INDOOR LOCALIZATION AND CONNECTIVITY MAINTENANCE IN RESCUE

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Abstract

In rescue scenarios, it is becoming more and more mandatory to provide information to various responders, including potential victims, inside the structure. Unfortunately for several structures, such as underground and historical buildings, localization strategies based on external sources (e.g. GPS) are unfeasible. To overcome such a problem, the EU co-funded project REFIRE has presented an approach based on the use of inertial sensors used to estimate the displacement of the responders. However, to counteract the distortions due to the drift and magnetic mass, the project suggests collocating emergency lamps with a passive RFID tag able to provide their position (plus other data of interest). Providing the first responder with a RFID reader enables one to merge such information with the data provided by the inertial devices to correct the position of the responders. However, this is only one aspect of the solution. We also need to transmit the position of the responder to the outdoor command unit whilst understanding that direct communication appears unfeasible in deep indoor scenarios thus eliminating wired solutions. To overcome this limitation, the paper suggests use of a platoon of mobile robots able to automatically arrange themselves in order to create a sort of virtual chain that operates as an ad-hoc network. Specifically, each robot functions in a decentralized fashion and changes its position in order to avoid obstacles and guarantee that it is constantly in communication with its previous and ensuing node in the communication chain (e.g. the first robot in the chain is with the base and the last robot in the chain is with the first responder). The approach is sufficiently robust and capable of automatically reconfiguring in case a link is missed when one or more robots fail. Some preliminarily experimental results illustrate the feasibility of the proposed solution.

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Introduction

Localization and tracking support is useful in many contexts and becomes crucial in emergency response scenarios: being aware of team location is one of the most important pieces of knowledge for the incident commander. The availability of such resources affords emergency personnel the capability to increase safety, efficiency and coordination while simultaneously decreasing mission time. Moreover, a reliable localization system reduces the possibility of disorientation (a contributing factor in rescuer deaths) in search and rescue scenarios.

In Italy, tracking firefighters became a priority after the 1999 Roman Historical Palace fire, in which two firefighters were permanently injured after becoming lost in the thick smoke [1]. In the same year, six US firefighters were killed for the same reason in the Worcester Cold Storage Warehouse fire [2]. The topic became again hot after the September 11 terrorist attacks, when federal leadership tasked scientists with developing technologies that could track firefighters in buildings where GPS is unavailable.

Localization and tracking are important technologies and represent one of the industry's top priorities, as outlined by the US National Institute for Occupational Safety and Health (NIOSH). Due to the relevance of the issue, NIOSH explicitly highlights the need for a localization and tracking systems in its reports [3] and [4]:

- ✓ Consider using exit locators such as high intensity floodlights, flashing strobe lights, hose markings, or safety ropes to guide lost or disoriented fire fighters to the exit;
- ✓ Ensure that the Incident Commander receives pertinent information (i.e., location of stairs, number of occupants in the structure, etc.) from occupants on scene and information relayed to crews during size–up;
- ✓ Conduct research into refining existing and developing new technology to track the movement of fire fighters inside structures.

Moreover, in 2012 the US Inter Agency Board listed the development of an emergency responder body-worn integrated electronic system as its top priority for the R&D industry. This system, according to the priority report, should integrate enhanced communication capabilities, locations and tracking capabilities, situational awareness and environmental sensing capabilities, and physiological status monitoring capabilities.

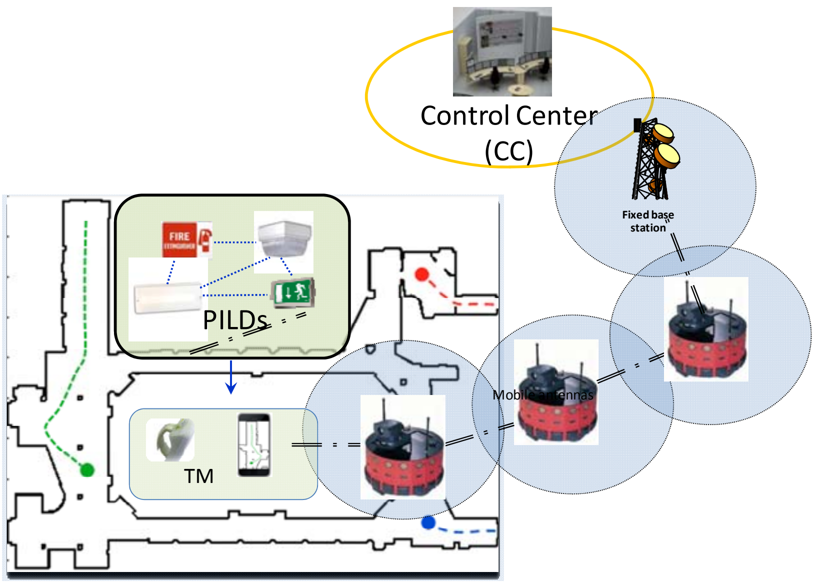
Following the classical "*divide et impera*" approach, the problem can be logically separated between the localization of the first responder inside the crisis scenario and those outside his/her position. Specifically, this paper adopted the solution developed inside the EU co-funded project REFIRE (http://www.refire.org/) for inside crisis zone localization [5] and exploited the possibility of using a platoon of mobile robots that automatically and dynamically arrange themselves in order to create a mesh network able to guarantee communication outside the crisis area [6]. These mobile antennas suitably move to dynamically ensure a multi-hop communication link, handling the occurrence of obstacles, signal fading areas and failures (e.g., the fault of one or more mobile robots). The technique has been experimentally validated in the framework of the NECTAR project funded by the Italian Government (http://webuser.unicas.it/nectar/). In the following, we briefly illustrate the overall architecture and then provide details regarding the approaches used for the localization and communication tasks. Some preliminarily experimental results are very encouraging about the feasibility of the solution.

