Cooperative Control of Heterogeneous Robotic Systems

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Abstract – Establishing a cooperative heterogeneous robotic system comprising autonomous vehicles operating in air, on ground and on/under water is a challenging task that can significantly contribute solving complex problems related to environmental monitoring (e.g. prediction, prevention and recovery from natural disasters) and security (e.g. border control, fight against terrorism). This paper presents a short overview of a project that involves cooperative control of heterogeneous robotic systems at the University of Zagreb Faculty of Electrical Engineering and Computing. An overview of the vehicles to be used in the heterogeneous systems is given and the envisioned scenario of neutralization of suspicious underwater objects is presented. Tasks of each vehicle are described and emphasis is placed on the actions and communication routes that are required to ensure cooperative behavior.

I. INTRODUCTION

Heterogeneous robotic systems are systems that comprise mobile robotic units operating on land, in air and on/under water. While individual robotic systems today successfully perform complex tasks in their medium, activities through all three media are imposed by industrial needs as well as in seven societal challenges defined by the European Commission within the Horizon 2020 programme, specifically in the areas of:

1. environment: prediction, prevention and recovery from natural disasters; development of systems for global surveillance and informing about the state of the environment, and

2. security and protection: fight against crime and terrorism; strengthening security through border control; increasing resilience in cases of crisis and disasters.

The primary motivation for research in the areay of cooperative control of heterogeneous robotic systems is to enable sinergy between autonomous unmanned land, air and marine robots for the purpose of accomplishing a joint mission (e.g. surveillance of sea and land borders). The idea of the research is to unite existing robotic systems acting in different media into a unique cooperative heterogeneous system shown in Fig. 1.

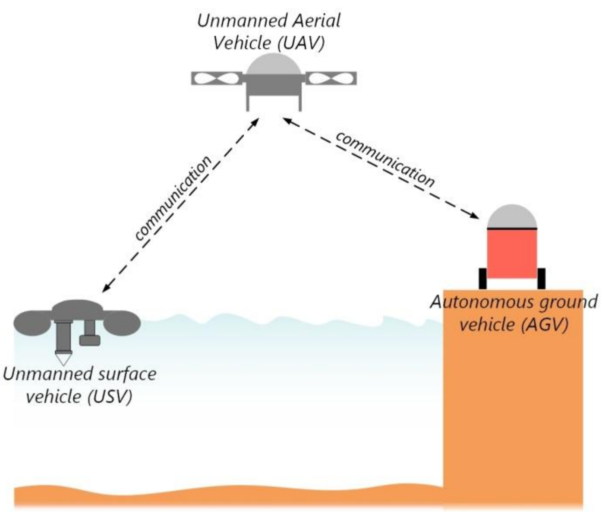

Figure 1. Concept of a cooperative heterogeneous robotic system.

The aim of the proposed research is to develop and experimentally validate cooperative control algorithms that maintain formation comprising three autonomous mobile robots (land vehicle, surface marine vessel and an autonomous aerial craft) and thus ensure their coordination. In order to accomplish this research goal, the following activities have to be performed:

1. Development and implementation of robotic cooperative control algorithms with kinematic and dynamic constraints as well as constraints in the communication channel.

2. Field trials using real robotic systems for the purpose of experimental validation of the developed algorithms and identification of necessary modifications and improvements. The developed algorithms will be tested in a scenario where autonomous robots are moving in a formation in which the aerial craft has a function of ensuring communication channel between the land vehicle and the surface marine platform.

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a) b) c)

Figure 2. Photos of the vehicles comprising the heterogeneous robotic system: a) autonomous surface marine platform (*PlaDyPos* made at UNIZG-FER), b) autonomous aerial vehicle (*ArduCopter Quad* by jDrones) and c) autonomous ground vehicle (*Guardian* by Robotnik) with a manipulator.

