Heterogeneous Teams of Unmanned Ground and Aerial Robots for Reconnaissance and Surveillance - A Field Experiment

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***Abstract*—The paper presents the results of cooperative work done by three different research institutions. The cooperation concluded in a large field experiment with six heterogeneous unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs). It is shown, that it is possible to do reconnaissance and surveillance, namely detection of pedestrians and vehicles, with an autonomous multi-robot system under real world conditions.**

The participants were all using different robotic middlewares and interfaces to the graphical user interface. Hence, it has been agreed to use common interfaces and standards for communication. The Robot Operating System (ROS) is used as a communication layer, supported by commercially available 3G mobile radio communication for large operating distances. A standardized markup language has been used for the description of tasks and feedback from the robots to the control station. Moreover, the applied UGV control strategies and the implemented approach for detection, tracking and classification are presented.

The concluding field test showed that it is possible to realize a multi-robot system of dynamic size, and that such teams are well-suited to perform reconnaissance and surveillance without constant observation by a human operator.

I. INTRODUCTION

Autonomous outdoor robots can be equipped with numerous sensors for a multitude of purposes. In most cases, one single robot is not able to perform a complex task on its own due to limited sensor capabilities or constrained mobility. Therefore, teams of heterogeneous mobile robots should be applied in security scenarios. Lacroix and Le Besnerais identified in [1] future scenarios and issues for the application of multi-robot systems, especially cooperative surveillance and target tracking tasks. The deployment of heterogeneous robots results in the need for common communication interfaces and coordination. Moreover, multi-robot systems can consist of different platforms, namely unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs).

This paper presents cooperative work done by three different research institutions. It describes the communication interfaces and standards, the control strategies for the coordination of all UGVs and the implemented detection, tracking and classification of moving objects based on laser scanners. Several real world task scenarios have been implemented in cooperation, and common interfaces have been agreed upon for communication and coordination. To show the applicability of the developed approaches, each institution contributed with one or more autonomous vehicles to the final real world experiments, resulting in six heterogeneous mobile robots (see Fig. 1). One institution provided a graphical user interface for setting tasks to the robot team and vizualizing returned sensor data and status information. The work is based on a previous field scenario testing which has been presented in [2], [3] and [4]. Details of the graphical control interface and the semantic description of tasks can be found in [5].

Two test scenarios were performed. First, the team of unmanned ground and aerial vehicles had to move to a destination point in a coordinated convoy formation. Second, a user set a single point of interest (POI) for surveillance, where the team had to take up positions for the observation of the POI. Focusing all sensors on the POI, each mobile robot could aquire sensor data for reconnaissance and surveillance. Basically, the implemented control strategies were capable of controlling an arbitrary number of ground and aerial systems.

Because all participating robots were using different middlewares, we had to agree on common communication standards and interfaces. It has been decided to use the well-known Robot Operating System (ROS) [6] as a communication layer. ROS has been successfully integrated into other robotic middlewares [2]. To enhance the operating distance compared to IEEE 802.11 (WiFi), 3G mobile radio communication has been used as a layer for the IP-based ROS communication.

Very few real world tests have been done with cooperating autonomous teams of UGVs and UAVs. Usually, research work focuses on single aspects of UGV/UAV cooperation. For example, [7] deals with the control of the formation of the ground robots by an UAV. In [8], a UGV is accompanied by an UAV ("Flying Eye") to detect negative obstacles like holes or steep slopes. To the best of our knowledge, the only publications beside ours that deal with the complete realization of UGV/UAV teams in real field tests are presented in [9] and [10]. In contrast to our work, the aerial vehicles have been used only to identify possible regions of interest, so that ground vehicles can start approaching these regions and fulfill their tasks.

Instead of transmitting video streams to the control station, the user should be disburdened from parallely observing

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Fig. 1. Four ground vehicles in action: UGV HANNA (1) followed by UGVs LONGCROSS (2), GARM (3) and AMOR (4). Two quadrocopter drones not in the picture.

multiple streams. Hence, the vehicles should preprocess their sensor data in a way of extracting moving objects in the observed environment. Via submitting detected objects to the control station, a user could request images or video streams thereupon. The UGV HANNA uses laser scan data for object detection and tracking. For example, Darms et al. [11] are using a similar approach of target tracking in the DARPA urban challenge. Unfortunately, they focus on 2D LIDARs. In contrast, we are using the Velodyne HDL-64E 3D data to extract, track and classify objects. In two more steps, we fuse the resulting objects with tracked objects coming from the Ibeo Lux LIDAR (an automotive laser scanner with built-in object tracking and classification), and the object recognition performed by other UGVs/UAVs.

