained stagnant.

1.1. Laboratory for Robotics and Intelligent Control Systems (LARICS)

Since its very beginning in 1996 LARICS has been involved in research on integrated robotics and process control. LARICS researchers mainly participated in the research devoted to unmanned aerial systems [6], intelligent control systems [7], service robotics, control of multi agent systems, robot formations, planning, scheduling and decision making in autonomous systems and application of new technologies in industrial control systems [8]. Looking at the above list of main Industry 4.0 technologies, LARICS is engaged in the fields of real-time locating systems, cyber physical systems, industrial automation and intelligent robotics. These interests were further expanded by developing compliant and heterogeneous robotic systems and deploying them in branches of flexible manufacturing, medicine, agriculture, civil engineering, and power generation. Emphasis was given to collaboration with industry, which resulted in many successful implementations of novel control algorithms and human-machine-interfaces in industrial plants. Particularly active we were in the field of autonomous vehicles and logistics where we worked continuously almost two decades on the following projects:

- Control of Automated Guided Vehicle (AGV), Euroimpianti s.p.a., Schio, Italy, 2003 [9],
- Control of Multi-AGV Systems, Euroimpianti s.p.a., Schio, Italy, 2004-2005 [10],
- Autonomous mobile sensor platform for closed space surveillance and cleaning, Sitek s.p.a., Verona, Italy. 2005-2007 [11],
- Estimation and Control for Safe Wireless High Mobility Cooperative Industrial Systems (EC-SAFEMOBIL) – FP7 IP Project, 2011-2015 [12],
- Automated map calibration for markerless localization (AMaCal), HAMAG-BICRO PoC6 Programme, 2016-2017,
- Software modules for SLAM, Navigation and Mapping, Phoenix LiDAR Systems Ltd., Los Angeles, USA, 2017-2019.

2. Automated warehousing systems

Automated warehousing systems with AGVs represent the backbone of material handling operations within manufacturing facilities and distribution terminals. While developing such complex system, one should treat it as a handful of smaller subsystems, as shown in Fig. 1 [12]:

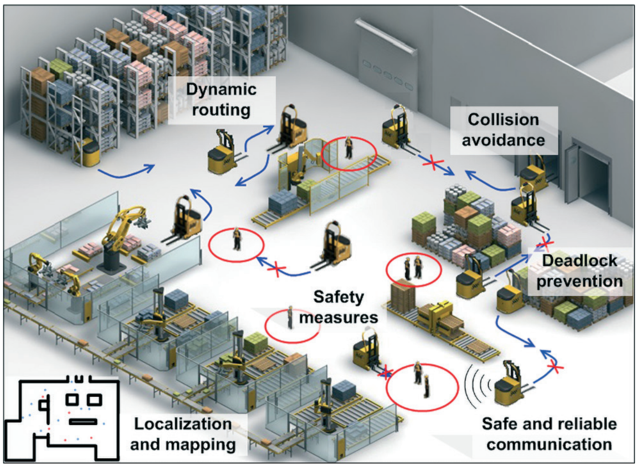


Fig. 1. Main subsystems of automated warehouse [12]

- Accurate localization and mapping of the warehouse environment,
- Safe and reliable communication,
- Collision avoidance,
- Dynamic routing,
- Deadlock prevention, and
- Safety measures.

All subsystems presented in Fig. 1 below are necessary for the safe and efficient operation of an automated warehouse. Accurate localization of the AGV needs to be maintained in all sections of the warehouse, mission control of AGV groups and dynamic routing with safe trajectory planning are important issues to be resolved.

Regarding the traffic control and mission execution aspects, a top-down control hierarchy starts with a mission assignment. For most industrial warehouse systems missions are issued in a centralized manner, coming sequentially from a central task dispatching unit. Missions can be assigned either by a human operator or through acquired commands from integrated warehouse components (e.g. loading and unloading stations). An alternative way is through decentralized task dispatching, which assumes each industrial automated vehicle bids for new missions and negotiates with its neighboring vehicles future mission assignments.

It is worth noticing that the operation of AGV traffic control systems developed in the first three listed LARICS projects completely relies on prepared floors for motion guidance. Ten years later, the focus was already moved to freely navigating AGVs to be used in large-scale manufacturing and logistics applications. Freely navigating AGV's mainly use laser scanners for navigation; these provide an accurate two-dimensional map of the actual environment for self-localization and obstacle avoidance.

