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Search and Rescue Robots: the Civil Protection Teams of the Future

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***Abstract*—After an earthquake or the collapse of a built structure, and facing a scenario of large destruction, the response time to search and locate trapped survivors is crucial. The human intervention of urban search and rescue (USAR) teams, including USAR dogs, has to be done cautiously so as to protect the rescue workers from further collapses. Debris may be so cluttered that prevent the close human access to the victims. Also, potential risk of further landslide requires the propping of the structures before human intervention. Rescue preparation operations may be time consuming, and a fast action to locate survivors and to take them human voices, light and/or water is a crucial factor for life. Therefore, there is the clear need for search and rescue robots that can be released immediately after a disaster in which the conditions are too dangerous and too cluttered for people and dogs to begin searching for victims. Teams of such robots should desirably be heterogeneous (e.g., aerial robots to perform scenario reconnaissance, powerful land robots to remove debris, small agile land robots to reach survivors buried under the debris), be able to perform with a given level of adjustable autonomy (as the presence of humans in the team to take crucial decisions will always be required) and be easy-to-learn and simple to launch and friendly to operate. In this paper we refer to some of the achievements in the area of USAR robots worldwide, and then focus on R&D work towards increasing the autonomy of USAR robots that has been done over the past 10 years at the Institute for Systems and Robotics of the Instituto Superior Técnico, TU Lisbon, in collaboration with Portuguese companies and Civil Protection institutions, including a land tracked wheel robot and aerial robots of different types (blimp, quadcopters).**

***Keywords*-Search and rescue robots, cooperative robots, adjustable autonomy, aerial robots, land robots**

I. INTRODUCTION

Teams of heterogeneous robots can represent an invaluable help for search and rescue operations. Robots can crawl over the collapsed structures, depositing small sized robots, and feeding air, water, food and medication to trapped individuals through tubes snaked into the collapsed structure. Small-sized robots can sneak inside very confined spaces, taking with them tiny cameras and other sensors to detect survivors and map survivor locations. Aerial robots can provide a broad view of the search and rescue scenario and map high-destruction locations [1]. Cooperation among human-operated stations, a distributed network of sensors located around the disaster area and teams of tele-operated and/or autonomous robots can increase the amount of available information to the rescue teams. Whenever communications with the networked sensors or the sensors themselves fail due to an earthquake impact, robots can be dispatched to cover the areas most inaccessible to humans and help finding victims at those locations. These mobile robot networks can also provide a dynamic view of the scene at relevant locations.

Well-known work on Urban Search and Rescue (USAR) robots in the US has been carried out by R. Murphy and co-workers, namely on the usage of several tele-operated robots for real search and rescue missions, in cooperation with professional human teams, including the participation in the rescue operations of the World Trade Center (WTC), after the September 11 attacks [2]. But this technology has been tested during other real catastrophes including Fukushima [3], Chernobyl [4] and the Sago Mine Disaster [5], and in conflict zones [6], as well as at natural disasters like hurricane Katrina [7] and the La Conchita Mudslide [8]. Daily operations of response robots for incident prevention include surveillance operations in the United Nations building at Geneva, in sport stadiums during the soccer world championship in Germany, and in several indoor and outdoor storage facilities [9] [10].

The US National Institute of Standards and Technology (NIST) has also developed the USAR Performance Metrics and Test Arena [11], a real scenario which emulates several real-world situations faced by human teams after an earthquake, which has been widely used worldwide, e.g., in Europe, at the Intelligent Systems for Emergencies and Civil Defense in Rome, Italy, and which has been serving as the testbed for the RoboCupRescue initiative [12], which joins together annually dozens of teams in a search and rescue robotic competition. Demonstration, test and evaluation events play a major role in this field as it is still a newly emerging technology. NIST, in cooperation with the US Federal Emergency Agency (FEMA) and the Department of Homeland Security (DHS) conducts the annual Response Robot Evaluation Exercise. These exercises are conducted

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at Disaster City, a 210.000 m^2 test area where large scale incidents can be simulated. This test and training facility features facilities like a complete mall that was constructed solely for the purpose of controlled destruction or complete derailed passenger and freight trains. European examples for according events are the European Land Robot Trials (ELROB) and the Rescue Robot Fieldtest.

