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EDITOR-IN-CHIEF'S WORD

HATZ Bulletin ENGINEERING POWER is published by the Croatian Academy of Engineering and it promotes scientific achievements of our Academy members, especially those dealing with challenging or contemporary research activities in technique and technology at an appropriate publishing level.

The Bulletin is published quarterly on an annual basis. In this issue our guest editor and prominent member of the Academy Stjepan Bogdan and his team have tried to briefly present laboratory achievements in the exploration of robotic systems of special aerial and marine robotics which today presents a future research area.

Editor-in-Chief
Vladimir Andročec, President of the Croatian Academy of Engineering

EDITOR'S WORD

Dear readers,

Mobile robotics, utilizing state-of-the-art artificial intelligence and sensory subsystems, is a 'game-changing' technological field that influences many contemporary industries and research areas.

To this end, it is our pleasure to present in this edition of Engineering Power research activities in the field of autonomous robotic systems that were conducted in three laboratories of the Faculty of Electrical Engineering and Computing of the University of Zagreb.

The Guest-Editor of this issue is Stjepan Bogdan, Associate Member of the Academy and Professor at the Faculty of Electrical Engineering and Computing, University of Zagreb. I am sure that you will enjoy reading presented contributions that cover various topics of this attractive field of modern science.

Editor
Zdravko Terze, Vice-President of the Croatian Academy of Engineering

FOREWORD

A rapid increase in computational power of embedded computers followed by miniaturization of sensors and actuators and development of new, lightweight materials have forever changed the shape and functionalities of robots by providing the basis for the implementation of complex control algorithms, multifaceted decision making processes, perception based on high definition video streams and very precise positioning systems. This in turn provided an unprecedented expansion of robots autonomy. Witnessing this technological rise, it is not strange that societal demand and financial incentive emerged so that estimates predict that by 2025 advanced robotic and autonomous systems could have a worldwide economic impact of \$1.7 trillion to \$4.5 trillion annually with an emerging market value of €15.5 billion per year. Based on these estimates EU formed Robotics in Europe, the largest civilian research and innovation program in robotics, with the main goal of the initiative – called SPARC – to maintain and extend Europe's leading position in this strategic area. This clearly shows that the sector of development, manufacturing and application of autonomous robotic systems capable of operations in dynamic and non-deterministic environments is one of the most progressive sectors in modern economy. We have witnessed an increased interest in self-localization and mapping (SLAM), perception and cognition, and decision making in autonomous robotic systems, especially related to decentralized approaches. In comparison with centralized control, decentralized approach avoids a single point of failure which, in turn, increases overall robustness of the system, allows for inexpensive and simple agents and lowers the implementation cost. In this edition of Engineering Power we are presenting the state-of-the-art research in the area of autonomous robotic systems that was conducted by three laboratories – LABUST-Laboratory for Underwater Systems and technologies, LAMOR-Laboratory for Autonomous Systems and Mobile Robotics and LARICS-Laboratory for Robotics and Intelligent Control Systems of the Faculty of Electrical Engineering and Computing of the University of Zagreb jointly active under the brand name ROBOTICS@FER.HR. The papers presented herein include an overview and results of the cooperative robotics in marine environment through SLAM and mission planning in industrial warehouses to the implementation of robotic manipulators on unmanned aerial vehicles (UAVs).

Guest-Editor
Stjepan Bogdan, University of Zagreb, Faculty of Electrical Engineering and Computing

CONTENT

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Aerial Robotics – Unmanned Aerial Vehicles in Interaction with the Environment

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Abstract

Defined as technology that provides services and facilitates the execution of tasks (such as observation, inspection, mapping, search and rescue, maintenance, etc.) by using unmanned aerial vehicles equipped with various sensors and actuators, aerial robotics in one of the fastest growing field in research as well as in the industry. While some of the services provided by aerial robots have already been put into practice (for example aerial inspection and aerial mapping), others (like aerial manipulation) are still at the level of laboratory experimentation on account of their complexity. The ability of an aerial robotic system to interact physically with objects within its surroundings completely transforms the way we view applications of unmanned aerial systems in near-Earth environments. This change in paradigm conveying such new functionalities as aerial tactile inspection; aerial repair, construction, and assembly; aerial agricultural care; and aerial urban sanitation requires an extension of current modeling and control techniques as well as the development of novel concepts. In this article we are giving a very brief introduction to the field of aerial robots.

Keywords: *unmanned aerial vehicle, aerial robotics, aerial manipulation*

1. Introduction

A huge impact of Unmanned Aerial Vehicle (UAV) technologies evolution has been pointed out by several studies. According to the report [1], the total addressable value of UAV powered solutions in all applicable industries is estimated at over $127 billion (bn) in 2015 in the world (see Table 1).

Table 1. Value of UAV powered solutions (in $bn)

Infrastructure	45.2	Telecommunication	6.3
Transport	13	Agriculture	32.4
Insurance	6.8	Security	10.5
Media and Entertainment	8.8	Mining	4.3
Total			127.3

The industry with the best prospects for UAV applications is the infrastructure with total addressable value of just over $45bn. This includes investment monitoring, maintenance and asset monitoring. The study [2] is devoted to UAV inspection applications Beyond Visual Line of Sight (BVLOS) and has pointed out that in oil and gas a 1% change in downtime can result in $600,000 revenue lost in a day. In this industry any slight improvement in asset utilization can result in a significant gain in revenue and cash flow: Companies could lose up to 5% of production due to unplanned down. The average impact of unscheduled downtime caused process companies to lose more than $20 billion in production annually. UAVs reduce inspection costs by approximately 66%. For example, the cost with traditional methods is $80-$90 per well pad, with 5-10 inspected per day. The costs with drones in the Visual Line of Sight (VLOS) is $45-$60, with about 8-16 inspected per day. For BVLOS applications it is $30-$50 with 100-125 inspected per day. The SESAR UAV study [3] is very relevant concerning the impact in Europe. According to the study, the

European demand will be more than EUR 10 billion annually by 2035 and over EUR 15 billion annually by 2050. Particularly, government and commercial business applications will represent the majority with more than EUR 5 billion of annual value by 2035 (the estimated potential is over 100,000 UAVs by 2035). All these numbers clearly show that industries related to UAVs are one of the fastest growing market with huge potentials.

As many of potential applications require interaction of UAVs with the environment (contact between robotics arms or tools on-board the vehicle with infrastructure), one of the major research topics in the UAV research field is related to the analysis of phenomena once an UAV is in contact with the surrounding as well as the synthesis of the controllers that ensure the stable behavior of an aerial manipulator.

2. UAV related research in LARICS

Starting in 2006, research of aerial systems has become one of the major research lines of LARICS (larics.fer.hr) over the last 10 years. Mainly focused on multirotor systems, studies included i) UAV design [4, 5], ii) analysis of UAV dynamics and kinematics [6], iii) design of UAV controllers [7], iv) design and control of aerial manipulators [8], and v) mission planning and scheduling for cooperative teams of aerial and ground vehicles [9].

Currently LARICS researchers are involved in the following projects that are related to UAVs: AeroTwin – Twinning coordination action for spreading excellence in Aerial Robotics (H2020), ENCORE – ENergy aware BIM Cloud Platform in a COst-effective Building REnovation Context (H2020), MORUS – Unmanned system for maritime security and environmental monitoring (NATO), Specularia – Structured Ecological CULtivation with Autonomous Robots In Agriculture (HRZZ), EuRoC – Wind generator remote inspection system (FP7), and MBZIRC – Mohamed Bin Zayed International Robotics Challenge (Khalifa University). In the rest of the paper we shortly present our results of research on UAVs in interaction with the environment, namely, transportation of a package and an ultra-light ground vehicle and peg-in-hole insertion task.