2.1. Accurate localization and mapping of the warehouse environment

Low level control subsystems, involving path planning and path following, depend on the correct selection of path planning and path following algorithms, resolution of on-board sensors and most importantly on the precision of localization. This was the challenge that the LARICS research team took for its goal within the EC-SAFEMOBIL project – to develop high-precision localization for markerless navigation as well as dynamic routing and decentralized control of a fleet of free-ranging AGVs. At the time, there were several indoor localization solutions using Kalman filters, particle filters and scan-matching algorithms [14-18], but the achieved precision was still an order of magnitude worse than required for safe operation in manufacturing environments [19].

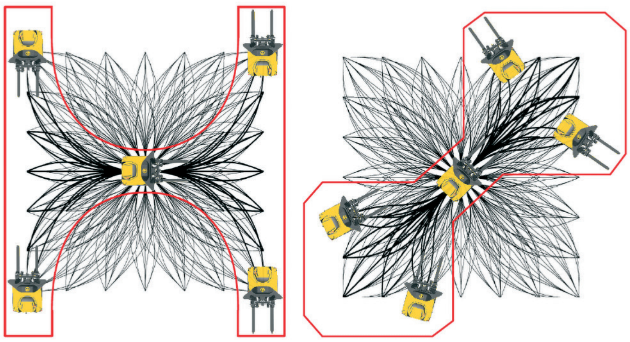
The LARICS research team pursued the approach that combines Adaptive Monte Carlo Localization (AMCL), Iterative Closest Point (ICP) scan matching and Discrete Fourier Transform (DFT)-based pose estimate refinement into one algorithm stack for high-precision localization in industrial indoor environments [20]. The experiments were performed in an industrial warehouse setting, with a full-sized autonomous forklift and with the localization accuracy <0.01m, 0.5° (Fig. 2). The localization module worked in closed loop with the vehicle control module, so any significant localization error would cause a failure in path execution.

Fig. 2. Markerless pallet delivery of an AGV in the industrial facility with the localization accuracy <0.01m, 0.5° provided by the AMCL+ICP+FFT localization algorithm stack [20].

2.2. Dynamic routing and decentralized control for free-ranging AGVs

The adoption of the free-ranging motion scheme is more suitable for performing localization experiments as it allows for easy definition of arbitrary motion sequences within any part of the dynamic working environment. An important aspect that must be considered during the design of the path planning algorithm is related to path feasibility due to the non-holonomic vehicle constraints. Considering the desired free-ranging properties together with the path feasibility requirements, we decided to implement a path planning method based on the use of a state lattice [21]. In [22] we used the state lattice with $\pi/8$ orientation resolution and 0.25m distance between any two adjacent states in the x-y plane (Fig. 3). The number of states that each state is connected to, as well as the state sampling density is chosen based on the size of the vehicle, the size of workspace and vehicle steering limitations. The path planning part of the algorithm implements a free-ranging motion scheme by determining the shortest feasible paths considering non-holonomic vehicle constraints (Fig. 3).

The motion co-ordination part of the algorithm ensures safe vehicle motions by reliable detection and resolution of different conflict situations with other vehicles in the shared workspace. Conflict resolution is based on a vehicle priority scheme and results in temporary stopping



(a) $\theta = 0$ (b) $\theta = \pi/4$

Fig. 3. Dynamic routing and decentralized control for free-ranging AGVs – concept of the state lattice with associated private zones [22].

or removal of the lower priority vehicles taking part in the conflict. Removal action is always performed within the vehicle's private zone (Fig. 3, top left and right), i.e., the pre-allocated local region of the workspace surrounding the vehicle. By encoding information on the vehicle size and its kinematic constraints, the introduced private zone mechanism provides the necessary physical space required for successful execution of every removal action. It can be seen at the top of Fig. 4 that in the implemented free-ranging mode of navigation mission commands for all AGVs come from the central control center while the rest of the functions needed for free-ranging navigation is performed onboard each AGV. As it can be seen at the bottom of Fig. 4, once a conflict situation is detected, there is a message flow among the AGVs involved in the removal negotiation process. The proof of the theorem is given in [23] that the presented decentralized control algorithm based on the private zone mechanism and the collision avoidability property of the state lattice ensures successful resolution of every negotiated conflict situation with an arbitrary number of vehicles.