Most existing search and rescue robots rely on a frequent interaction with the human operator(s), namely through tele-operation procedures of some kind. This stems on the fact that search and rescue teams tend not to trust full robot operation autonomy, due to legal issues and given that human lives are at stake. Nevertheless, there is an increasing trend towards adjustable autonomy, under which the robot operation is still subject to human supervision and/or tele-command, but the autonomy level of the tasks performed by the robots increases, so as to free the human operator from tedious and/or difficult actions (e.g., figuring out the distance to an object from the visual observation of one or more cameras installed on the robot, climbing stairs by adjusting wheel speeds and moving robot parts to change its mass center, dragging a robot formation by a tele-operated virtual or real robot leader).

In this paper we describe some of the R&D achievements towards increasing the adjustable autonomy of USAR robots that have been accomplished over the past 10 years at the Institute for Systems and Robotics of the Instituto Superior Técnico (ISR/IST), in collaboration with Portuguese companies and Civil Protection institutions, including a land tracked wheel robot and aerial robots of different types (blimp, quadcopters), some times under cooperative settings.

The paper is organized in 3 major parts: Section II describes the long-term vision of our research. Section III focus on the RAPOSA robot, designed and developed in 2005 by our group and the Portuguese SME IdMind, and goes over several works on adjustable autonomy that were carried out based on it since then. Section IV explains how the group evolved from blimp to quadcopter robots, regarding the aerial component of the USAR team, including some cooperation with a land robot. Section V closes the paper, drawing the main conclusions and listing topics of interesting future work.

II. MOTIVATION AND OBJECTIVES

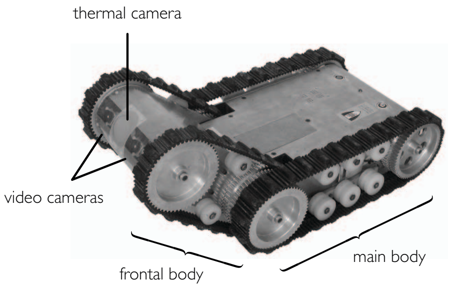
ISR started a multi-group research effort on USAR robots in 2000, under a national project. The main goal of the project was to provide integrated solutions for the design of teams of cooperative robots operating in outdoor environments, with a particular initial focus on perception and representation issues, as well as on cooperative navigation. A reference scenario for the project was conceived with the long-term goal of developing robotic teams to help humans in search and rescue missions [13], and was based on one land and one aerial robot, with two main goals: it should refer to a reasonably realistic situation, and it should be rich enough to accommodate all the research topics of interest for the involved groups.

The scenario includes two robots: one aerial blimp and one land outdoor robot. The aerial robot performs several tasks, such as obtaining a vision-based topological map of the destroyed site. The map includes information on the relevance of each of the mapped locations, e.g., concerning the degree of destruction and the presence of victims, as well as on the difficulty of traversing regions between locations, due to the presence of debris or obstructed paths. The map is stored as a graph and used to choose the best path for the land robot to reach a goal location (e.g., one with a larger number of victims). Map representation issues arise here, as the views of the land and aerial robots are different, even when they refer to the region associated to the same node of the topological graph. The land robot uses several sensors (GPS, inertial, vision, laser scanner, sonars) to navigate towards the goal, handling the details associated to the actual path (e.g., debris, trees, people on the way, etc). While the land robot moves towards the goal location, the aerial robot tracks it, so as to keep a reliable communication link and to serve as a relay for information that the land robot may need to send to distant stations. An animation illustrating the scenario above was developed and is available online at http://rescue.isr.ist.utl.pt/videos/rescue_web.mpeg.