3. UAV in interaction with the environment

The first example we present herein considers a system comprised of two distinct agents with specific capabilities – a mobile unmanned aerial vehicle (UAV) with a manipulator and a lightweight ground vehicle (L-UGV) [9]. This two-agent system has a task to find a package in an unknown environment and to deliver the package to the predefined position by executing a mission that is optimal from the energy point of view. UAV is the most versatile of the robot agents in the system (and the most energy expensive). It surpasses the ground vehicles with its four degrees of freedom enabling it to access every section of the environment. The UAV in this example goes beyond the well-known and rather simple concept of eye-in-the-sky since it has the ability to physically interact with its surroundings – both the parcel and the L-UGV – by using on-board dual-arm manipulator with two degrees of freedom.

To find and track both the package and the L-UGV,we designed two vision-based algorithms (UAV has onboard camera pointing downright), one based on AR marker tracking and the other based on tracking the IR LEDs placed on top of the L-UGV. In order to successfully find and pick up the L-UGV, an infrared LED tracking algorithm was designed. The final result, the UAV carrying the L-UGV and the package during mission execution, is shown in Fig. 1.

The second example is related to the experimental validation of canonical peg-in-hole manipulation task using an aerial robot [10]. The same as in the previous example, the robot consists of a multirotor platform equipped with a dual arm multi-degree of freedom manipulator. The research of aerial manipulators is often accompanied with use-case scenarios, ranging from single degree of freedom (DOF) grippers [11], [12], multi DOF grasping [13], [14], to more complex missions which require strong interaction with the environment. Such missions include valve turning [15], opening and closing a cupboard drawer [16] or surface cleaning [17]. In most cases the information about the applied force to the environment is not used. For instance, the authors in [18] performed an aerial robotic contact-base inspection without any knowledge about the applied force. Instead, they set the position reference of the UAV inside the environment. There is also a variety of the aerial manipulation tasks where the force information is not taken into account.

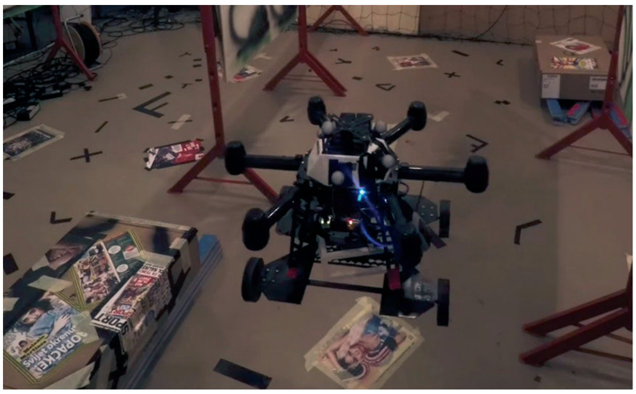

Fig. 1. Multirotor UAV in a mission of carrying an L-UGV and a parcel.

The objective of the proposed peg-in-hole experiment is to validate UAV controller whose purpose is to control UAV's end effector impedance in Cartesian coordinates in order to provide a stable physical interaction. The ba-

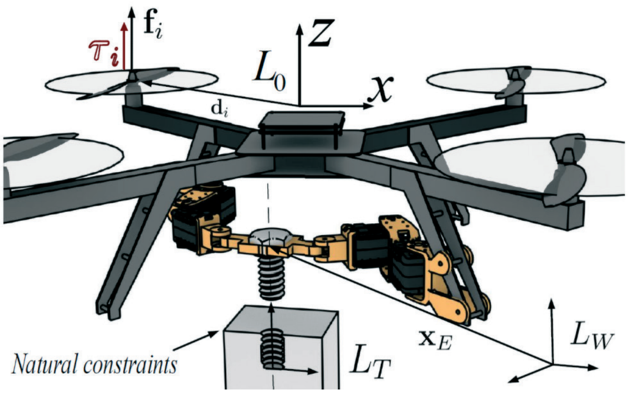

Fig. 2. Multirotor UAV with dual-arm manipulator executing peg-in-hole task.

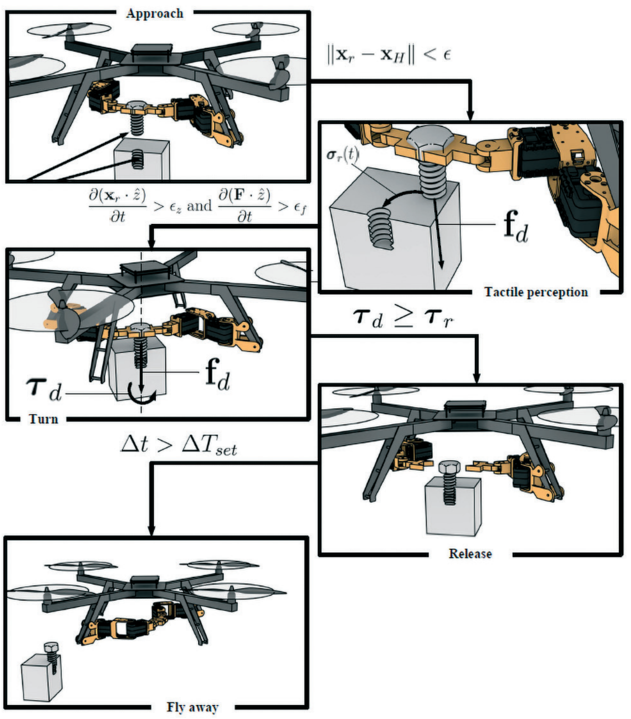

Fig. 3. Five-state automaton describing multirotor UAV with dual-arm manipulator executing peg-in-hole task.

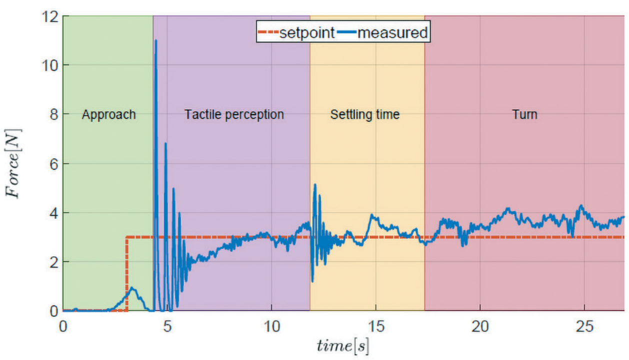

Fig. 4. Force setpoint in z-axis direction and response during each task frame. The oscillations in the forces are due to bouncing the multirotor during the contact.

sic impedance control concept is to establish a desired user-specified dynamical relationship between the contact force and position. Fig.2 shows the proposed aerial

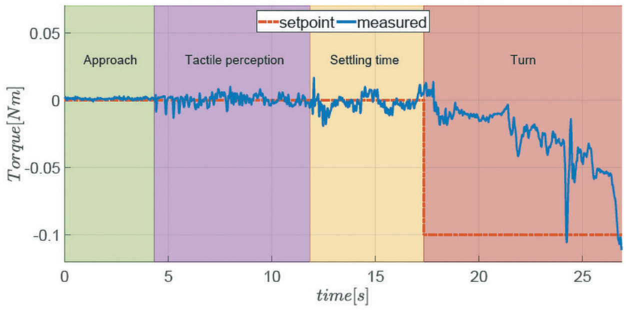

Fig. 5. The end-effector z-axis twist response on fastening a bolt. The bolt is released in the moment when the measured torque is bellow threshold value.

robot w.r.t. the task frame, the insertion point for the bolt. The image shows forces and torques produced from within a specific rotor and relates the defined coordinate systems.

However, to drive the bolt in the hole, we humans seldom rely purely on vision, but rather choose to use our sense of touch. This personal experience teaches us to define the second state of automaton (Fig. 3), as touch perception. During this state, the impedance control is utilized to regulate a constant pressure force normal to the surface around the hole. Results of mission execution are presented in Figs. 4 and 5 in a form of responses of the transitions between each phase as well as triggers that ultimately drive the robot to tighten the bolt.