II. AUTONOMOUS MOBILE ROBOTS

Mobile robots that will be used are available from three research laboratories from the Faculty of Electrical Engineering and Computing at the University of Zagreb: Laboratory for robotics and intelligent control systems – LARICS (unmanned aerial vehicles), Laboratory for Underwater Systems and Technologies - LABUST (unmanned underwater and surface marine vehicles) and Autonomous Mobile Robotics Group (autonomous land vehicles)

The **unmanned surface vehicle (USV)** is an overactuated platform with 4 thrusters forming the "X" configuration. This thruster configuration enables motion in the horizontal plane under any orientation. The platform has been developed at LABUST and the current version is 0.35m high, 0.707m wide and long, as it is shown in Fig. 2a), and it weighs approximately 25kg. The control computer (isolated from environmental disturbances inside the platform hull) is in charge of performing control and guidance tasks (dynamic positioning, path following, diver following) and all the data processing. Apart from the compass, batteries and CPUs, the platform is equipped with a GPS for determining the platform position, Ultra-Short Baseline (USBL) used to determine the position of the diver relative to the platform, a wireless modem used to transmit data from the platform to the surface station. The platform has been primarily developed for the purpose of diver tracking, [1]. More information on the characteristics of the platform can be found in [2].

Due to its simple mechanical design and open-source software, **unmanned aerial vehicle (UAV)** *ArduCopter Quad*, from jDrones company, shown in Fig. 2b) is one of the most popular aerial platforms with 4 propellers. Electronics, designed around Arduino processor, comprise complete set of sensors and features – 6 Degree of Freedom IMU stabilized control, gyro stabilized flight mode enabling acrobatics (loops and barrel rolls), magnetometer for heading determination, barometer for altitude hold, IR sensor integration for obstacle avoidance, and sonar sensor for automated takeoff and landing capability. Sophisticated control algorithms allow mounted camera stabilization. Ground station software modules provide automated waypoint navigation and wireless command & telemetry for long distance communication with real-time graphs of flight data. On board flight telemetry data storage can be used as well. This vehicle has recently been used to test hybrid adaptive control for aerial manipulation, [3].

The **autonomous ground vehicle (AGV)** is a *Guardian* produced by Robotnik from Spain, specially designed for applications in the domains of safety, inspection, research, and the high level of mobility allows it to move in rough and inaccessible terrain (stairs, slopes, etc.). The vehicle has an embedded computer with Linux OS that can be connected to either wirelessly or via etherner. The complete programming platform is based on ROS (Robot Operating System) that allows easy extension if the vehicles capabilities. Fig. 2c) shows the Guardian vehicle with a Powerball manipulator and a tool, both produced by a German company Schunk.

III. SCENARIO DESCRIPTION

The scenario that has been chosen for the demonstration of the cooperative heterogeneous robotic system is neutralization of unexploded underwater ordnance (UxO) which is an extremely dangerous and destructive activity since an underwater explosion has a destruction radius much higher relative to the one on land. The scenario does not deal with the neutralization process itself (defusing the UxO) but rather with handling the UxO and transporting it to a safe location. The proposed scenario can significantly contribute to expelling UxOs to the surface and taking them to a safe place on land autonomously, without human intervention or with limited intervention from a safe distance.

The proposed procedure is described in the following steps:

- <u>Step 1: Attaching and activation of the self-inflatable balloon to the underwater object</u>

A diver or a remotely operated underwater vehicle (ROV) attaches a balloon that can be inflated either by using acoustic activating signal from a safe distance, or by using a timer. Once the diver or ROV are at a safe distance, the balloon is inflated and the unknown dangerous object emerges to the surface. The balloon can optionally emit GPS coordinates so the location of the

UxO is known with a precision of a couple of meters radius.

- Step 2: Positioning the heterogeneous cooperative robotic system

The unmanned surface vessel (USV) and the unmanned aerial vehicle (UAV) that hovers above the USV, go to the location where the UxO is positioned.

- Step 3: Tugging the UxO to land

The USV followed by the UAV tugs the UxO to the location on land, next to the sea line, where the autonomous ground vehicle (AGV) with a robotic manipulator is located.

- Step 4: Autonomous ground vehicle takes the UxO

The AGV, equipped with a manipulator, takes the object out of the sea and carries it to a safe location where neutralization can be performed.

As a part of the proposed experiment, the following simplified mission will be executed. The mission is explained from the perspective of each individual vehicle.