Some of the initial goals of the reference scenario were achieved since then, namely the topological and metric navigation of an outdoor land robot [14] and the vision-based tracking, by an autonomous aerial blimp, of a land robot [15]. Meanwhile, a consortium project with a Portuguese SME (IdMind), and the Lisboa Fire Department led to the development of a tele-operated USAR land robot, RAPOSA (Figure 1(a)), which was used by the firemen in several training sessions, including a drill during the international exercise Eurosot 2005, 13-16 October 2005, in Sicilia, Italy. IdMind later commercialized a new version of RAPOSA (RAPOSA NG - see Figure 1(b)) which has been used at ISR/IST for further developments. Since 2010, the group engaged in a collaboration with another Portuguese SME, UAVision, that develops open architecture quadcopters. UAVision has been providing quadcopters for tests and innovative add-ins by ISR/IST, whose main goal is to replace blimps by quadcopters as the reference scenario aerial robots.

III. THE RAPOSA LAND ROBOT

RAPOSA was originally designed and built to operate in outdoor environments hostile to the human presence, such as debris resulting from the collapse of built structures, through sewing pipes and climbing partially destroyed stairs. The robot is targeted to the tele-operated detection of potential survivors using a set of specific sensors whose information is transmitted to a remote human operator. An innovative



(a) original RAPOSA robot

(b) RAPOSA-NG

Figure 1. Two generations of the RAPOSA robot.

feature of the original robot is the use of wireless communications, with an option for tethered operation. The tether carries both power and communications, with a wireless transceiver on its end. Docking and undocking the robot to the tether is accomplished remotely by the operator with the help of a camera located inside the robot, with no need to bring the robot to the base station. RAPOSA dimensions (17.5cm tall, 37cm wide and 75cm long) were specified so as to make it fit within sewing pipes and to help it climb standard-sized stairs. Furthermore, the mechanical structure, consisting of a main body and a frontal body, whose relative vertical orientation with respect to the main body is adjustable, with two-side tracked wheels to provide locomotion for both modules, provides the ability to change the robot center of gravity (by moving the two bodies with respect to each other) and extra traction power, useful features to get over obstacles. Other features of the robot are detailed in [16]. Most of RAPOSA characteristics are typical of a large class of available search and rescue robots, therefore the methods presented here can be generalized for such a class.

The adjustable autonomy methods described here take advantage of the above characteristics of the robot, but also of its onboard navigation sensors (namely inclinometers, 2 front cameras and one back camera looking through the docking hole).

A. Autonomous Tether Docking

One of the most innovative aspects in RAPOSA design is the remote docking feature, *i.e.*, the robot is able to attach and detach from the tether without direct physical human intervention. First, the tether end that attaches to the robot was designed so that its end stays at the same height and orientation with respect to the floor whenever left on the ground. Second, the tether attaches to the robot through a hole in the back of the robot, together with a motorized locking mechanism that can be remotely operated. Moreover, there is a video camera, mounted inside the robot and pointing towards this hole, so that the robot can be remotely operated towards the tether, by moving backwards [17].

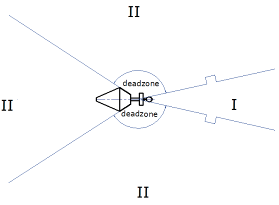


Figure 2. Partition of the space surrounding the docking pyramid.

Even though docking (and undocking) can be made remotely, an operator is still required to navigate the robot. With the goal of relieving the operator from such tedious task, an autonomous docking process was developed. This process uses the images captured from the robot rear camera to locate and guide the robot towards the tether.

The approach is based on visual servoing. To facilitate the task of locating the tether, colored markings were added to the pyramid at the tether end. However, due to the small camera field of view, it is not always possible to keep visual contact with these markings. In these cases, dead reckoning is used to reposition the robot in such a way that docking can proceed using visual servoing. This approach is based on dividing the space with respect to the pyramid in several regions, based on the feasibility of using visual servoing: in region I, the robot is able to dock using visual servoing alone, in region II, a maneuver using dead reckoning is performed with the goal of positioning the robot in region I, and in region III there are not enough visual cues to perform the automatic docking. A fourth region, designated “deadzone” represents the area where the robot can hardly manouver without colliding with the pyramid.