4. Conclusions

In this article we have very briefly introduced the field of aerial robotics. Details of the current trends in the research and on the market are presented together with an overview of the running projects in which LARICS – Laboratory for Robotics and Intelligent Control Systems is participating. Finally, two sets of results of experiments are given in order to present just a glimpse of various possibilities that are offered by this novel technology that belongs to the field of autonomous robotics systems.

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Cooperative Robotics in Marine Monitoring and Exploration

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Abstract

Marine robotics play a great role in modern exploration of marine environments. The Laboratory for Underwater Systems and Technologies of the Faculty of Electrical Engineering and Computing of the University of Zagreb is involved in marine robotics research and is currently participating in a number of marine robotics related projects. This paper addressed the issue of using multiple cooperative marine robots (surface and underwater) for marine monitoring and exploration within the scope of CroMarX project. The project brings a new dimension to marine monitoring and exploration by introducing cooperative marine robots that increase operational efficiency. The main objective of the CroMarX project is to investigate and develop cooperative control algorithms in the area of marine robotics, taking into account both unmanned surface marine vehicles (USVs) and an unmanned underwater vehicle (UUV) for the purpose of marine monitoring and exploration.

Keywords: *marine robotics, cooperative robots, unmanned surface marine vehicles, unmanned underwater vehicles.*

1. Introduction

About 70% of Earth is covered in water and thus poorly accessible for exploration. As a result, we know more about the surface of the Moon and Mars than we do about our own planet. Even the Adriatic Sea with the maximum depth of around 1,200 meters remains fully unexplored. The underwater environment is harsh and under constant influence of disturbances such as sea currents, winds and waves. However, the oceans and the seas are home for a myriad of species, many of which have yet to be discovered, and a great source of resources much needed for the humankind. Human presence in the marine environment is possible only with the help of technical equipment such as SCUBA gears or manned submersibles – both approaches involve high risk for people involved.

In order to avoid direct human presence in the underwater, and still be able to monitor and explore the marine environment, unmanned marine surface vehicles (USVs) and unmanned underwater vehicles (UUVs) are successfully exploited. Unmanned marine vehicles play a large role in different application fields such as

- marine biology, for exploration and preservation of marine species and habitats,
- marine ecology, for detection of pollutants and invasive species
- underwater archaeology, for mapping and preservation of submerged cultural heritage,
- aquaculture, for maintenance of fish farms,
- marine security, for monitoring marine borders,
- offshore industry, for remote maintenance and repair of offshore infrastructure) and many more.

All maritime countries, as well as Croatia, with jurisdiction over almost half of the Adriatic Sea, have the obligation to monitor, explore and protect their marine environment.

Advances in small embedded processors, sensors and miniaturized actuators have increased interest in study and development of multi-robot systems, where a number of USVs cooperate in a common operative framework, coordinating their motion, in order to achieve a global mission goal. The fleet operation shows the potential to drastically improve the means available for ocean exploration and exploitation. The use of multiple autonomous robotic vehicles acting in cooperation will drastically increase the performance, reliability, and effectiveness of automated systems at sea. Multi-vehicle operations render possible tasks that no single vehicle can solve as well as increase operational robustness toward individual failures. This paper addresses the issues of cooperative robots used for marine monitoring and exploration.

The paper is organized as follows: the following section describes activities of the Laboratory for Underwater Systems and Technologies where research related to marine robotics is conducted; Section 2 describes state of the art in the area; while Section 3 describes CroMarX project dealing with cooperative marine robots.

1.1. Laboratory for Underwater Systems and Technologies (LABUST)

LABUST (http://labust.fer.hr) is a research laboratory of the Faculty of Electrical Engineering and Computing of the University of Zagreb that holds expertise in marine robotics: development and adaptation of marine vehicles; acoustic networks and sonars; identification, navigation, guidance and control of marine vessels; cooperative and coordinated formations of marine vehicles. LABUST has large experience in coordinating research projects (FP7 CURE, FP7 CADDY, H2020 EXCELLABUST, H2020 aPad) and participating in projects such as FP7 EUROFLEETS2, FP7 CART, H2020 subCULTron, H2020 PlaDyFleet, ECHO-DG e-URready4OS, INTERREG BLUEMED. In the last 5 years the group has also participated in other 6 international and 3 national projects related to marine robotics. LABUST have organized 10 annual field trainings "Breaking the Surface" with the purpose of conducting multidisciplinary research within marine biology, archaeology and security.

Several USVs and UUVs available in LABUST allow validation of the developed algorithms on real vehicles in real environmental conditions that are challenging and under constant influence of disturbances such as waves, sea currents and winds.

Five **USVs H2OmniX** were developed at UNIZG-FER LABUST as multipurpose vehicles with a great number of sensors, capable of executing numerous guidance and control tasks in sea state 3. Each USV (shown in Fig. 1) is a small, one man portable overactuated platform with four thrusters positioned in such a way that they form an X-shaped which allows movement in every direction while maintaining arbitrary desired heading. The dimensions of the vehicle are 707x707x450 mm and the weight is about 35 kg. The hull is made of carbon fibre which guarantees robust operation in real environmental conditions. All USVs are equipped with an Inertial Measurement Unit (IMU) and Real Time Kinematic Global Positioning System (RTK GPS) for navigation on the water surface, Ultra-Short Base Line (USBL) for acoustic localization and communication with underwater agents, e.g. divers or underwater vehicles and down looking high definition (HD) camera for diver tracking or shallow water mosaicking.

Fig. 1. The fleet of unmanned surface vehicles (USVs) H2OmniX.

UUV „BUDDY" shown in Fig. 2 was developed at LABUST with the primary purpose of assisting divers during their underwater operations, hence the name „BUDDY". The UUV has high manoeuvring capabilities (full

Fig. 2. The unmanned underwater vehicle (UUV) BUDDY on dry land during experiments in Biograd na Moru, Croatia

actuation) due to four horizontal and two vertical thrusters and is capable of dealing effectively with underwater environment. Integrated on the UUV are proprioceptive sensor devices needed to develop a precise navigation module, i.e. IMU, DVL and USBL based positioning system. To be able to recognize postures and gestures of the diver, a set of exteroceptive sensors (stereo video system and sonar) were integrated. The frame of the autonomous underwater vehicle is made of an engineered plastic and the overall dimensions of the vehicle are 1220x700x750 mm and the weight is about 70 kg.

LUPIS UUV is torpedo shaped autonomous underwater vehicle by OceanScan, equipped with camera, forward looking sonar and sidescan sonar.

2. State of the art

2.1. Formation control

Large research interest is focused on the formation keeping. Historically different formation control frameworks were investigated such as Behavioural, Virtual Structure or Leader Follower. Distributed behavioural model suggested simple motion primitives for each group member such as collision avoidance, velocity matching and neighbour tracking, resulting in an overall complex motion behaviour resembling that found in nature, [1], [2]. The virtual structure approach is rooted in analytical mechanics for multi-body dynamics and facilitates a flexible and robust formation control scheme [3], [4].

Some works describe cooperative path following, where a group of vehicles is required to manoeuvre along pre-specified paths while keeping a desired formation pattern. In [5] work is reported in the area of absolute formation control where each vehicle is required to know its absolute position and those of the neighbouring vehicles. This is in contrast with the work in [6], where relative formation keeping is proposed where each vehicle is only required to know the position of neighbours in its own reference frame. In more recent work [7], the authors advance algorithms to coordinate the formation of vehicles when they can only measure the distances to their respective neighbours.