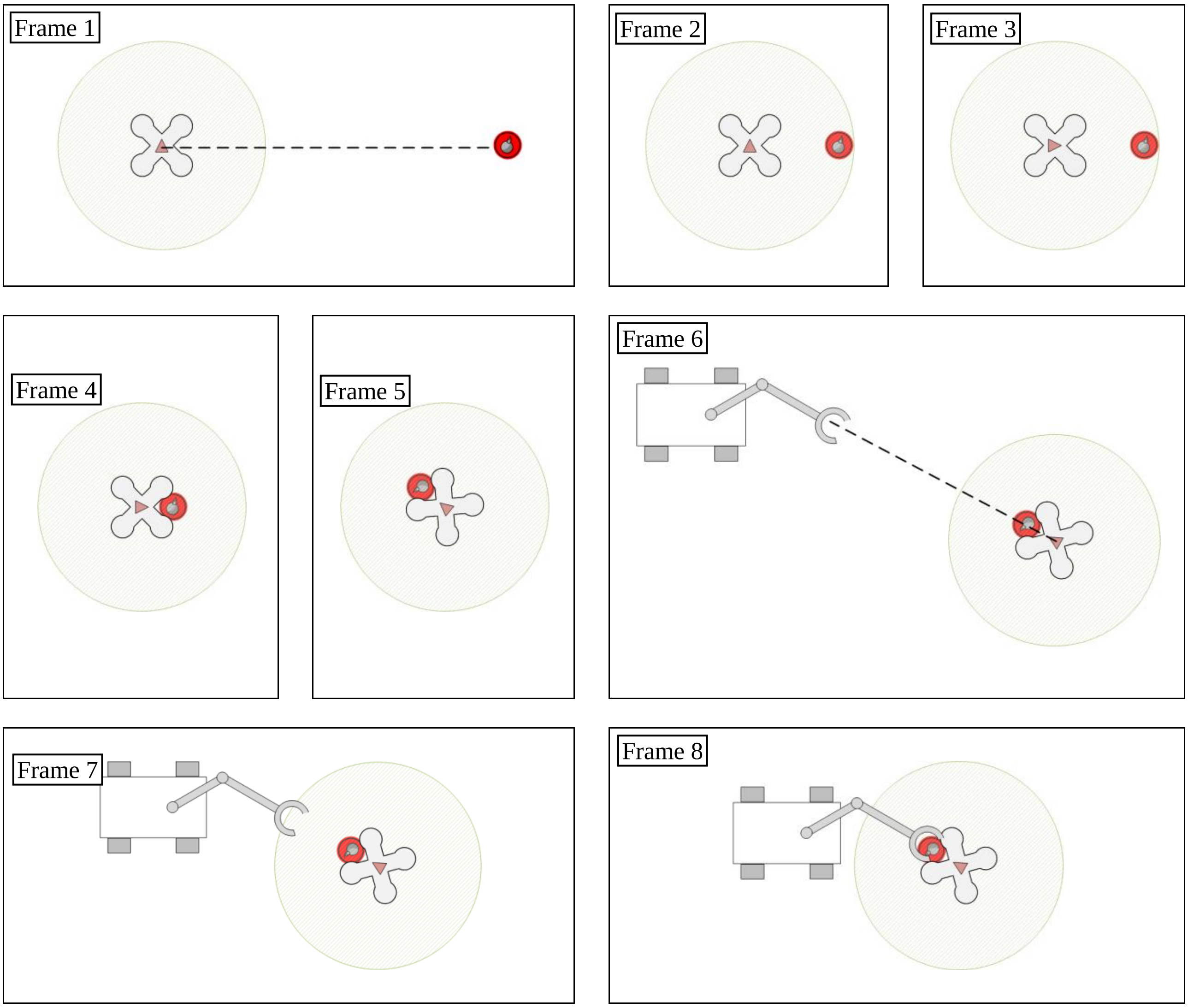

Figure 3. The scanario execution shown in time frames. The gren circle around the USV shows the dowwards field of view of the UAV hovering above the USV. Red circle represents the UxO.

A. The USV mission states

The USV mission states are comprised of the following elementary maneouvres: dynamic positioning (DP), heading control, and line following. Detailed description of the implemented algorithms used to execute these maneouvres can be found in [4], [5].

The following five states are executed sequentially.

