RAPOSA:
Semi-Autonomous Robot for Rescue Operations

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Abstract— **This work describes a semi-autonomous robot for rescue operations, nicknamed RAPOSA (FOX in English). The robot was designed and built to operate in outdoor environments hostile to the human presence, such as debris resulting from the collapse of built structures, and 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. RAPOSA's mechanical structure is composed of a main body and a front body, whose locomotion is supported on tracked wheels, allowing motion even when the robot is upside down. The front body has variable tilting capabilities, providing means to overcome edges higher than the robot main body (e.g., when climbing a stair) and is also useful to grab the lower ground when only the main body has ground contact. This front body has one thermal camera and two webcameras installed. Additional sensors include gas, temperature and humidity sensors, web cams, light diodes, microphone and loudspeaker. The robot uses wireless communications, with an option for tethered operation. The tether carries both power and communications, with an access point on its end, and can also be used to suspend the robot inside a deep hole. Docking and undocking the robot to the tether is accomplished remotely by the operator with the help of a camera located inside the robot, and represents the most innovative feature of RAPOSA.**

I. INTRODUCTION

Search and rescue in emergency scenarios arising from natural and man-made disasters is one important application of mobile robots. 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 as it is known that after 48 hours of the disaster the probability of survival is low. 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 are small, cheap and light, and 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.

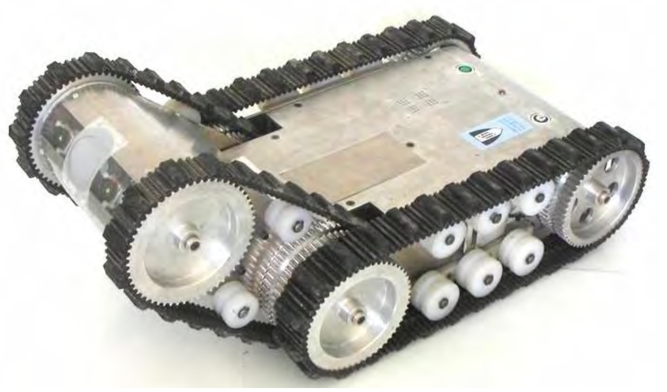

Fig. 1. Robot RAPOSA: External View.

The most well-known work on USAR robots in the US has been carried out by R. Murphy and co-workers, namely on the usage of several teleoperated 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 [1]. The National Institute of Standards and Technology has also developed the USAR Performance Metrics and Test Arena [2], 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 RoboCup Rescue initiative [3], which joins together annually dozens of teams in a search and rescue robotic competition.

This strong worldwide interest in search and rescue robots research and development has attracted several companies that have developed USAR commercial platforms, such as iRobot (Packbot, a very robust, light and mobile tele-operated robot, used in the WTC operations but recently re-targeted towards military operations), RoboProbe Technologies (bomb disarming and inspection robots), Inuktun (tele-operated robots also used in the WTC operations), Foster-Miller (demining and bomb-disarming robots, some of them appropriate for USAR operations, also used in the WTC operations), or the South Korean Domy and Co., whose robots can be teleoperated using wireless communications and provide remote audio interaction with victims. One common feature of these platforms is that teleoperation is possible either using wireless communications or a tether, but not both. Accordingly, when the tether is used, the onboard batteries are useless, since it is not possible to switch from the tether-supplied power to the batteries-supplied power during normal operation, without changing the robot structure. The robot described in this work combines tether-supplied wireless communications, tether- and battery-supplied power, exchangeable during operation, to take advantage of the positive features of wireless and tethered solutions.

This paper describes the robot RAPOSA, represented in Figure 1, designed and built to operate in outdoors environments hostile to the human presence, such as debris resulting from the collapse of built structures. 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 feature of our work is the use of wireless communications, with an option for tethered operation. The tether carries both power and communications, with an access point on its end, and can also be used to suspend the robot inside a deep hole. Docking and undocking the robot to the tether is accomplished remotely by the operator with the help of a camera located inside the robot. RAPOSA was developed by a consortium composed of the Portuguese SME IdMind, and the Institute for Systems and Robotics at Instituto Superior Técnico, with Lisbon Fire Fighters Department as the end user.