In Leader-Follower framework which has been extensively investigated lately, the formation consists of one or more (real or virtual) leaders to which a number of followers are assigned [8]. Paper [9] focuses on the guidance systems associated with guided motion control and presented full-scale formation control results using the coordinated target tracking functionality. The work in [10] and [11] addressed the simplified problem of maintaining an autonomous vehicle in a moving triangular formation with respect to two leader vehicles that move at the same speed and with constant separation. In [12] a control strategy for the follower vehicle is proposed that uses simple feedback laws for speed and heading commands to drive along track and cross track errors to zero. The performance of the algorithm was demonstrated in sea trials with the vehicles equipped with acoustic modems and ranging devices affected by noise, outliers and communication losses.

2.2. Collision avoidance

Another issue to be addressed, when two or more autonomous vehicles work in cooperation in the same operative area, is the problem of vehicles collision avoidance. Even if the mission is planned and cleared of any conflict between robots, vehicles can come to a collision due to external disturbances, different dynamic and kinematic characteristics, unpredicted conditions, online operation re-planning. A paper providing a general description of a multi-vehicle systems with integrated procedures and control laws to deal with the problem of inter-robot collision can be found in [13]. In [14] collision avoidance algorithm is presented based on the virtual target approach relying only on the known position of the robots in the operative frameworks. The approach offers a simple and robust methodology to achieve the collision avoidance task only on the basis of the known position of the vehicles.

2.3. USV-UUV cooperation

Cooperation between an unmanned surface vehicle (USVs) and an underwater vehicle (UUV) is of great interest to many research groups, mostly due to the fact that the USV can significantly assist the UUV in navigation through cooperation – this approach is referred to as cooperative navigation aiding (CNA). This type of scenario was applied in different research efforts. Pure CNA was utilized in the FP7 TRIDENT project [15] for aiding the navigation of an intervention AUV and in NATO project ANMCM [16] for aiding the navigation of smaller vehicles with low-quality sensors. Cooperative tracking and localization aiding of an underwater vehicle and a human diver is researched in the FP7

CADDY project [17] while the FP7 CO3AUV project [18] investigated navigation aiding of multiple UUV in parallel to cooperative movement. Different online motion planning algorithms for USVs to improve the overall quality of underwater position aiding is still an active research topic [19].

Navigation aiding and cooperative motion becomes problematic in complex underwater structures where line-of-sight acoustic communication is not possible. Multiple layers of navigation aiding by combining USV and UUVs for mapping of underwater slopes was researched in FP7 MORPH project [20].

While CNA seems to be well established in research projects during the last 6 years, different cooperation aspects between USVs and UUVs are less prominent. The H2020 subCULTron project proposes biologically inspired cooperation where interaction between USV and UUVs is not limited to navigation [21].

2.4. Mission control for multiple vehicles

It should be possible for users who are not necessarily familiar with the technical details of marine robot development to do mission programming and mission execution tasks. The development of a mission control system for single or multiple vehicles reflects the background of the developing team, the applications envisioned and the hardware available for mission control system implementation. References [22 -25] provide some background material and a historical perspective. The review of the major control architectures employed on a marine vehicle are described in [26].

The mission design layer usually provides mission map (map of the area to be covered), menu of the vehicles available to execute the mission, functionalities of each vehicle and the corresponding payload, a set of mechanisms enforcing spatial/temporal multi-vehicle synchronisation and path planning (to meet adequate spatial / temporal/energy requirements). The mission execution layer translates high-level plans into low-level primitives' execution, monitors the execution and handles the events raised for them. Popular approaches use state machines or Petri Nets to describe mission relating primitives to be executed in each state with the events that produce the transition between these states.

3. CroMarX project

"CroMarX – Cooperative robotics in marine monitoring and exploration" is a project financed by the Croatian Science Foundation. The main objective of the CroMarX project is to investigate and develop cooperative control algorithms in the area of marine robotics, taking into account both unmanned surface marine vehicles (USVs) and an unmanned underwater vehicle (UUV) for the purpose of marine monitoring and exploration. The global vision of the project is shown in Fig. 3 where a fleet of USVs is deployed at sea, exchanging information and maintaining optimal formation, while an UUV explores the underwater environment and cooperates with the USVs by taking advantage of their measurements to increase its navigation capabilities.

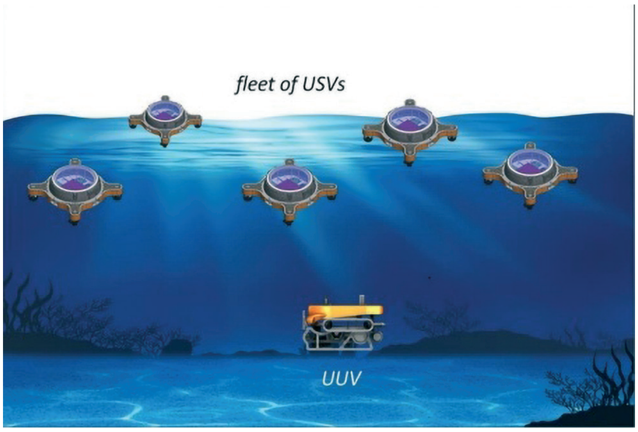

Fig. 3. The concept of the CroMarX project which includes cooperation between USVs and UUVs for the purpose of marine monitoring and exploration.

The main scientific objectives of CroMarX project are

1. Development of **cooperative control algorithms for a fleet of unmanned surface marine vehicles** for the purpose of marine monitoring

In order to achieve persistent marine monitoring (which includes monitoring marine borders, offshore structures and underwater habitats, etc.), CroMarX proposes to use a fleet of USVs that maintain a formation in order to cover a certain area. This objective includes both the development of cooperative control algorithms for controlling the formation and position of the fleet of USVs as well as formation control based on environmental inputs such as direction of sea currents.

2. Development of **cooperative control algorithms for an unmanned surface vehicle and an unmanned underwater vehicle** for the purpose of underwater exploration

In order to achieve underwater exploration, specifically seabed mapping UUVs are required to navigate precisely in order to provide georeferenced maps. Since conventional global navigation systems do not work under water, measurements from surface vehicles can be used to aid in their navigation. This objective is devoted to cooperative control algorithms for this purpose.

3. Development of the **mission control software and user interface** suitable for multiple surface and underwater marine vehicles

Controlling and monitoring multiple marine vehicles poses a challenge due to their spatial distribution and invisibility in the underwater environment. This objective is devoted to developing a mission control software that will have the function of monitoring the position of each agent involved, as well as commanding missions for individual and group of robots.

4. **Experimental validation** of the developed cooperative control algorithms applied on the fleet of unmanned surface vehicles and an unmanned underwater vehicle.

Experimental validation is of great importance in marine robotics due to the harsh nature of the environment in which the robots operate. Constant influence of external disturbances such as sea currents, waves and wind require testing of developed control algorithms in real environments. The CroMarX project is focussed around three validation scenarios that prove the functionality of the developed algorithms and show the project progress.

Scenario 1, USV fleet formation control for distributed marine monitoring, demonstrates the first USV fleet topology control. This scenario will demonstrate the functionalities of formation control with the topologies being commanded from the ground station, with special emphasis put on ensuring collision-free topology change enabled by the developed algorithm. This scenario is graphically shown in Fig. 4.

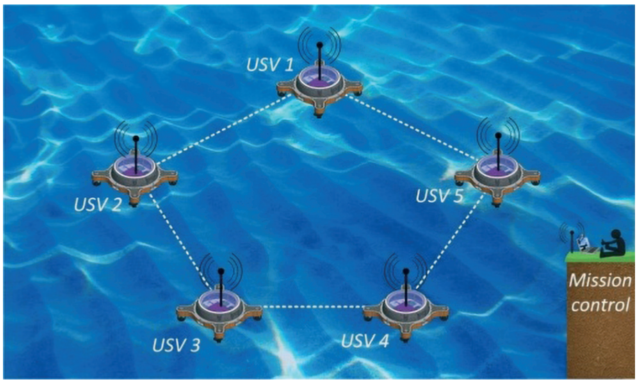

Fig. 4. The concept of Scenario 1 where the formation of the fleet of USVs is controlled from the ground station.