The paper is organized as follows: The next section presents communication architecture, interfaces and standards. In Sec. III, the graphical user interface is introduced. Sec. IV describes our approach of object tracking, classification and fusion used on the UGV. Control and coordination strategies for the UGVs are part of Sec. V, while Sec. VI presents results of our field experiments. The paper ends with a conclusion.

II. COMMUNICATION

Because three research institutions were involved in the presented work, it was mandatory that all parties agreed in advance on clearly defines interfaces. All institutions were using their own robotic middleware. To connect the GUI with the vehicles, a markup language called Battle Management Language (BML) has been used. It will be quickly revised in Sec. II-A. For communication between the vehicles, it was decided to use the Robot Operating System (ROS) [6] as a communication layer. ROS offers well-defined data types for most kinds of data, is open source and hence freely available, and has a constantly growing community contributing to the software repository. Moreover, all published status information of each single robot is available to all other robots via the ROS messaging system. The integration of ROS into the corresponding middlewares has been described in [2] and [3]. To connect the ROS communication layer with the GUI, a ROS component called BMLConnector has been developed in Python. It is also subject of Sec. II-A. The ROSCore has been placed at the control station computer.

Due to the large testing ground, IEEE 802.11 (WiFi) coverage could not be assured everywhere. Hence, we applied 3G mobile radio communication for the IP-based ROS network as described in Sec. II-B.

A. Connecting GUI and ROS

In order to express commands to be pushed from the GUI to the vehicles, and data returned to the GUI, we used Battle Management Language (BML). BML [12] is human readable, unambiguous, and in standardization process of Simulation Interoperability Standards Organization (SISO). BML can be used to express tasks, reports, and requests between command and control systems, simulation systems and real units. In addition, BML also may be used to interact with robotic units. Please refer to [5] for more details.

The communication between the GUI and the ROS nodes is done by translating between BML Messages and ROS messages. To handle the translation we implemented a ROS node called BMLConnector. The BMLConnector has a TCP connection to the GUI. The received BML command is translated to a defined ROS message which is then published as a ROS topic. For status reports, the ROS messages will be translated back to BML. Status reports can contain information like position and orientation data, operational status, or information about the task execution progress. Moreover, detected object positions and classifications can be returned to the control station. For other sensor data, particularly with regard to binary data such as images or videos, there is currently no representation in BML. In this case, the ROS message is converted to an XML based format.

B. 3G Communication

In contrast to previous experiments [2], the aim here was to make the multi-robot system independent of the distance to the control station. By using commercially available mobile radio communication standards, it has been made possible to place the control station anywhere all over the world while observing and controlling the multi-robot system. Therefore, a provider of mobile telecommunication services supplied a cell tower and an own IP-based subnetwork.

Because the communication was based on IP, integration of 3G communication with ROS was smooth. Since no real time critical data was transmitted over the network, the round-trip-time of 200+ ms was negligible. Transmission of new orders could cope with small delays, as well as status information from one robot to another, and to the control station. Please note, that network delays would probably increase in international roaming.

III. GRAPHICAL USER INTERFACE

For the control of the multi-robot system we used two different graphical user interfaces (GUIs). One for a stationary PC, called C2LG GUI [4], and a web based "Mobile GUI" for the use on a tablet PC (see Fig. 2) [5]. Both GUIs allow the input of BML Orders and show the current situation of the multi robot team on a map. Moreover, returned status information and sensor data can be vizualised. The tablet PC is connected to the system via 3G cellular network communication.

The input of the commands follows the same order in both GUIs. In a first step the action type is selected, for example "move", "patrol", "observe", "image gathering" or "cancel". The second step is to select the single robot or robot group that should execute that action ("taskee"). In the third step the user can enter geographic information for that command. For example, in the case of a move command it is the point where the robots should move to. In a final step the user confirms the information by pressing a "send" button and receives a confirmation when the command is successfully sent to the vehicles.