The paper is organized as follows: Section II describes the mechanical structure of the robot and the design constraints imposed by the environments where the robot is supposed to operate. Sensing capabilities and the mixed tethered/wireless communication system, the most innovative feature of RAPOSA, are described in Section III. Section IV covers the graphical user interface, a relevant part of this teleoperated robot. A description of several tests made so far in very realistic environments is made in Section V. Section VI closes the paper, drawing the main conclusions and listing topics of interesting future work in the robot.

II. MECHANICAL STRUCTURE

The robot RAPOSA is targeted to be used in Urban Search and Rescue operations, in particular in debris resulting from collapsed or unstable man-made structures. The project specification in all the aspects related with mechanical design, sensors, Graphical User Interface (GUI) and functional capabilities was defined in a close collaboration with the Lisbon Fire Fighters and Portuguese Civil Protection Departments. This allowed a categorization of the several types of scenarios to consider, the obstacles to overcome and also the scenarios where this robot should not operate, given their extreme complexity (e.g., underwater). The more important constraints consider that the robot should fit in sewer pipes with a standard diameter of 40cm used as a way to reach locations otherwise unaccessible in disaster scenarios and should be able to climb and descend stairs with steps of standard dimensions of 17cm of height × 23cm of width (see Figure 2).

Fig. 2. The robot RAPOSA inside a sewer pipe and downstairs.

Those constraints determined the major components of the mechanical design, namely:

a) two modules, a main body and a frontal body, whose relative vertical orientation with respect to the main body is adjustable,
b) two-side tracked wheels to provide locomotion for both modules. The frontal body locomotion is coupled to that of the main body,
c) when the robot "flips" upside down, it continues its operation flawlessly. This implies that the robot does not have a top or bottom part, and that it self-detects its orientation and automatically exchanges the commands to the motors and flip the cameras images, as an example of adjustable autonomy.

When completely stretched, the robot's width × length is 37cm × 75cm. It has a total height, from ground to vehicle's top, of 17,5cm and a ground clearance of 3cm. The weight, including batteries and all accessories, is 27Kg. The maximum velocity of the platform is 0.5m/s.

The front body features two webcams, each with an associated light and a thermal camera. The two webcams assemblage provides a 30° horizontal pan that, associated with the front body ±90° tilt range, enables a large field of view.

Three 5Ah Li-Ion batteries were chosen to be on the front part of the main body (see Figure 3), as it is crucial that the robot center of mass is located on its front, so that the robot "falls to its head" when climbing stairs, rather than the opposite (flipping or falling). On the front of the main body there are two wheels on each side. One is connected to the locomotion track on the main body and the other to the front body track. They are attached in such a way that the movement of the main body wheels is transmitted to the front body wheels, both rotating at the same speed, and the front body positions itself without interfering with the locomotion.

III. SENSING CAPABILITIES AND COMMUNICATION

The temperature and humidity sensors provide a measurement of both relative humidity from 0% to 100% and

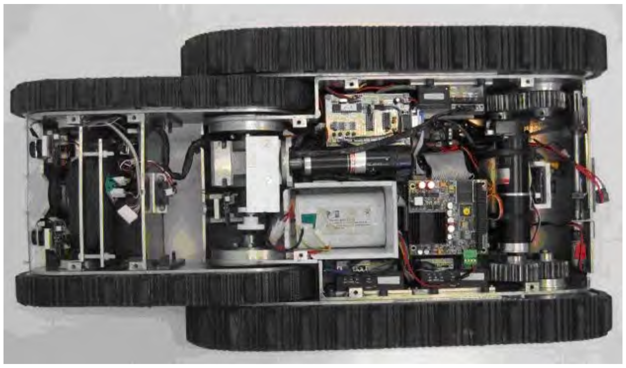

Fig. 3. Robot RAPOSA: Inside View.