Scenario 2, cooperative seabed mapping using USV and UUV, demonstrates the USV-UUV cooperative control algorithms where both vehicles move in a cooperative manner while the USV is aiding the UUV in its navigation. This scenario will demonstrate the capability of seabed exploration. This scenario is graphically shown in Fig. 5.

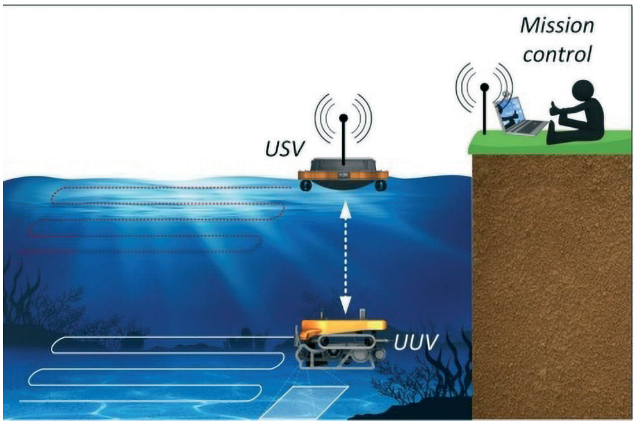

Fig. 5. The concept of Scenario 2 where a UUV and a USV cooperate in a way that the USV aids the UUV in navigation while the UUV is exploring a part of the seabed.

Scenario 3, environmentally adaptive fleet of USV formation keeping, is the final step of the USV fleet cooperative control with the addition of adaptation to environmental influences. The fleet will demonstrate how sea current can be estimated in a distributed manner, and how the fleet adapts the formation topology and orientation in order to minimize power consumption. This scenario is graphically shown in Fig. 6.

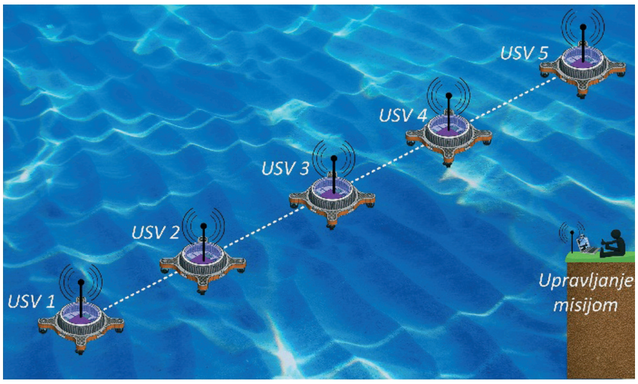

Fig. 6. The concept of Scenario 3 where a formation of the fleet of USVs autonomously adapts to the environment, i.e. so that the formation topology changes according to the direction of the current in order to minimize energy consumption.

Acknowledgement

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Autonomous Navigation of Mobile Robots in Complex Dynamic Environments

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Abstract

Most of the future robots will be mobile, and the main challenge is to develop algorithms for their autonomous navigation as well as for human-robot interactions. The Laboratory for Autonomous Systems and Mobile Robotics (LAMOR) at the Faculty of Electrical Engineering and Computing of the University of Zagreb is involved in the research of such mobile robotic systems, and currently participates in a number of related international and national research projects. This paper addresses the issue of autonomous navigation of mobile robots in complex dynamic environments, providing state of the art of the domain and major LAMOR's contribution to it. At the end, we present an application example of the autonomous navigation technologies in flexible warehouses, which we have been developing within a Horizon 2020 project SafeLog.

***Keywords**: autonomous systems, mobile robotics, navigation, safe human-robot interaction*

1. Introduction

There is no doubt that robotics, as a disruptive technology, will change the life as we know it over the next 50 years, enriching and augmenting all the aspects of life. The main robotics challenges in the next few decades will be to develop autonomous robotic systems that can perform complex tasks in human environments and safely cooperate with humans in arbitrary settings. Robots with these capabilities will transform our everyday lives as well as industrial processes, like the Internet, cell phones and computers had in the past two decades. Most of the future robots will be mobile, and therefore the main challenge is to develop algorithms for their autonomous navigation.

The paper is organized as follows. Section 2 and 3 describe respective activities of the Laboratory for Autonomous Systems and Mobile Robotics and the state of the art in the area autonomous navigation, while Section 3 describes the SafeLog project that deals with human navigation and safe interaction with robots in large flexible warehouses.

2. Laboratory for Autonomous Systems and Mobile Robotics (LAMOR)

LAMOR (lamor.fer.hr) is a research laboratory at the Faculty of Electrical Engineering and Computing of the University of Zagreb (UNIZG-FER) that holds expertise in autonomous mobile robotics systems. LAMOR's research activities are focused on the following aspects:

- Autonomous navigation of mobile robots in complex dynamic environments with three major research axes: (i) motion planning and control, (ii) simultaneous localization and mapping and (iii) detection and tracking of moving objects.
- Safe human-robot interactions to enable cohabitation of autonomous mobile robots and humans in the same environment with two major research axes: human intention recognition and human aware motion planning.

LAMOR's methodology relies on a strong coupling between theoretical research, algorithm development, experimental evaluations and a healthy dose of serendipity. The Laboratory is equipped with the state-of- the-art ground and aerial robotic platforms, advanced perception sensors, and a motion capture covered arena.

LAMOR has large experience in conducting international and national research projects. For example, LAMOR is currently involved in the following projects:

- SafeLog – Safe human-robot interaction in logistic applications for highly flexible warehouses (H2020 RIA project)
- L4MS – Logistics for Manufacturing SMEs (H2020 IA project)
- DIH2 – A Network of Robotics DIHs for Agile Production (H2020 DT-ICT-02-2018 – Robotics – Digital Innovation Hubs project)
- RoboCom++ – Rethinking Robotics for the Robot Companion of the future (FLAG-ERA project)
- SafeTRAM – System for Increased driving safety in public urban rail traffic (ERDF project)
- DUV-NRKBE – Development of a remotely controlled vehicle for operation in extreme CBRNe conditions (ERDF project)

- MAS – Development of a multi-functional anti-terrorism system (ERDF project), and
- DATACROSS – Advanced methods and technologies for data science and cooperative systems (ERDF – Top-level researches in Centres of Excellence project).

3. State of the art in autonomous navigation of mobile robots

3.1. Motion Planning and Control

Current state-of-the-art motion planning methods focus on the trajectory optimization aspects and they play two important roles in robot motion planning. Firstly, they can be used to smooth and shorten trajectories computed by other planning methods such as sampling-based planners. Secondly, they can be used to compute locally optimal, collision-free trajectories from scratch starting from naive trajectory initializations that might be in collision with obstacles.

The CHOMP algorithm introduced in [1] was one of the first successful attempts at using such methods in robotics. This method significantly outperformed naive RRT as well as grid search methods. STOMP introduced in [2] and ITOMP [3] further improved upon the CHOMP paradigm, exploring gradient-free optimization methods and dynamic obstacle avoidance, respectively. In [4] authors used sequential quadratic programming over a discrete trajectory representation, showing that it can be used to enforce both equality and inequality constraints. The underlying sparsity of the problem graph can be exploited by using exactly sparse Gaussian process (GP) regression [5]–[6]. GPs inherently provide a notion of trajectory optimality through a *prior*. Using this representation, a gradient-based optimization algorithm called GPMP (Gaussian Process Motion Planner) was proposed that can efficiently overcome the large computational costs of fine discretization while still maintaining smoothness of the result [7]–[9].

LAMOR's major contributions: In [10] we presented a framework for estimating intention of workers in a robotized warehouse. An active SLAM algorithm based on D* planning was introduced in [11], while a convergent navigation receding horizon control for differential drive robots was proposed in [12]. We also proposed for robot path planning a real-time approximation of clothoids with bounded error in [13].