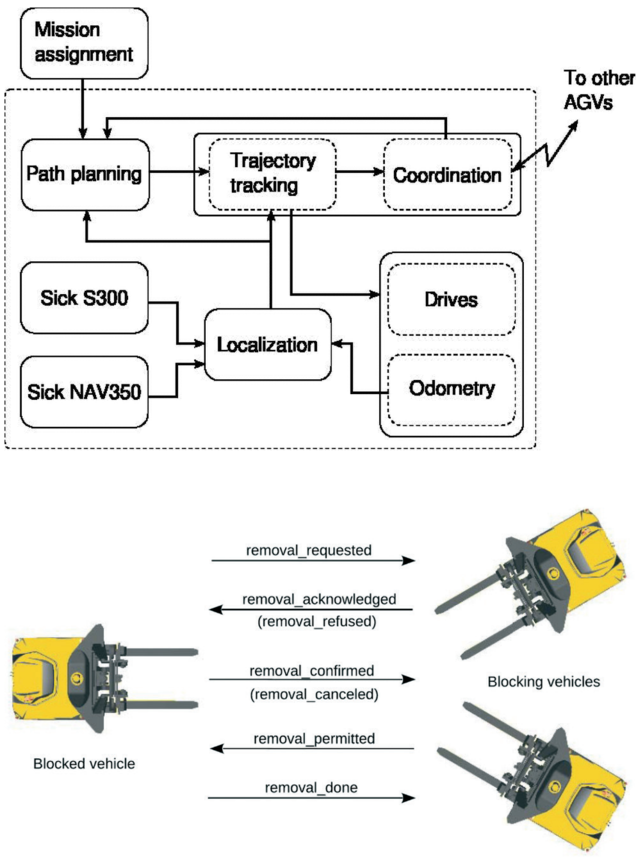


Fig. 4. Top: The concept of a decentralized free-ranging navigation control running on each vehicle in the system. Bottom: Message exchange flow during the removal negotiation process [22].

The effectiveness of the algorithm performance was tested in three ways: by simulation validation on a system with up to fifty vehicles (Fig. 5), by experimental validation on a system with six Pioneer 3DX robots (Fig. 6) and by experiments with two autonomous forklifts, Euroimpianti Skilled 1000 and Skilled 1400 (Fig. 7).

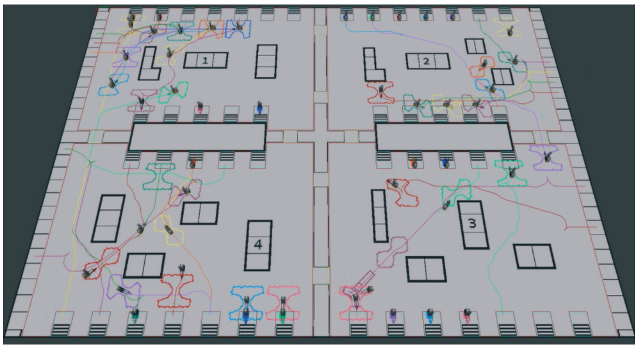


Fig. 5. Validation of the algorithm performance on a system composed of fifty vehicles in an environment with static obstacles. [23].

Fig. 6. Validation of the algorithm performance on a system composed of six Pioneer 3DX robots in a laboratory environment with terminals and corridors. [23].

Fig. 7. Validation of a co-ordination maneuver between two autonomous forklifts in an industrial environment. [22].

2.3. Automated map calibration for markerless localization

The core of each autonomous vehicle navigation system that navigates in the unstructured and previously unknown environment is the algorithm for Simultaneous Localization and Mapping (SLAM). The idea of automatic calibration of the map is based on the automatic use of the CAD architectural design as a priori knowledge of building a laser-based map that is used for extension of a GMapping SLAM algorithm [24-25]. Experiments in industrial environments were conducted in two different locations: in the Konzum CFC Vrbani warehouse in Zagreb (Fig. 8) and in the System Logistics production facility in Italy (Fig. 9). As a result of the AMaCal project, submission of the International PCT Patent Application PCT/HR2017/000019 was made in December 2017.