Proposed Solution

Although some location-based services are becoming common to the general public by means of mass-market outdoor and indoor location systems, localization and tracking are still a challenge in GPS-denied environment and especially during emergencies due to demanding working conditions. A great deal of research efforts have been spent on these issues over the past years, however, there is not any “off-the-shelf” solution to provide location and data communication services for rescuers in deep indoor environments. In fact, in these deep indoor environments, localization fails against physics: it is not possible to obtain a line-of-sight electromagnetic wave penetration through multiple steel-reinforced concrete walls. The only common result of such research is related to the need of a pre-deployed localization infrastructure combining some positioning technologies.

The major drawback using different technologies is related to the lack of interoperability between the various devices. Interoperability is only guaranteed through the adoption of highly standardized protocols and devices. The definition of those standards is the main focus of the REFIRE project [13], which aims to provide a reference capable of concretely verifying implementation and industrial aspects.

Figure 1: Localization & Communication architecture



The REFIRE system architecture (see fig.1) is composed of Mobile Terminals (MTs) carried by the rescuers, a number of low-cost highly standardized Pre-Installed Location Devices (PILDs) to be embedded within existing preinstalled safety devices (e.g. emergency lights), and a Control Centre (CC) located outdoor in the emergency area, where the coordinator of the operational forces manages the situation. Experimental trials have shown that even using military-derived radios, the capability to communicate between indoor and outdoor environments is seriously limited. Obviously, due to the dynamic circumstances of a crisis area, it is impossible to use pre-deployed solutions. The only effective strategy seems to create an ad-hoc multi-hop network capable of transmitting data directly from the rescue scenario to the CC.

Moreover, because the potential area of responsibility for an emergency responder can be vast, the communication network should automatically update to provide coverage of the various areas of interest and maintain a communication link with the outside commander. This approach also takes into account the possible failure of one or more components due to the changing environments. This task can be realised exploiting the solution proposed in [6] where a platoon of mobile antennas is used to overcome some of the classical drawbacks of wired and wireless communication techniques in rescue scenarios. Specifically, the mobile antennas, in a full-distributed way, autonomously reconfigure their position to guarantee the presence of a communication link from the rescuer to the outside CC (avoiding obstacles etc).

Localization

The Rescuer Localization Algorithm (RLA), developed inside the REFIRE project, exploits the lessons learnt from robot localization: the MTs, carried by the rescuers, are equipped with 3D-inertial measurement sensors and are able to calculate a rough estimate of the position of the rescuers by using dead reckoning. To correct the unavoidable drift, the estimate of the position is refined using data fetched from PILDs within reach.

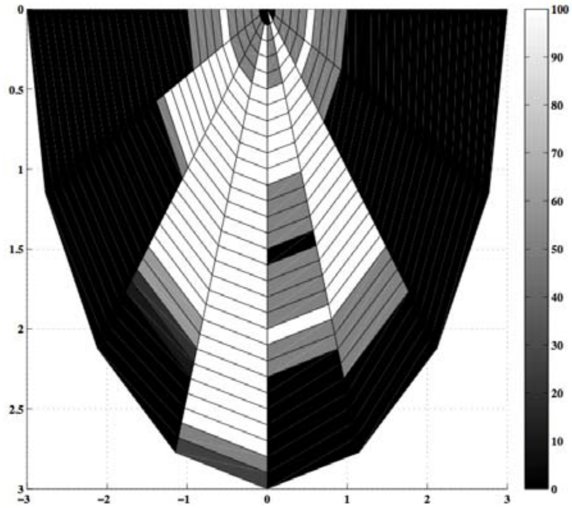
The MT consists of an IMU evaluating the proprioceptive measurements plus an RFID reader that provides exteroceptive information. Specifically, the IMU is equipped with three orthogonal sensor triads: the first having three accelerometers, the second having three gyroscopes and the last having three magnetometers. The inertial devices, used as part of the rescuer MTs, are solid-state Micro-Electro-Mechanical Sensors (MEMS).