3.2. Simultaneous Localization and Mapping

The simultaneous localization and mapping (SLAM) is a prerequisite for mobile robot's autonomy with applications in many areas, including modern logistics, autonomous driving, transportation, search and rescue missions, human assistance etc. The SLAM problem was introduced in the late 80's in the work of Smith et al. [14], but it came to focus at the beginning of 20th century. For a long period of time, the SLAM solutions were based on the filtering methods [14]-[17], but in the past years the focus has shifted to optimization methods that structures SLAM as an undirected graph in which nodes represent either the robot's pose or map's landmarks, and edges represent robot's observations. The approach uses *maximum a posteriori* method to find the relations of poses and landmarks that maximize the probability of consistent robot and landmark poses. Most prominent examples of this paradigm are square-root SAM [18], GraphSLAM [19], and *incremental* SAM (iSAM) [20]. In the last few years the implementation of graph based SLAMs has been made easier since there are open source libraries like g2o [21] and Ceres [22]. One of the most popular SLAM approaches in robotics are those using cameras, either in monocular or stereo setups. The most accurate and used approaches include semi-direct visual odometry method (SVO) [23], large-scale direct monocular SLAM (LSD-SLAM) [24], ORB-SLAM [25], and SOFT-SLAM [26].

LAMOR' major contributions: In [26] we introduced stereo visual odometry, dubbed SOFT, which ranked as the most accurate visual odometry on multiple popular datasets. In [27] we proposed LG-ESDSF, the exactly sparse delayed state filter on Lie groups which can solve SLAM accurately and efficiently. Combined with the SOFT odometry, it yielded SOFT-SLAM, a SLAM algorithm ranking first among visual SLAM approaches on several datasets. Finally, a theoretical foundation for LG-ESDSF lies in the extended information filter in Lie groups which we introduced in [28].

3.3. Detection and Tracking of Moving Objects

Tracking of a multiple moving object is another fundamental component of autonomous robotic systems. The objective of multi-target tracking (MTT) is to jointly estimate the number of objects as well as their dynamic states. In addition to the time varying number of targets, there are many other difficulties in MTT such as clutter detections (false alarms) and unknown association between detections and targets. In recent years there have been major breakthroughs in the MTT field resulting in diverse tracking algorithms, although most of them can be divided into these three paradigms: probabilistic data association (PDA) [29]-[30], multiple hypothesis tracking (MHT) [31]-[33] and random finite sets (RFS) [34]-[37].

LAMOR's major contributions: We introduced two interesting versions of the PHD filter: one on the unit circle with the von Mises distribution [38] and the other on Lie groups [39]. Furthermore, joint integrated PDA filter on Lie groups for MTT with the radar and stereo camera was introduced in [40], while a JIPDA using the von Mises-Fisher distribution was proposed in [41].

4. SafeLog project

4.1. About SafeLog

SafeLog – Safe Human-Robot Interaction for Highly Flexible Warehouses (safelog-project.eu) is a four-year H2020 research project (1/2016 – 12/2019, grant No 688117). It is coordinated by Prof. Björn Hein from the Karlsruhe Institute of Technology (KIT). It has six partners in total and, besides KIT, also includes the industrial partner Swisslog, whose automated warehouse system is used as a case-study in the project (Fig. 1).

Fig. 1. SafeLog partner Swisslog's automated CarryPick system

In the sequel we continue with the LAMOR research activities carried out within the project, and end with concluding remarks.

4.2. LAMOR Research Results

Moving objects detection using a wearable stereo camera

The aim is to detect moving objects from a stereo camera mounted on a human, as part of a Safety Vest. The stereo camera was modeled as two pinhole cameras which project the three-dimensional space on two-dimensional image plane. With a stereo camera it is possible to reconstruct the three-dimensional space back from its two two-dimensional projections. Apart from the Euclidean representation, which is the usual way of describing three-dimensional space, there are other representations. One such representation is the disparity space where x and y coordinates remain unchanged, but the third coordinate is the inverse of the depth z, and this inverse is called disparity. The disparity image is a way of showing the scene's depth by using pixel intensities.

We implemented the *Semi-global matching* method that efficiently computes consistent disparity images. Our problem was oriented to the reconstruction of depth from a video sequence. Previously computed disparities are used to improve the disparity computation, where the ego-motion estimation is used to transform the disparity from the previous step into the next step. Under the assumption of a static world, the transformed disparity is equivalent to the newly computed disparity. In reality, this is not true because of the noise (dynamic objects, discretization noise, errors in disparity computation etc.) and the transformed disparity will not always match the new one. Nevertheless, the disparity prediction from the previous step is still used. For each pixel we deterministically compute the displacement based on ego-motion and stochastically track the value of its disparity while updating its uncertainty through time with Kalman filtering. The disparity of each pixel is estimated by combining the newly matched (measured) disparity map and predicted disparity map. This way we managed to reduce the complexity of the algorithm.

The described framework is focused on stable, precise and fast spatio-temporal reconstruction, thus constraining the use case of the proposed method to static scenes. Although this can be seen as a limitation, in fact, this approach forms the base for dense stereo detection of dynamic objects by detecting discrepancies between static and dynamic flow. The assumption of the static world is not valid for the moving objects and they will cause discrepancies between the predicted and measured disparity images. By grouping such areas in the image, we manage to find the parts of the image with moving objects. In order to avoid the need to introduce any other sensors, we obtain ego-motion using the visual odometry algorithm.

The implemented algorithm is evaluated on real-world data from the KITTI dataset (Fig. 2) and the results are compared with an open source implementation of semi-global matching method in OpenCV library. The results show that our implementation is faster and more accurate than the implementation from OpenCV.

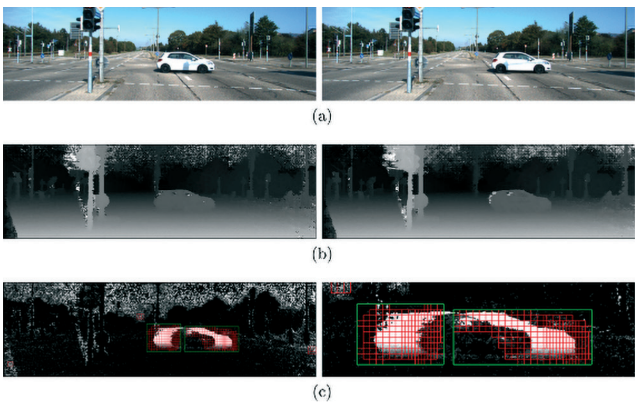

Fig. 2. Process of moving object detection. Part (a) shows the first and second scene in the sequence. Part (b) shows the predicted disparity map and the matched one. Lastly, part (c) shows the difference between the disparity maps and the final result of detection.

Multiple Moving Objects Tracking

This task is mainly concerned with the stochastic estimation of the state of multiple moving objects. We leverage moving object detections from the previous section and use them as inputs into the tracking algorithm. We present the Gaussian mixture PHD (GM-PHD) filter tested on various simulated and real-world scenarios. In Fig. 3 we show tracking of a rather complex scenario with 13 moving objects, from which we can see that even with a high clutter rate, the algorithm is capable of estimating the position of multiple moving objects on the scene.

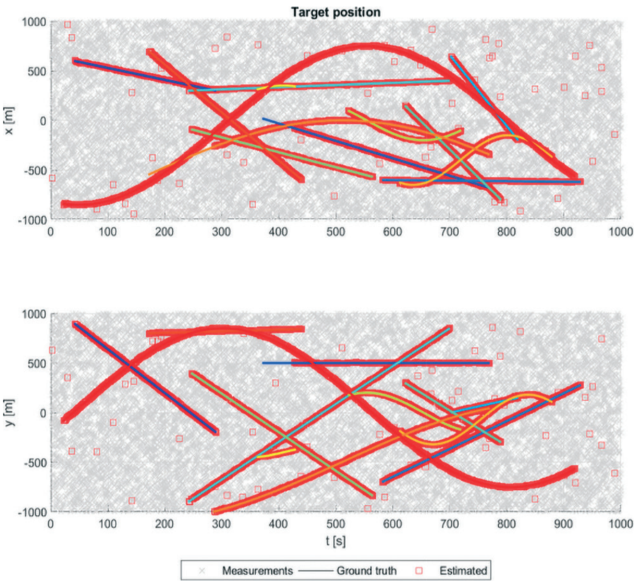

Fig. 3. GM-PHD tracking 13 moving objects in a high clutter rate.