1. **Initial dynamic positioning (DP)**

The USV dynamically positions around a predefined point A until the UAV receives the information about point B where the object (UxO) is located. The transition to the following mission state is executed when the USV receives position B.

2. **Line following towards the object**

Once the point B is known, the USV begins the line following maneuver from its initial point to point B where the UxO is located, as it is shown in Frame 1 of

Fig. 3. For this maneuver, only sensors onboard the platform are used (compass and GPS). At the moment when the UAV detects the UxO in the field of view (as shown in Frame 2 of Fig. 3), i.e. when relative distance between the platform and the object can be determined, the transition to the following state is executed.

3. "Grasping" the UxO

In this state, fine positioning of the platform relative to the UxO is possible since precise data on relative distance between the Uxo and the USV in the USV's coordinate system are available. The USV rotates towards the UxO so that it can "grasp" it between the two legs as it is shown in Frame 3 of Fig. 3. Once the desired orientation is achieved, the DP algorithm that minimizes the distance between the platform and the object is initiated, as shown in Frame 4 of Fig. 3. The mission transitions to the following state once the contact between the platform and the object is detected from the UAV field of view, and when the position of the autonomous ground vehicle (AGV) C sent by the UAV is available.

4. Line following towards the AGV

Once the contact between the USV and the UxO is achieved, and when position C is available, the USV rotates towards the ground vehicle while holding the object between the two legs as it is shown in Frame 5 of Fig 3. Once the desired orientation is achieved, line following from the current position to position C is initiated as shown in Frame 6 of Fig. 3. Only sensors onboard the USV are used (compass and GPS) for this maneuver. When the UAV detects the AGV in the field of view as shown in Frame 7 of Fig. 3, i.e. when relative distance between the USV and the AGV can be determined, the transition to the following state is executed.

5. Approaching the AGV

In this state, fine positioning between the USV and the AGV is possible since precise data on relative distance between the USV and the AGV is available. The USV dynamically positions itself to a point in front of the AGV, determined by the UAV, as shown in Frame 8 of Fig. 3. Once the desired position is obtained, the USV rotates with the UxO towards the AGV so that simple object grasping by the AGV is enabled.

B. The UAV mission states

The UAV mission states are based around hovering above the USV extending the field of view from above. The field of view of the UAV is represented as a green circle in Fig. 3.

The following five states are executed simultaneously during the whole mission.

1. Visual DP above the USV

The UAV detects the USV position within the video frame at all times and positions itself above the USV using DP algorithms based on position obtained from the video image. The UAV keeps constant altitude at all times while the orientation is arbitrary.

2. Transmitting UxO coordinates

If the UAV has information about the UxO coordinates (these coordinates will be transmitted to the UAV by an operator through the wireless link), they are transmitted via WiFi to the USV below. In this state, the UAV serves as an extended antenna for the USV.

3. UxO detection

The UAV searches for the UxO (a predefined marker on the object) within the video image all the time. If the object is found, the UAV sends the relative distance between the detected object and the USV to the USV.

4. AGV detection

The UAV searches for the AGV (a predefined marker on the AGV) within the video image all the time. If the AGV is found, the UAV sends the relative distance between the detected AGV and the USV to the USV.

5. Transmitting AGV coordinates

The UAV sends the AGV coordinates via WiFi to the USV all the time. These coordinates are received from the AGV itself.