It is assumed that the automatic docking is launched in a situation that the robot has visual contact with the tether pyramid. Using the visual cues provided by the markings, the robot then determines in which region it is in. Based on that, the appropriate control algorithm is executed. The markings consist of an orange bi-conical metal guide (Figure 2) and a blue tape on a square shape around the pyramid. Figure 3 shows the pyramid with these markings, as seen by the robot rear camera.

The vision algorithm to estimate the pyramid relative

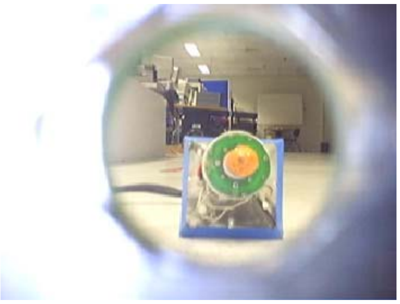


Figure 3. Pyramid color markings, as seen by the RAPOSA rear camera.

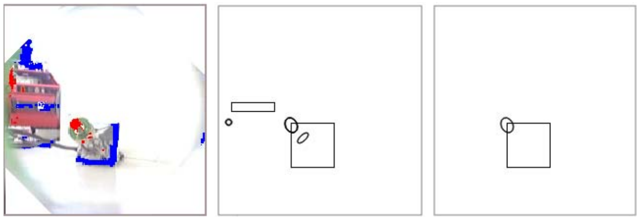


Figure 4. Vision algorithm intermediate results: from left to right, the color segmentation output, the ellipses and rectangle fitting, and the chosen marking pair.

position has three steps. First, the image is segmented based on color (in HSV space) in order to identify all blue and orange regions. Then, ellipses are fitted to the orange blobs, while rectangles are fitted to blue regions. The result is then filtered (geometric constraints) and the ellipses are matched with the rectangles, so that only the pairs that have a plausible geometric relationship are considered. This method has proved to be considerably robust to the presence of other similarly colored objects. An example of a successful pyramid detection can be found in Figure 4.

The visual servoing performed while in region I is based on maintaining the detected orange ellipsis in the center of the image horizontally. A simple linear controller is used to control the robot in differential drive mode. The robot is guided with constant velocity, close to a distance below which the robot is slowed down to allow a smooth docking. In this latter stage, the front body is actuated such that the ellipsis is also maintained centered vertically in the image.

For the region II, the robot performs a manouver in dead reckoning in order to reposition it into region I. If the accumulated error is not excessive, the robot will be located in region I, and use the visual servoing for the final approach, as described above.

To evaluate the docking performance, a systematic study was conducted whose results can be found in [17]. This reference provides also further technical details on the work.

B. Autonomous Stair Climbing

One of the design goals of RAPOSA's mechanical design was the capability of climbing stairs. This capability depends critically on the interplay between the center of mass of the robot, and its support contact points with the ground. For the particular case of stairs, as the contact points are on the edges of the steps, the overcome of a single step becomes a necessary condition.

It is assumed that the stairs are horizontal, meaning that all stair edges are parallel. Although the algorithm proposed here proved to be effective for (mildly) circular stairs, the design of the controller was based on this assumption.

The autonomous stair-climbing algorithm comprises two stages. In the first stage a computer vision approach is used to align the robot with the stairs, while in the second the actual stair-climbing takes place.

The alignment of the robot with the stairs, using vision, is based on the detection of the stair edges. The contours of the stairs are detected using the Canny edge detection method [18]. Assuming that stairs always present several parallel straight contour lines, their identification is made using the Hough Transform for straight lines detection [19]. From the lines detected, the one that minimizes the midpoint along the vertical axis is chosen. The angle that this line makes with the horizontal axis is then used to turn the robot to become aligned with the stairs.