For real-world experiments we used a dataset recorded with a hand-held PerceptIn Ironsides stereo camera at the premises of UNIZG-FER. Inputs into the tracking algorithm were detections produced from the previous section. In Fig. 4 we can see some examples for the Ironsides dataset.

Human Worker Localization with the Safety Vest

The aim is to develop a localization concept that will provide a stable and consistent location of the worker in the warehouse. The first part of this research dealt with estimating ego-motion of the worker from a stereo camera.

The stereo camera odometry can be seen as a sequence of several constituent blocks. Firstly, after a new stereo-pair acquisition, high-quality features are detected. Feature management starts with extraction and matching of corner-like features in both left and right images of the stereo pair. For this purpose, we utilize blob and corner masks on the gradient image and apply the non-maximum suppression, thus obtaining a set of available features. The features are then used in the matching

Fig. 4. Tracking example for the Ironsides dataset.

process, where the correspondences are determined by calculating the sum of absolute differences (SAD) over a pattern of pixels around the detected maxima. The inertial measurement unit (IMU) is used to predict the relative displacement of the worker in order to define a search radius for feature matching. Features are then weighted based on the distance to the predicted coordinates. The output of this step is a sparse feature set that can be further used within a RANSAC optimization procedure in order to yield final displacement information.

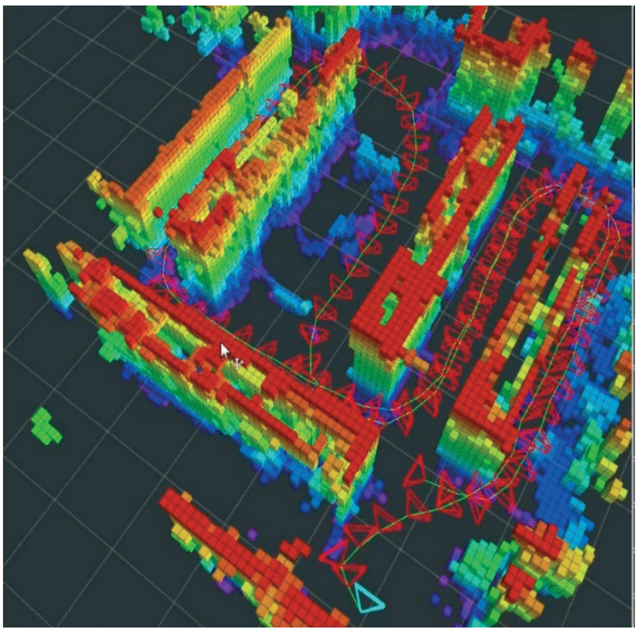

Fig. 5. An example of a 3D map built with the stereo visual odometry. Besides the map, the estimated trajectory (green line) is shown together with key frames (red pyramids).

Fig. 6. An example of an image of the stereo camera during the experiment in the library. The numbers represent tracked feature statistics that are used to decide whether to keep or discard the feature.

In order to test the odometry in a relevant scenario we made an experiment at the Library of UNIZG-FER that consists of bookshelf rows quite similar to the robotized warehouses of Swisslog. The main feature is that the lighting of the Library was also artificial, thus making the experiment even more relevant. In Fig. 5 we can see an example of a 3D map that was built in the library experiment, while in Fig. 6 we can see an example of the scene in the Library.

Human Worker Intention Estimation

The Fleet Management System of the automated warehouse needs to be able to estimate the worker's intentions correctly and control the robots accordingly, so that the warehouse operation efficiency is ensured.

Only the actions with the greatest influence on intention perception should be considered. For example, in the warehouse domain, the worker's orientation and motion have a large effect on the goal intention recognition and in this section, we track them using augmented reality glasses localization algorithm worn by the human worker. The human intention recognition algorithm is developed based on worker's movement validation which is used as observation for hidden Markov model (HMM) framework. Worker's movement is validated with respect to potential goal locations (i.e. warehouse racks and picking stations) using graph search algorithm on Generalized Voronoi Diagram's (GVD) nodes generated on the preexisting warehouse layout. If the mobile robot is located on a GVD edge, we cut that edge from the graph. The goal locations can be added or removed during the experiment.

The proposed HMM framework has one hidden state for every potential goal, one state indicating that the worker's intentions are not certain, and a state that declares the worker irrational meaning worker is not following path towards any. The irrational worker state includes the cases of the worker not following any proposed goal location or the worker's desire to go to an unknown goal. Every time the worker moves or turns significantly, we estimate the worker intention using Viterbi algorithm. The Viterbi algorithm outputs the most probable HMM's hidden states sequence and their probabilities which we consider intention estimates.

We carried out multiple experiments both in a real-world industrial setup in a test warehouse using augmented reality glasses and in a virtual reality generated warehouses in order to demonstrate the scalability of the algorithm (Fig. 7). Results corroborate that the proposed framework estimates warehouse worker's desires precisely and within reasonable expectations.

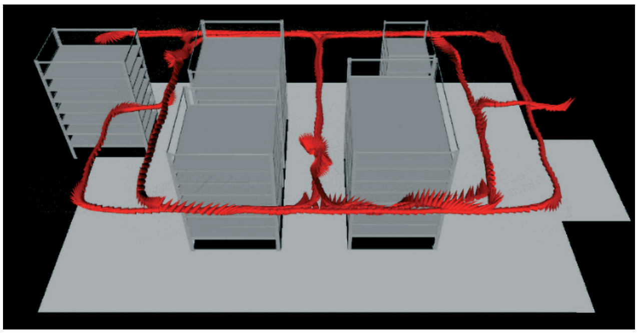

Fig. 7. Conducted experiment showcasing qualitatively the precision of the Hololens' localization. We have created s warehouse model in RViz – Robot Operating System's 3D visualization tool.

3.3. Ongoing research activities

As the SafeLog project is nearing its completion, we are working on the final integration and testing in a realistic real-world working automated warehouse. The final goal is to have a fully functional Safety Vest that will guarantee worker safety and localize the worker accurately in real-time relying just on the onboard sensors and onboard computing power. The data provided by the Safety Vest can then be utilized by other algorithms of higher safety levels, providing human intentions to the fleet management system, thus ensuring high efficiency of the warehouse and increasing worker comfort. We are optimistic that SafeLog results will also find its place in other industries and be exploited beyond the activities of the project itself.

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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]:

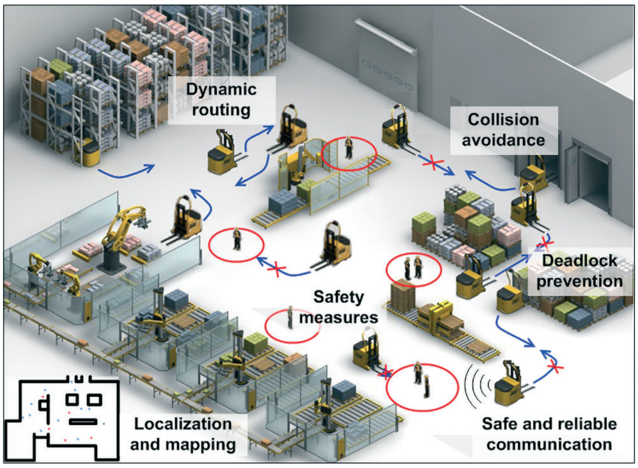


Fig. 1. Main subsystems of automated warehouse [12]

- 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.