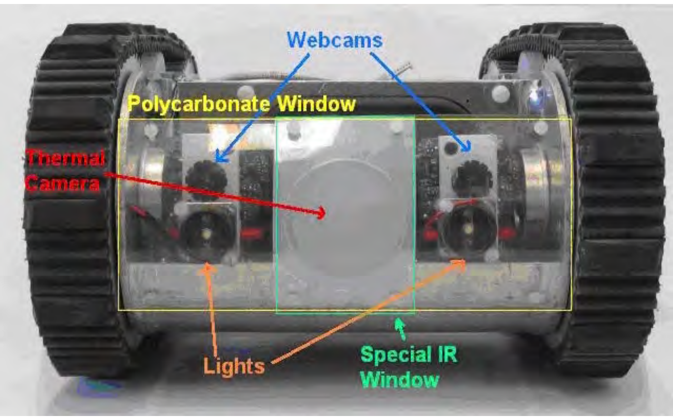

Fig. 4. Front body with cameras (thermal and webcams), lights and IR sensors.

temperature measurement from -40°C to 120°C in a single sensor, using a digital interface. This sensor is located close to the gas sensor, in such a way that its measurements are used for humidity and temperature compensation for the gas sensors. Four different gas types can be detected by the on-board sensors: methane, propane, butane and other gases that indicate high explosive level, hydrogen sulphide and carbon monoxide.

Four webcams are installed on the robot: 2 on the front of the tilting arm, providing a flexible field of view to the remote operators, one on the front of the main body, and one on the robot rear. Besides providing data for the perception of the nearby environment, the rear webcam also supports the docking operation of the communications and power cable. In dark environments, artificial illumination is provided by low consumption light LEDs installed nearby the cameras, as displayed in Figure 4.

In a disaster scenario, there is usually a considerable amount of dust in the air so, even with artificial illumination, no distinguishable image at all can be retrieved using conventional cameras. A thermal camera, on the other hand, is sensitive to heat radiation, thus allowing the perception and detection of heat sources. This is very useful to help finding survivals under debris or dust. Figure 7, on the Graphical User Interface (GUI), shows on top the images of the two webcams and, on the bottom, the thermal image of a potential survivor. Moreover, the thermal camera data can be used to estimate the temperature in a given zone, warning that a fire may hide behind a hidden door or wall. A Raytheon Series 300 Digital (thermal) Camera with 18 mm lens is placed in the central location of the front arm. The camera is capable of detecting people up to 150–200 m, weights less than 1 Kg and provides a greyscale image at 30 frames per second.

Real experiments of the robot tele-operation in realistic scenarios have shown that, particularly when overcoming large slopes (e.g., a stair), the perception of the distance to the terrain is of great help. For this purpose, a set of infra-red sensors was installed on the front body, facing down. The robot is able to climb 45^o degrees inclinations and, if it flips, the operator should be aware of that fact. The image acquired by the camera(s) does, sometimes, provide an elusive idea of the correct robot orientation. Furthermore the robot is allowed to operate turned "upside down". This requires frequent adjustments of the orientation estimates. Two analog tilt sensors were installed to measure and provide the operator with the knowledge of roll and pitch angles of the robot. Similar information for the front body is provided and displayed in the GUI as represented in Figure 7.

Analog tilt sensors are devices based on analog accelerometers measuring gravity. Currently there are only two-axis devices, with a limited range of about 70 to 75 degrees. For complete determination of the robot orientation, two devices orthogonally assembled are required. This accelerometer-based solution is affected by the robot accelerations. However, this effect can be minimized by low pass filtering the output of the sensor.

Concerning communications, existing robots, such as the iRobot Packbot or Domy and Co.'s robots, have one of two main configurations: tethered or wireless. Both solutions have strong and weak points. The tethered solution provides better autonomy and ensured bandwidth. It can also be used to sustain or pull the robot. However, a cable may get stuck, broken, etc, thus limiting the robot mobility. The wireless solution, on the other hand, is less dependent on the terrain where the robot moves and the number of turns it has to make. Its autonomy depends solely on batteries. Nevertheless, wireless communications may prove very unreliable. Standard wireless LAN devices can reach a maximum of 50m indoors, in good conditions. This is not the case on disaster scenarios where twisted metal, big piles of concrete, all kinds of obstacles, edges, electrical wires, etc, block and reflect the signal, making it difficult to communicate at high data rates (or to communicated at all). The feedback received from other search and rescue teams advises the use of a tether. In many cases the electromagnetic noise is too high and wireless communications may not work at all. A cable, although being a “dead weight”, provides stable power and communication. Traditional solutions allow either configurations, but even if the same robot supports both of them, the change must be done at the setup stage, being a time consuming job. The solution