The control strategy for the second stage (stair-climbing) follows two objectives: (1) steer the robot in order maintain it perpendicular with the stair edges, and (2) maintain the speed of the robot low enough in order to prevent it from falling back, due to the dynamics of the body (check [20] for details).

The robot is equipped with a two-axis accelerometer. This sensor allows the measurement of the robot pitch and roll angles, under a quasi-static assumption. The kinematics of the robot is essentially unicycle[1], and thus the control input can be seen as comprising a common mode and a differential model velocity. A third degree of freedom used is the frontal body angle. It is used firstly to rise this body prior to start climbing, to better overcome the first step.

The stair climbing algorithm follows a feedback control law approach. The minimization of the roll angle is equivalent to aligning the robot with the stairs, following a path perpendicular to the step edges, for horizontal stairs, by differentially driving the robot wheels. The common mode control is used to adjust the speed with which the robot climbs the stairs. In order to avoid the robot to fall down on its back, this speed is lowered as the pitch increases. The frontal body angle is controlled in such a way that the robot center of mass is kept as low as possible: as the pitch angle increases, the frontal body is lowered accordingly. The resulting feedback control law can be written in the

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[1] Since RAPOSA is a tracked vehicle, there is a large uncertainty on the contact points of the tracks with the ground. Nevertheless, the kinematics can still be modeled as for a unicycle (also known as differential drive), taking into account this uncertainty.

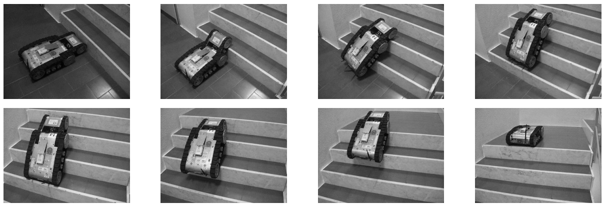


Figure 5. Picture sequence showing RAPOSA climbing stairs

following compact form:

$$\mathbf{r} = \mathbf{C}\mathbf{d} + \begin{bmatrix} \epsilon \\ \epsilon \\ 0 \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} = \begin{bmatrix} -\eta & -\mu & 0 \\ -\eta & \mu & 0 \\ -\delta & 0 & -\nu \end{bmatrix}$$

where $\mathbf{r} = (v_l, v_r, \sigma_a)^T$ is the control input, i.e., the left and right track velocities, v_l and v_r, and the frontal body angle increment σ_a (in degrees), $\mathbf{C}$ is the gain matrix, $\mathbf{d}$ contains the current sensor readings of pitch (ϕ_p), roll (ϕ_r) and front body angle (ϕ_a), $\mathbf{d} = (\phi_p, \phi_r, \phi_a)^T$, and ϵ is a constant bias speed. The gains η, μ, δ, and ν where empirically adjusted to yield a satisfactory performance under a variety of stairs (see [20] for further details on the way these gains were tuned).

The above linear control law allowed for an adequate behavior, except in extreme situations, such as stair height close to the physical feasible limit. To overcome this limitation, a gain scheduling approach was used, in which the above control law is disabled in specific circumstances. This was implemented introducing three exception states (S1–S3). The first one (S1) is reached when the pitch is higher than a threshold T_1 (35° in the tests). In this case, the robot stops until the front body is sufficiently lowered, then it starts moving slowly. If pitch keeps rising until reaching a second threshold T_2 (42° in the tests), the exception state (S2) is triggered, in which the robot starts moving backwards slowly, until leaving this second exception state. If S2 is achieved consecutively in the same step, the algorithm assumes that there is some obstacle blocking the way. In this case, the robot moves back and asks the robot operator to choose, using the images captured by the robot, the best direction to proceed avoiding the obstacle. If the front body is lowered significantly, when the robot falls forward to the next step, it will get stuck in the corner formed by the next step. Hence, the robot stops moving (exception state S3), while waiting the front body to return to its nominal angle (aligned with the body).