IV. OBJECT TRACKING

For the observation of objects, a multi stage object detection, tracking and classification system has been implemented at the UGV HANNA. In a first step, the Velodyne HDL-64E 3D laser scanner is used to detect and classify objects in sensor range. Based on a segmentation of the Velodyne point cloud using the approach of Talukder [13], the 3D point cloud is selectively reduced by the "Virtual 2D Scan" approach [14]. Afterwards, relevant bounding boxes can be computed and selected. Only boxes, that match the dimensions of pedestrians and vehicles, are classified and added to the list of detected and classified objects.

Fig. 2. The mobile GUI on a tablet PC, connected to the system via 3G mobile radio communication.

In the next step, the resulting bounding boxes are tracked by a simple α-β-filter. By tracking, the velocities of the objects are calculated and can be used as a further filtering step, as only moving obstacles should be detected. To increase the robustness, the extracted objects will be fused with objects detected by the Ibeo Lux LIDAR, an automotive laser scanner with a built-in object detection, tracking and classification. The objects tracked by the Ibeo Lux are taken as a second input to the α-β-filter. Hence, we obtain a fused object list of the UGV.

Finally, the resulting object list can be fused with objects detected by other UGVs or UAVs in the robot team. Their submitted objects are fused with the object list by a simple distance-based fusion algorithm. At this project stage, only the UAVs were executing a camera-based change detection for the identification of objects.

V. CONTROL STRATEGIES

Tasks can be set at an individual or at a team level. When a task is assigned to a team of robots, some kind of intelligent task distribution and coordination is necessary. Moreover, the approach should cope with an arbitrary number of currently operational vehicles and adapt the task execution accordingly.

Our approach consists of three levels. When a task for a robot team is sent, the task is split up into seperate tasks for the ground, and for the aerial vehicles, as described in Sec. V-B. In the second level, the corresponding group (UGVs or UAVs) is responsible for their own task organisation. Two different task assignment strategies have been implemented for our experiments: centralized and decentralized coordination. The UAVs coordinate themselves in a fully decentralized way, the detailed approach will be published separately. Previous work on the UAV coordination can be found in [3]. The centralized approach, used by the UGVs, will be presented in Sec. V-C. The third level describes the execution of single tasks on each robot. The description is not part of this paper, but can be found for example in [2] or [3].

Two types of tasks will be presented in the experimental results. The following subsection describes the desired behaviour of the autonomous robots at a team level in both scenarios.

A. Scenarios

The MOVE scenario is meant to let the whole multi-robot system move to a specific destination in a coordinated fashion. Therefore, the UAVs take a constant formation, depending on the number of currently active UAVs, and escort the leading ground vehicle until the destination point is reached. The leading UGV is approaching the destination by staying on a pre-known road network, and the rest of the currently active UGVs are following one by one in a convoying manner.

In the OBSERVE scenario, the user defines a point of interest (POI) to be observed by the UGV/UAV team. First, the team approaches the POI as described in the MOVE scenario. When the POI is reached, the UGVs distribute equally around it and turn themselves to having their sensors focused on the POI. One UAV is taking position directly above the POI, pointing its camera downwards. Subsequently, an object detection is performed continuously by the UAV and all UGVs. Meanwhile, all other UAVs start orbiting around the POI having their cameras constantly pointed at it.

B. Group Tasks

A central planner is responsible for the group task planning. It can be located anywhere in the multi-robot system. Here, it is located at the leading vehicle, namely the UGV HANNA.

When a new MOVE task for the team arrives at the planner, two group tasks are created. The UAVs get the order to follow the leading vehicle in a fixed formation (via decentralized coordination), and the UGVs are ordered to approach the destination point in a convoy formation (via centralized coordination, see next subsection).

The OBSERVE task is initialized exactly as described previously to approach the POI. When the team is in a predefined distance of the POI, both groups get an order to observe it, which is handled by the corresponding task assignment planner.

C. Centralized Task Assignment

In our experiment, the UGV group applied a centralized task assignment planner. In each scenario, the planner checks which vehicles are currently available, i.e. are sending an ”operational status”, at the beginning of the task assignment. The benefit is that the planner can cope with a varying number of participating vehicles adapting dynamically to possible vehicle breakdowns.

For the MOVE task, the planner calculates a following order for the vehicles to avoid deadlocks in navigation. This is done by taking into account all current vehicle poses and the calculated route to the destination. Vehicles nearer to the destination will get a more forward convoy position. Afterwards, each vehicle gets a message containing a single vehicle name to follow, and a following distance. Hence, each vehicle is self-responsible for following exactly one vehicle.