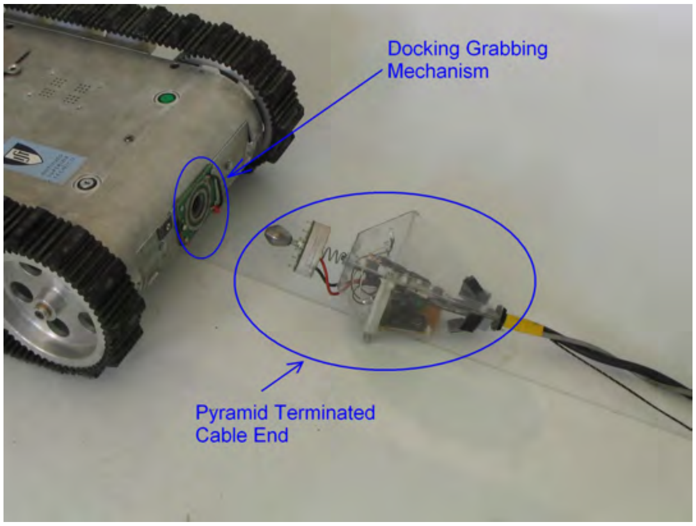

Fig. 5. RAPOSA docking to its cable.

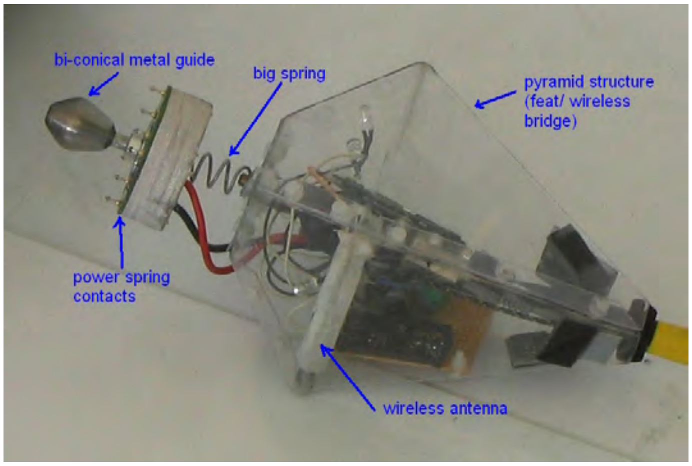

Fig. 6. Details of the docking system cable end.

proposed for this robot goes a step further, allowing the cable to be attached / detached whenever necessary in real time and while the mission is undergoing. To that purpose, a “docking mechanism” was installed on the back of the robot. The robot comes close to the cable, grabs it and attaches it, through a perpendicular lock.The robot can be operated with or without a cable and the switch can be made remotely in real time. The cable supplies power and acts as a wireless transmitter.

If the cable is not required anymore, the lock is pulled off. As the robot moves, the cable releases itself from the robot. This solution requires an additional camera on the back of the robot (the fourth webcam), to assist on finding and attaching the cable.

The docking system is composed by two parts: the cable part, that is released on the ground, and the grabbing mechanism on the robot back. The robot features an opening in the back, where a cable shall enter and be locked. The lock is strong enough to hold the robots weight, so that it can be lowered by the cable into a hole. The docking mechanism allows real-time docking / undocking of the cable, anywhere on its course (see Figure 5). At its actual stage of development it is moderately dust tolerant, but neither water nor mud tolerant.