Figure 5 shows a sequence of images showing the robot climbing stairs.

This autonomous method for climbing stairs obtained better results than that of human operators (details in [20]). Such tests, made by different people with different skills operating the robot, showed that the wasted time when people is tele-operating is usually due to sending wrong commands to the robot, such as lifting the front body instead of tilting it down, or moving to the left instead of to the right. These small errors make the task of climbing stairs much longer than needed and sometimes it may lead to accidents.

C. Immersive 3-D Teleoperation

One critical aspect when tele-operating field robots is situation awareness, defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” [21]. The way the environment perceived by the robot is presented to the operator has a deep impact on its awareness of the robot situation, namely when the operator has no direct visual contact with the robot location. Most interfaces display of video stream from the cameras onboard the robot, in a 2D screen, usually shared with other interface elements. The original tele-operation console for RAPOSA was designed in this way: about 9.8% of the total screen area is occupied by each camera image (since 3 camera images are displayed simultaneously in the GUI, only 29% of the total screen area is used for video display). Moreover, if the operator wants to inspect the environment from a different viewpoint, it has to navigate the robot and/or manually adjust the frontal body to do so.

With the goal of mitigating the limited perception an operator has, given the conventional GUI, an immersive 3D interface was designed for RAPOSA. This interface is based on a Head-Mounted Display (HMD) equipped with a head-tracker, making it possible to determine the attitude of the operator head relative to a world frame.

The HMD displays the images from the pair of video cameras located in the robot frontal body, where the video stream of each camera is displayed to each operator eye. Since these two video streams pertain to two slightly different viewpoints, provided that the images are properly rectified, it is possible to endow the operator with depth perception (stereopsis).

The head-tracker built into the HMD is used to further improve the immersiveness of the interface: the pitch angle is used to control the robot frontal body up/down, the yaw angle is used to rotate the robot, and the roll angle is used to rotate the images (since the HMD rotates with the operator head, it is necessary to counter-rotate the images to compensate for this).

The human eye is very sensitive to the alignment of the displayed images in the HMD. The proposed image rectification algorithm corrects the images misalignment and endows them with a comfortable 3-D effect, by processing a rotation transformation and a crop transformation (vertical and horizontal) on the original stereo pair of images. The

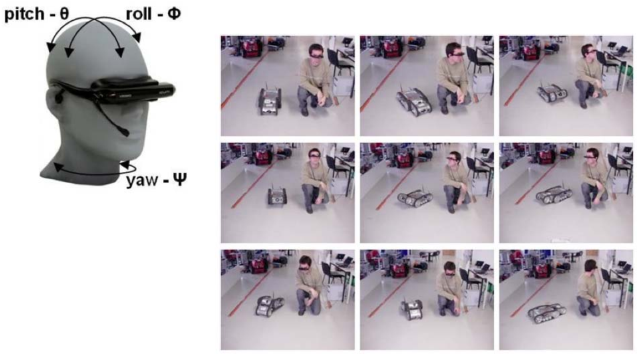


Figure 6. RAPOSA Head-Mounted display at work, showing the robot movements corresponding to pitch and yaw head angles.

HMD has a 3-DOF tracker integrated in it, enabling the detection of the users head motion, in terms of yaw, pitch, and roll angles. On the other side, RAPOSA can perform yaw movements (by sending symmetric velocities to each of its track wheels) and pitch movements (by ascending/lowering its articulated frontal body), but it is unable to perform roll movements. Hence, the yaw and pitch head angles are used to move the robot (see Figure 6), while the head roll angle is used to rotate the image, so that compensating for the head rotation.

More details and results of usability tests can be found in [22].