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].

2.1. Accurate localization and mapping of the warehouse environment

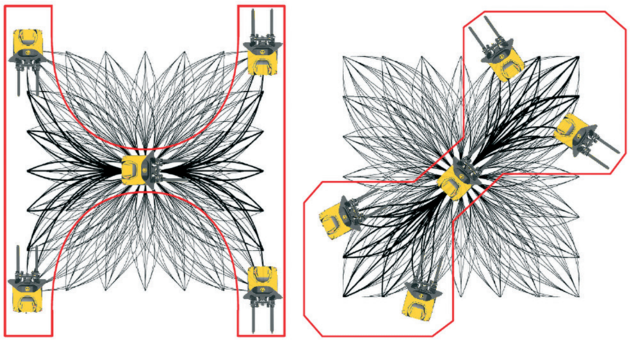
Low level control subsystems, involving path planning and path following, depend on the correct selection of path planning and path following algorithms, resolution of on-board sensors and most importantly on the precision of localization. This was the challenge that the LARICS research team took for 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.

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.

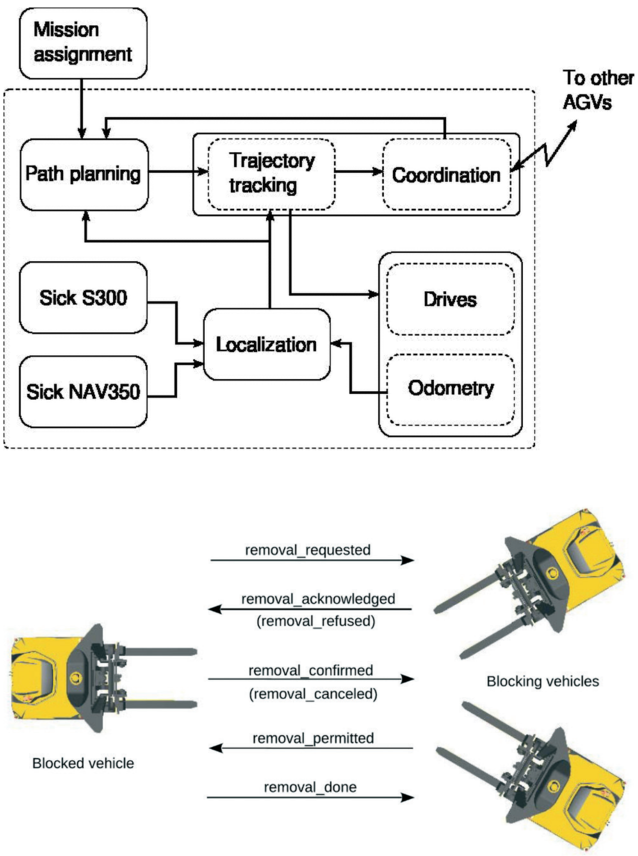


Fig. 4. Top: The concept of a decentralized free-ranging navigation control running on each vehicle in the system. Bottom: Message exchange flow during the removal negotiation process [22].

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).

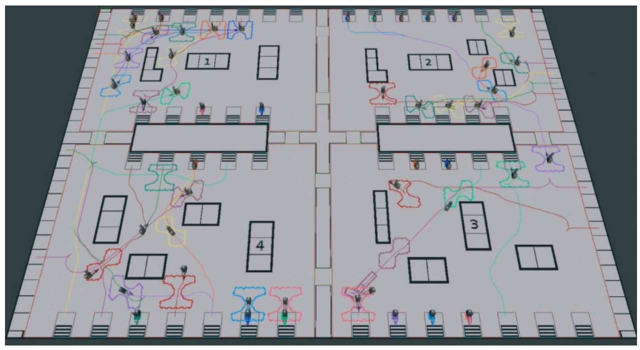


Fig. 5. Validation of the algorithm performance on a system composed of fifty vehicles in an environment with static obstacles. [23].

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.

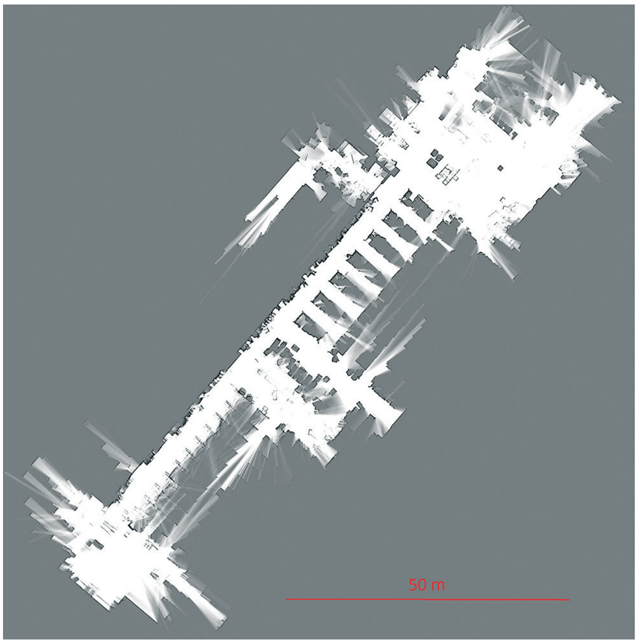


Fig. 8. Mapping of the Konzum warehouse in Zagreb.

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.

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].

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

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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Activities of the Croatian Academy of Engineering (HATZ) in 2019

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Auspices

- Faculty of Textile Technology and Zagreb Innovation Centre, 12th TZG – Textile Science and Economy 2019 – French-Croatian Forum 12th Scientific and Professional Conference "Textile Science and Economy", January, 23 to 24, 2019
- Faculty of Electrical Engineering and Computing, Round Table under the name "Croatian Central Sound Archives", Gray Hall of the Faculty of Electrical Engineering and Computing, February 6, 2019
- Faculty of Architecture of Zagreb, Professional Conference "Buildings 2020+", February 21, 2019
- Croatian Chamber of Mechanical Engineers, 6th International Conference Days of Mechanical Engineers, Vodice, March 20 to 23, 2019
- Croatian Color Societies and University of Zagreb (Faculty of Textile Technology, Faculty of Graphic Arts and Faculty of Architecture), International Color Day 2019 – "Color and Materials", Technical Museum, Zagreb, March 21, 2019
- Faculty of Civil Engineering and Architecture, Osijek, 8th International Convention "WATER FOR EVERYONE 2019, March 21, 2019
- Croatian Microbiological Society, Symposium Power of Microbes in Industry and Environment, Sv. Martin na Muri, May 15-18, 2019
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- Faculty of Civil Engineering and Naval Architecture, Conference MOTSP 2019 "Industry 5.0 – Return to Humanity", Marija Bistrica, June 5-7, 2019
- Faculty of Electrical Engineering and Computing, lecture and workshop "„Computational Sport Science: Human Motion Modelling and Analysis", FER, Zagreb, June 7, 2019
- Faculty of Food Technology and Biotechnology, Zagreb – Congress "10th International Congress "Flour-Bread '19" and "12th Croatian Congress of Cereal Technologists "Brašno-Kruh 19", Faculty of Food Technology, University of Osijek, June 11-14, 2019
- Croatian Society of Mechanics, Conference "9th Meeting of the Croatian Society of Mechanics", Sljeme, July 11-12, 2019
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- Croatian Engineer's Day, Zagreb, Faculty of Chemical Engineering, Zagreb, February 22, 2019
- International Scientific Conference "Printing&Design", Školska knjiga Zagreb, March 14, 2019
- Workshop of the Economic Council of the Croatian Academy of Engineering "Needs of Croatian Economy for Lifelong Learning with Emphasis on Secondary Vocational Education" , Croatian Academy of Engineering, Zagreb, March 29, 2019
- Workshop "Patents and Patent Application", Zagreb, April 3, 2019
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