The cable is flexible, but ends in a solid structure that has a pyramidal shape. This allows both unrestricted movement and a way to raise the bi-conical metal guide so that the robot can grab it. The pyramidal structure has a weight on the cable side and does not rotate easily, even if dropped in a non-horizontal plane and thus the bi-conical metal guide maintains its orientation approximately, independently of the way the structure is dropped on the ground (see Figure 6). The average distance from the ground to the end of the bi-conical metal guide was projected to be at the same height of the robot docking hole. Nevertheless, in the docking phase the vertical alignment can be cleverly done: if the frontal arm is pushed down, the main body rear comes closer to the ground. On the robot back, two sliding doors are able to release or grab the cable part. When the doors are closed the cable part is pulled to the robot inside due to its bi-conical metal guide. Meanwhile, electrical power spring contacts are pressed against two concentrically arranged rings on the back of the robot. The rings are made of conductive material. Each ring is connected to a voltage pole. Since the spring contacts are also concentrically arranged, the poles are never inverted. Before attaching and prior to detachment of the docking system the power cable must be turn off to prevent electrical glitches. The power contacts and bi-conical metal guide are separated from the pyramid body structure through a large spring, whose purpose is to avoid breaking the docking mechanism when it is dragged to unfavorable positions, normally when the robot starts climbing an obstacle. The need of assuring physical contact of six Ethernet terminals once the cable is locked, for communications purposes, is quite demanding. We avoided the problem by using a wireless bridge/antenna at the end of the cable to communicate wirelessly with the robot, where two circular polarization antennas are located in the rear, nearby the cable. Although there is no physical contact, transmission is assured in the best possible conditions, since the distance between antennas is very small.

The power transmission (DC voltage to power the robot) needs to have physical contact, however. It is fundamental to have a rear camera to aid the docking process. The camera was placed inside the robot, behind the insertion hole, aligned with it, so that it is useful even when the robot is upside down. When the docking mechanism is not attached and the operation scenario has no dust, the docking hole can be open and this camera used to have a view of the environment on the back of the robot. Besides the Ethernet to wireless adaptor and corresponding antenna, the pyramid also features a small DC-DC 2A board power, the wireless bridge and 4 green LEDs. If the pyramid is dropped on a dark environment, this helps finding it again. The fact that the LEDs are also at an equal distance from the bi-conical guide helps precise maneuvering

Fig. 7. Graphical User Interface - Operation Console.

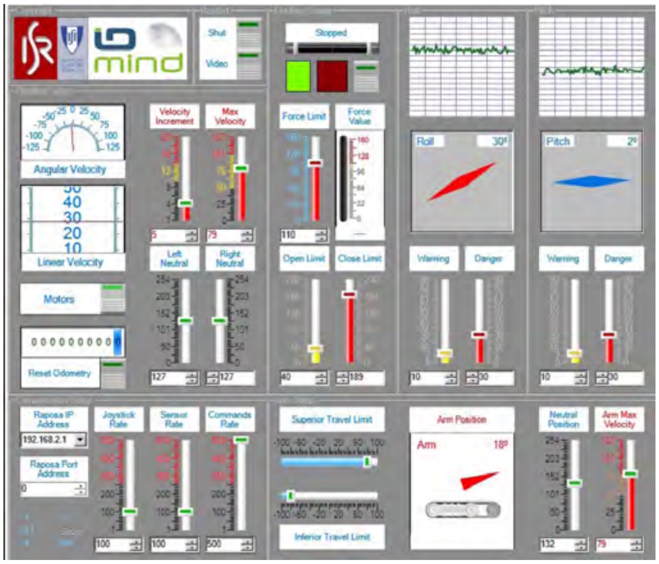

Fig. 8. Graphical User Interface - First Setup View.

to grab the cable end.

IV. USER INTERFACE AND SOFTWARE ARCHITECTURE

RAPOSA is a semi-autonomous robot whose normal operation is to be controlled by an human operator through a Graphical User Interface (GUI). The GUI is composed by four views. The first view (see Figure 7) is the Operation Console, used to drive the robot, in which the user has the camera (web and thermal) feedback images as well all the data from the robot sensors and the sensor and actuator commands, namely, on the top left, the pitch and roll angles, on the top right the arm position and the lights intensity, on the bottom right all the sensor values, as well as the network state, and on the bottom left the battery state, the motors velocity and the state of the docking mechanism of the power/communication cable.

The second and third are setup views for robot and sensor thresholds configuration. On these views the user can adjust the sensors and command rates, as well as to establish limits on the front body movement and to define limits on the motors speeds (Figure 8). The human operator can also set the Warning and Danger values of the Roll and Yaw sensors and to turn on or off a specific sensor. The fourth view is an advanced debug view, where the operator can watch and control in real time the low level micro-controller data tables. More configuration settings can be included on this view if necessary. The commutation between views is possible selecting each of the corresponding tabs on the top of the interface.