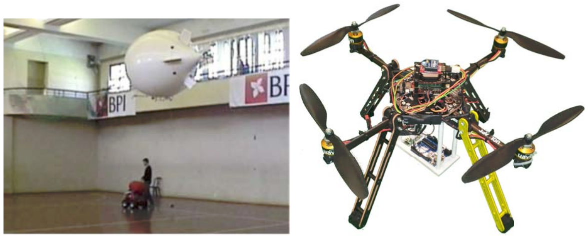
D. Improving Situation Awareness with RAPOSA-NG

Current research involving RAPOSA-NG is targeted to improving situation awareness to the human teams operating the robot. This effort addresses these two situations: first, during the online operation of the robot, sensor data (namely video) is conveyed to the operator in an immersive way, and second, offline analysis of collected sensor data (namely range scan data) is used to build a 3D map of the environment. The former allows operators to became aware of relevant aspects of the environment in real-time, such as passages between rooms, while the latter assists human teams to plan operations in a more informed fashion.

Concerning online operation, video stream from a Bumblebee2 stereo camera pair, mounted on a pan&tilt mounting, is being fed to the operator using a HMD. This way the operator gains the depth perception offered by the stereo image streams, since each eye of the operator is exposed to each one of the cameras the stereo pair. Moreover, the head tracker integrated with the HMD controls the pan&tilt mounting, thus allowing the operator to change the gaze of the camera by simply moving his head. This decouples the camera 's field of view from robot motion control (where a gamepad is used to send movement commands to the robot). This scheme has proven extremely effective in test scenarios, such as the well-known RoboCupRescue Robot League, where our team achieved 5th place (within 10 participating teams) during the GermanOpen'2012 competition.

Building a 3D map of the environment from sensor data is ongoing work being pursued from two different perspectives. The first one involves an autonomous 6D-SLAM (Simultaneous Localization and Mapping) algorithm to localize the robot in space, and thus to estimate the robot pose in real-time. The SLAM algorithm employs data from the Bumblebee2 stereo camera pair, the Inertial Measurement Unit (IMU) providing attitude measurements in SO(3), and odometry. The latter is considered unreliable to the kinematic nature of the tracks (high variability of the inter-wheel distance due to uncertain contact point between the tracks and the ground) and risk of extensive slippage. State-of-the-art feature extraction techniques are used to extract natural landmarks from the camera images (ORB features). The perception of these features, together with the IMU and odometry data are used in a EKF-based filter to simultaneously localize the robot in 6D (position and attitude) and build a 3D map of landmarks. Two challenges are being addressed by this research effort. Firstly, the temporal complexity of the filter does not scale well with the number of features, thus a bounded version of the SLAM algorithm is being developed. In particular, features are being added and/or removed from the filter state based on an evaluation of their utility. This utility is updated along time depending on the whether a given feature is observed once it is visible to the cameras. For instance, if one landmark is within the field of view of one of the cameras, its utility decreases if no feature matches it (otherwise, the utility increases). Features out of the field of view of the camera have their utility unchanged. Features not visible for a long time, have their utility decayed, and are eventually removed from the state. This keeps the dimension of the EKF state bounded and thus allows for real-time operation without degradation of performance along time. The second challenge addresses the problem of opportunistically updating the filter state using either a stereo observation model or a monocular one, depending on whether features are matched between the two cameras or not (i.e., only visible by one of the cameras). A stereo match provides a relative 3D position of the features with respect to the camera pair, while monocular visibility still provides useful information (even though it depends on parallax to get depth information). This allows the algorithm to employ 3D feature location from stereo match whenever possible, while still being able to update its location from monocular view of features (limited to azimuth and elevation of the feature with respect to the camera). Since the cameras are mounted on a pan&tilt mount, the camera observation model takes into account its the current configuration.

Map reconstruction in 3D is being pursued with the usage of ICP-based techniques on Kinect sensor data. The Kinect provides both depth and color data, thus reducing the map-building problem to a problem of colored 3D



(a) Passarola blimp tracking a tele-operated land robot.