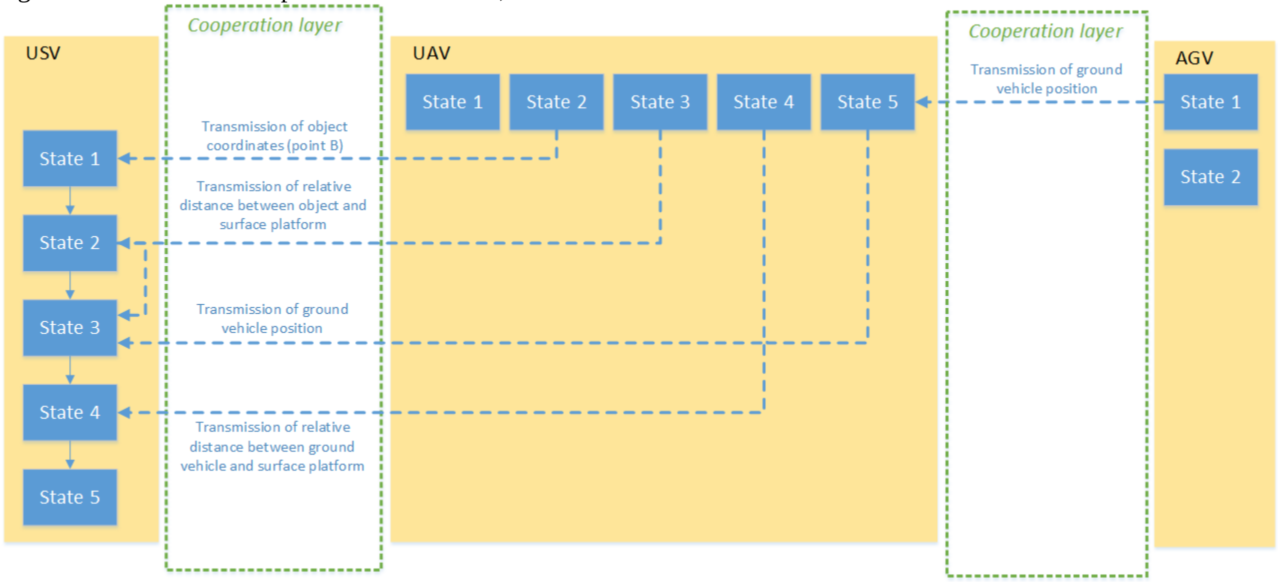

Figure 4. The conceptual representation of the mission flow from the perspective of the each unmanned vehicle.

C. The AGV mission states

1. Transmitting position coordinates

The AGV is at a location on ground next to the sea line and transmits its own GPS coordinates to the UAV through the wireless link all the time.

2. Remotely operated object grasping

Once the UxO is close enough to the AGV, the remote operator can use the manipulator onboard the AGV to grasp the UxO and carry it to a safe location for neutralization.

Fig. 4 graphically shows the mission states from the perspective of the individual unmanned vehicles. In the same figure, the cooperation layers are shown. These layers in fact represent the communication that occurs between the vehicles. The data that is being communicated is the baseline of the cooperation of the heterogeneous robotic system.

IV. CONLUSION

This paper presents an overview of the project with the task to establish a cooperative heterogeneous robotic system. The systems that will be used for experiments are described and the scenario of neutralization of the unexploded ordnance is given.

The next step is to combine already existing vehicle behaviors to support the cooperative system. The cooperation will be established by maintaining the formation between the unmanned surface vehicle and an unmanned aerial vehicle that serves as an extended antenna and a communication router. Once the algorithms are verified in a simulation, real life experiments will be conducted.

REFERENCES

[1] N. Mišković, Đ. Nađ, N. Stilinović, and Z. Vukić, "Guidance and control of an overactuated autonomous surface platform for diver tracking", Proceedings of 21st Mediterranean Conference on Control & Automation (MED), pp. 1280-1285, 2013.

[2] N. Mišković, Đ. Nađ, Z. Vukić and B. Marszalek, "Laboratory Platforms for Dynamic Positioning – Modeling and Identification", Proceedings of the 8th IFAC Conference on Control Applications in Marine Systems, pp. 161-166, 2010.

[3] M. Orsag, C. M. Korpela, S. Bogdan, and P. Y. Oh, "Hybrid Adaptive Control for Aerial Manipulation", Journal of Intelligent & Robotic Systems, Volume 73, Issue 1-4, pp 693-707, January 2014

[4] N. Mišković, Z. Triska, Đ. Nađ, and Z. Vukić, "Guidance of a Small-Scale Overactuated Marine Platform – Experimental results" Proceedings of the 34th international convention on information and communication technology, electronics and microelectronics vol. III (MIPRO/CTS 2011), pp. 39-44, 2011.

[5] V. Vladić, N. Mišković, and Z. Vukić, "Quick Identification and Dynamic Positioning Controller Design for a Small–Scale Ship Model" Proceedings of the 2012 20th Mediterranean Conference on Control & Automation (MED), pp. 1385-1390, 2012.