A game pad interface is used to control the robot on the field. This is thought to be a better way to control the robot on the field than the usual joystick. The game pad (Figure 9) is composed of two joysticks, one slider, a four key cursor and several buttons. One of the joysticks controls the robot motion, the other pans and tilts the front cameras. The slider is intended to control the front body position. The other buttons are used to select the active cameras, the LED lights intensity, to latch/unlatch the docking mechanism, to reverse the robot motion direction, as well as to enable and disable the motors.

An agent-based software architecture, including different types of agents that can be combined both hierarchically and in a distributed manner, was used. The architecture supports information fusion between several sensors and the sharing of information between the agents by a Blackboard and is geared towards the cooperation between robots. Agents are generically organized hierarchically. At the top of the hierarchy, the algorithms associated with the agents are likely to be planners (in this case replaced by the human operator), whilst at the bottom they are interfaces to control and sensing hardware. The planner agents are able to control the execution of the lower level agents to service highlevel goals. The latter can be distributed across several processors and/or robots. To offer platform independence, only the lowest level agents are specific to the hardware, and these have a consistent interface for communication with the planning agents that control their execution. The elements of the architecture are the Agents, the Blackboard, and the Control/Communication Ports, not described here in detail due to lack of space. For more details see [4].

V. TESTS IN REALISTIC SCENARIOS

The robot was tested in several scenarios of the Fire Fighters school, in March 2005. One of the scenarios consisted of a 40m pipe hidden below a great amount of rubble, which the robot traversed almost entirely (left side of Figure 2 and Figure 10). At some points, large tires located inside the pipe could not be overcome by the robot, that even flipped when trying to step over one of them, thus enabling the test of the adjustable autonomy system. This worked quite well, and the combination of pitch and roll sensors with the front cameras was fundamental, since given the pipe radial simmetry it is hard to figure out whether the robot is in its ”natural” position or not. Another scenario concerned the operation

Fig. 9. User Interface - Game Pad.

Fig. 10. RAPOSA moving out from a pipe within rubble.

inside a two-floor house (right side of Figure 2). The operator stayed outside and the robot was able to climb and descend stairs twice, as well as to undock and dock the power cable remotely, in a room with total absence of light. The robot did also traverse successfully a dark tunnel with a step at the end. The only minor problems encountered concerned wireless communications, both related to the antennas location on the robot body and interference with other wireless networks.

In this particular exercise, the robot reduced the inspection time down to 25% of the time that specialized firefighters teams would take to finish the exercise. This was due to the fact that the firefighters need to stabilize the environment in order to reduce live threats. In this case, as in many other similar situations, not only the robot provides a faster inspection method, but also a much safer one. Overall, the robot performed flawlessly, and the Fire Fighters are willing to use it in real operations.

In October 2005, RAPOSA was included on the portuguese Search and Rescue team of the Catastrophes Intervention Department of Lisbon Fire Fighters, that participated in the international exercise Eurosot 2005, 13-16 October, in Sicilia, Italy. In this simulated earthquake, RAPOSA was used to explore a pipeline system of a collapsed building.

VI. CONCLUSIONS AND OPEN ISSUES

This paper described a semi-autonomous robot designed and developed for urban search and rescue operations, namely its mechanical structure, sensing capabilities and communications, operator interface and software architecture. The robot uses wireless communications, with an option for tethered operation. The tether carries both power and communications, with an access point 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, and represents the most innovative feature of RAPOSA.

The robot was tested in very realistic scenarios, and a first prototype is expected to be used in real missions as soon as required. There are strong prospects to start its commercialization, after solving current minor problems with wireless communications and modifications of the mechanical structure, following lessons learned during the preliminary tests. Prospective applications to building surveillance and road tunnel inspections are also under consideration currently.

Future envisaged work concerns the widening of the adjustable autonomy capabilities, both to single-robots and to multi-robot teams, so as to free the operator from the most tedious work, and to help her/him locating victims and driving the robot(s) adequately. This may be especially interesting for robotic teams, where the operator would not need to drive the whole team but only, e.g., the leader of a robot formation.

Acknowledgments

This work was funded by the Portuguese *Agência de Inovação* and *Fundação para a Ciência e a Tecnologia* (ISR/IST plurianual funding) both under the POS_C funding programme. The authors would also like to thank Robin Murphy and her co-workers at USF for the technical support in the beginning of the project.

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