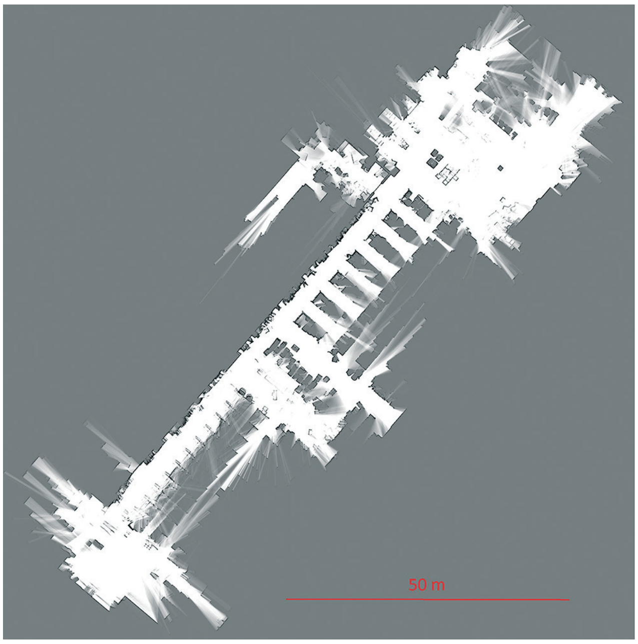


Fig. 8. Mapping of the Konzum warehouse in Zagreb.

3. Transfer of technology to industry

As demonstrated, after years the technology readiness level of achievements has become sufficiently high to initiate the process of technology transfer from the academy to the industry milieu.

Fig. 9. Mapping of the System Logistics production facility.

3.1. Collaboration with Phoenix Lidar Systems

In December 2017 LARICS started collaborating with the US high-end company Phoenix Lidar Systems, devoted to building complete seamless, easy-to-use mapping solutions by crafting and combining quality hardware and innovative software. LARICS is applying the state-of-the-art SLAM technology for performing indoor localization and seamlessly fusing indoor and outdoor data into a geo-referenced environment map. One of the problems solved in this collaboration is the fast frontier detection of unexplored (unmapped) areas by merging adjacent submaps [26].

3.2 Founding of spin-off RoMb Technologies

In October 2018 LARICS has founded a spin-off company devoted to robot mobility systems named RoMb Technologies Ltd. The company started its business activity after it established an agreement with the Faculty of Electrical Engineering and Computing (FER) about the transfer of intellectual property rights from FER to RoMb. Behind the scene there was a Chinese company RV Automation from Hong Kong, China, which expressed interest in the LARICS technology and made the first order – conversion of a standard Linde (renown Swedish manufacturer) forklift into a fully autonomous one. Final tests in May 2019 in the RV Automation facility and at the end user's warehouse were successfully completed, conducted under continuous supervision of Linde's experts (Fig. 10).

Fig. 10. Tests with a Linde T20 autonomous forklift in RV Automation facility in Hong Kong during execution of a pallet delivery task.

3.3 Collaboration with System Logistics

In February 2019 RoMb Technologies started collaborating with the Italian company System Logistics on the autonomous markerless navigation system that includes several Industry 4.0 technologies acquired from LARICS: path planning and navigation software modules, precise map calibration with a CAD layout of the warehouse, markerless localization that reduces costs during system commissioning. Experiments performed in the System Logistics facility in May 2019 convincingly demonstrated in situ the real value of the new solution for high accuracy SLAM and autonomous navigation of autonomous vehicles without the need for artificial markers installation.

4. Conclusions

The digitalization of production processes, interconnectivity and adaptability of all agents in the intelligent production ecosystem offers good chances for everyone to find one's own niche of expertise and become a leader in innovation and provision of ready-to deliver Industry 4.0 solutions. Thanks to continuing orientation to collaboration with industry and integration into the European research area, Laboratory for Robotics and Intelligent Control Systems (LARICS) of FER Zagreb has been slowly but steadily increasing its competence to actively participate in Industry 4.0 development segments. LARICS has been engaged over two decades in raising the level of digital culture and training of its students and partners, both in the industry sector and in the academic circles. By giving the description of projects in a chronological way, we show that belonging to the developed world means continuous investment in people, education and establishment of stimulating governmental instruments for academia and industry to connect better, collaborate more and learn continually to grab the position of desirable partners and possibly regional/global leaders in specific Industry 4.0 development segments. Two videos with experiments described in this paper with different autonomous vehicles – industrial forklifts are available at: https://youtu.be/Q-B2yvKRarU and https://www.youtube.com/playlist?list=PLC0C6uwoEQ8beVQCSdaIFHIs40q1Z8yGF.

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