(b) Quadcopter

Figure 7. ISR/IST aerial robots.

pointcloud matching among frames. Research is being done on the problem of bootstrapping the alignment using a classical ICP-based algorithm, and then involving the human operator in correcting misalignments. These misalignments can have various causes, such as ambiguous data (e.g., a flat homogeneous wall occupying a single pointcloud), as well as patterned shapes (e.g., stairs). Human operators are allowed to interactively correct the initial alignment done by an ICP-based algorithm. This correction is aided by the alignment cost function, thus constraining the movement of each pointcloud to the directions of movement consistent with their shapes. For instance, consider two flat pointclouds one over the other: displacement of one of the pointclouds is constrained to the directions of movement parallel to them. This constraining resembles the ”magnetic” feature often found in vector drawing programs, to facilitate the task of aligning shapes.

IV. AERIAL ROBOTS

A. *Passarola blimp*

Aerial blimps have been among the most popular unmanned aerial vehicles (UAVs) used in Robotics research in recent years. They have, over the other types of UAVs, the advantage of intrinsic stability and safeness, low noise, low vibration, vertical take-off and landing with hovering capabilities for a higher payload-to-weight-and-energy consumption ratio. Such characteristics made a blimp our first choice to implement part of the reference scenario concerning the tracking of a land vehicle by an autonomous aerial robot. A 4m-long indoor autonomous aerial blimp with onboard vision and computation capabilities, based on a digital signal processor (DSP), and including onboard vision, was developed. A realistic hardware-in-the-loop simulator was also developed over the USARSim simulator. This development environment enabled fast prototyping and implementation of navigation primitives for the blimp. The linearized blimp dynamics was identified using measurements made with the real robot flying in an indoor sports pavilion, and control algorithms were designed and implemented to follow ground lines and to track a ground vehicle [15]. Videos of the blimp tracking the land robot, as well as of the development system, can be visualized at http://mediawiki.isr.ist.utl.pt/wiki/Blimp_aerial_robot.

B. *Quadcopters*

Quadcopters have the advantage of having larger mobility and resistance to winds than blimps, enabling their effective usage outdoors, without requiring the handling and storage logistics associated to large blimps. Furthermore, some of the currently available quadcopters are endowed with lower-level control layers (rotor control, linear and angular velocity to rotor set points conversion) that enable its higher-level control in a simplified manner, thus very adequate for the purpose of our research.

The work developed so far using was based on UAVision (another Portuguese SME) quadcopters and is targeting mainly formation control of multiple quadcopters, and 3D-SLAM using sonars assembled around the quadcopter body. In both cases, the current developments were based on realistic (USARSim and Matlab) simulations of the quadcopter dynamics and sonar measurement characteristics. Formation control methods are based on artificial potential fields generated by harmonic functions to establish attractive and repulsive forces between formation members, obstacles and a virtual leader. The virtual leader can be joysticked by a human operator or result from the set points established by the motion of a land robot to be tracked, following the same technique previously used with the blimp.

V. CONCLUSIONS AND FUTURE WORK

In this paper we have described several developments of an ISR/IST long-term R&D project on USAR robot teams that cooperate with human civil protection teams for disaster response. Most of the paper focused on endowing land robots, developed by the team and the Portuguese SME IdMind, with increasing adjustable autonomy, namely autonomous stair climbing, autonomous tether docking and friendly teleoperation by humans, including the situational awareness, based on HMDs and pan&tilt stereo cameras. Recent developments concern the intervention of autonomous aerial robots, namely a blimp and, currently, quadcopters developed by another Portuguese SME, UAVision. The aerial robots can navigate autonomously and track land robots.

Future plans will be supported on a vision rooted on technology transfer objectives, so that adequate robust and reliable technology can be developed to run advanced software and experiment novel concepts on formation control, SLAM, cooperative perception and cooperative decision-making in real devices and operation scenarios. For this purpose, the collaboration with civil protection end-users, started in the past, shall be continued and reinforced.

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