When arriving at the POI in the OBSERVE scenario, the planner calculates observation poses (including orientation to the POI) for all active vehicles on a circular path with a predefined radius around the POI. The planner might take into account a pre-known road network to set the observation poses only on road segments. Thereafter, all vehicles are self-responsible for taking their assigned observation pose and for starting observation, object detection for example.

VI. FIELD EXPERIMENTS

To demonstrate the applicability of the developed interfaces and approaches, to gain experience with the use of mobile radio communications as a communication standard for mobile robots, and to show the possibility of autonomous reconnaissance and surveillance by a team of heterogeneous ground and aerial vehicles, we conducted some field experiments. The test site was a field camp of appr. 500m $\times$ 300m with gravel roads, fences, buildings and obstacles like parking vehicles and large stones. Six unmanned vehicles were participating, namely four UGVs and two UAVs. The vehicles are introduced in Sec. VI-A. All vehicles had a road network of the test ground in OpenStreetMap (OSM) format available. Sections VI-B and VI-C will present some results of the MOVE and OBSERVE scenario experiments.

A. Vehicles

Different types of unmanned ground and aerial vehicles have been used in the experiment. The UGV HANNA (see Fig. 1, (1)) [2] from the Leibniz Universität Hannover is based on an off-the-shelf Kawasaki Mule 3010 Diesel chassis, retrofitted with a drive-by-wire interface. It is equipped with a multitude of sensors and actuators, including 2D and 3D laser sensors, relative and absolute positioning sensors, and communication devices. Five embedded PCs are used for processing the sensor data, navigation and control of the vehicle.

The UGVs LONGCROSS and GARM (see Fig. 1, (2) and (3)) provided by the Fraunhofer Fraunhofer Institute for Communication, Information Processing and Ergonomics are driven by electric motors. With a payload of 150 kg the tracked vehicle GARM can operate autonomously for about 4 hours and the wheel driven LONGCROSS for about 2 hours. In addition to the front and rear laser range finders each chassis has a modular payload carrier for a quick replacement of sensors or manipulator pack. Here, both vehicles were equipped with a Velodyne HDL-64E, inertial measurement unit with GPS, cameras, a computer, and hardware for communication.

The University of Siegen supplied the tests with two types of unmanned vehicles: the UGV AMOR (see Fig. 1, (4)) and

Fig. 3. UAV PSYCHE 1000.

two UAVs PSYCHE 1000 (see Fig. 3). AMOR (Autonomous Mobile Outdoor Robot) is a modular all terrain vehicle based on a Yamaha Kodiak 400 quad. It is also equipped with multiple sensors for perception, navigation and communication. The UAVs PSYCHE 1000 are modified quadrocopter drones MD4-1000 by Microdrones, providing a maximum flight weight of 6 kg. Using a GPS receiver, accelerometers, gyroscopes, a magnetometer and a barometer, the UAVs are able of high precision stabilization and localization. Moreover, the UAVs are equipped with a 14.7 MP zoom camera each, mounted in a moveable frame deflected by two servos, and with IEEE 802.11 and 3G communication abilities.

B. MOVE Scenario

At the beginning of the MOVE scenario, the user defined a destination point on a map in the GUI. The task description (including the destination point) was transmitted to the leading UGV HANNA, which initialized the task distribution, group and task assignment planners (cf. Sec. V). After calculating and submitting a convoy order to all active vehicles, the UGV team started approaching the destination point. In this scenario test, the UAVs were not part of the team.

Fig. 1 shows the UGV formation during MOVE task execution. The corresponding GUI clipping at the same time instance is depicted in Fig. 4. It shows an aerial image overlaid with some information. The red arrow marks the destination point chosen by the operator. The blue symbols with contained square icons vizualise the current UGV positions, transmitted in real time via ROS/BML interfaces and 3G mobile radio communication. Although they were not part of the current task execution, the UAV positions are labeled as well by blue symbols with contained rotor icons.

This simple scenario showed the principle realization of an autonomous team of heterogeneous unmanned ground vehicles by standardized interfaces and communication. The team travelled appr. 300m full autonomously. Finally, the UGV team reached the destination point in its convoy formation successfully.

C. OBSERVE Scenario

First, a switch box mounted at a lamp post was chosen as point of interest (POI) for observation. After marking the POI

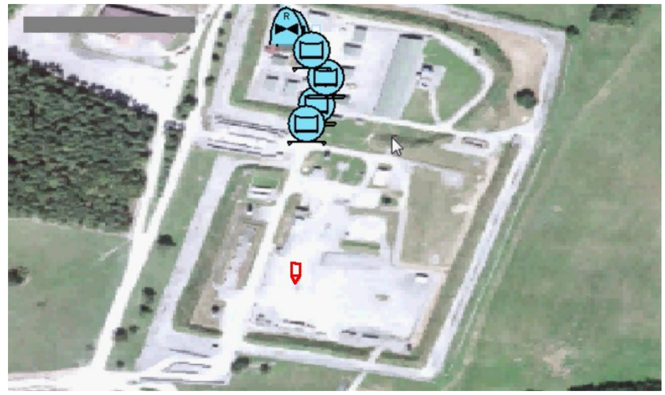

Fig. 4. GUI snapshot of the MOVE scenario. Robots poses marked with blue symbols, destination point with red arrow.

in the aerial image of the GUI by the operator, the team task was transmitted to the robot team, and the multi-robot system, consisting of four UGVs and two UAVs, approached the POI as discussed in Sec. VI-B. After reaching the proximity of the POI, the planners started to distribute the tasks as described in Sec. V, followed by the execution. After reaching the designated observation positions, or starting orbiting the POI respectively, the team (at this project stage the UGV HANNA and one UAV, cf. Sec. IV) started the observation using the moving object detection. After a few minutes, a vehicle entered the observed area, and persons started moving around the POI.

Fig. 5a shows the GUI clipping containing the aerial image of the POI area. Again, blue symbols mark the robot positions as described previously. The four UGVs are almost evenly distributed around the POI. One UAV is in observation, and one in orbiting position. Moreover, red symbols tag the detected moving objects. Red symbols with a cross icon represent detected pedestrians, while red symbols containing a circle mark represent detected vehicles. As can be seen, the pedestrians were successfully detected, as well as the unknown vehicle (fading red symbol). As a consequence, the operator was alarmed and may now request further pictures from the robots. Fig. 5b shows the aerial picture taken by the quadrocopter located above the POI. Compared to Fig. 5a it is slightly rotated counterclockwise. All four UGVs can be identified easily, as well as parking trucks and the detected unkown vehicle (dark blue) and pedestrians.

The scenario showed the applicability of multi-robot systems to autonomous reconnaissance and surveillance tasks. The unmanned vehicles have taken their observation positions autonomously. Unknown objects have been successfully detected and reported to the operator via ROS/BML and 3G cellular communication. In a next step, the operator could take further actions, for example sending ground personnel to the POI.

VII. CONCLUSIONS

In the paper, the realization of an autonomous team of heterogeneous unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) has been presented. The project was a

(a) GUI snapshot; robots (blue symbols) and detected moving objects (red symbols). (b) Aerial picture, taken by one of the quadrocopters.

Fig. 5. Results of the OBSERVE scenario.

cooperative work done by three different research institutions. It was concluded by a field test with six autonomous vehicles in a real world environment, namely a field camp. The paper presented the implemented approaches for common communication interfaces and standards, for the detection, tracking and classification of moving objects, the control strategies of the UGVs, and results of the concluding field test.

The preparation for the field tests showed that well-defined interfaces and a common communication standard are essential for the realization of such a multi-robot and multi-institutional work. Even if the integration of 3G radio communication instead of conventional techniques like IEEE 802.11 was smooth due to the IP-based network, the lower communication bandwidth was challenging. The usage of advanced features of ROS, such as `tf` or `time` on multiple robots led to a misconduct of the software, in case the ROSCore was run on a remote host. Therefore, in addition to the main ROSCore at the control station, each system fully integrated into ROS needed its own ROSCore using a ROS multi-master approach. With that, ROS communication via 3G mobile radio network has proven to be applicable in a multi-robot system.

The field test showed that it is possible to realize a multi-robot system of dynamic size, and that such teams are well-suited to perform reconnaissance and surveillance without constant observation by a human operator. The team was able to move to a destination point in a fixed formation, as well as to observe a point of interest and to fully autonomously detect moving pedestrians and vehicles in its proximity.

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