For that which concerns PILDs, the MT is connected to an RFID reader: this is the flipside of typical RFID applications, which envisages mobile tags and fixed readers, as suggested in [7]. On the other side, the RFID tags utilized UHF passive tags, which are embedded inside the emergency lamps. The tags adopted are UHF passive Omni-ID Ultra Long Range RFID tags [10], and the reader is the RFID CAEN A528 OEM UHF multi-regional compact Reader [11].

According to the operating mode of the RFID system, the reader transmits a query message. If the tag receives enough power through the query message, it replies the code stored in its internal memory. At the moment, on the base of the first release of the standard, the encoded REFIRE message is divided in two parts: a fixed one and a variable one. The fixed part, that is compulsory, includes six fields: Tag ID, Geographical coordinates (provided in WGS-84 standard), Device classification (identifies the type of device - e.g., emergency lamp, sign, etc. - and its position in the emergency area - e.g., floor, mezzanine, corridor, etc.); Tag classification (passive, semi-passive, and active tags); Accuracy (power of the electromagnetic field provided by the tag antenna); Orientation (direction of the electromagnetic field provided by the tag antenna); Date (last update of the device). The variable part is optional and includes information about relative risk and available resources.

Some tests have been carried out to set the Accuracy and the Orientation expected in the REFIRE standard message. A result of this test is reported in Fig. 2: the tag has a fixed location (i.e., the origin of the reference frame) and orientation, while the reader moves in the surroundings, changing the distance and the azimuth. The percentage of successful readings is depicted. Notice that the accuracy is substantially influenced by the environment and for this reason an average profile is adopted.

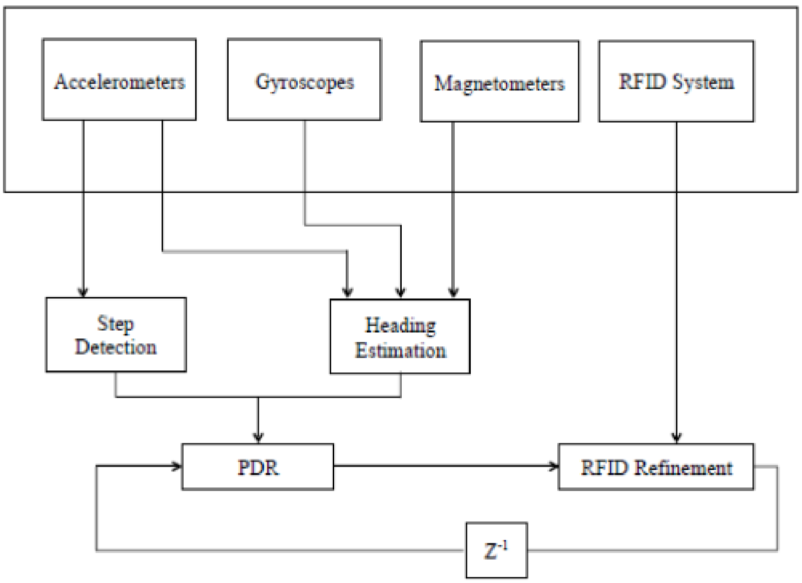
Figure 2 RFID experimental percentage of successful reading



As required by the Firefighter National Corp, the RFID reader is fixed on the chest and the IMU device is placed at pelvis level fixed to the rescuer belt with x, y and z axes pointing to the left, upward, and forward, respectively. The RLA is sketched in Fig. 3. Measurements provided by the sensory systems are pre-processed according to the results of the calibration step (for more details see [5]).

The IMU implement a Pedestrian Dead Reckoning (PDR) to estimate the heading of the rescuer in a reference frame describing the environment. The accelerations detected by IMU are used to identify the gait cycle and contribute to heading calculation. The heading is computed exploiting also data from gyroscopes and magnetometers. Once a step event is detected, it is possible to estimate the position of the rescuer. This is done using an Extended Kalman Filter which adopt quaternions, as proposed in [8] to describe the attitude of the rescuer.

Figure 3: Rescuer Localization Algorithm

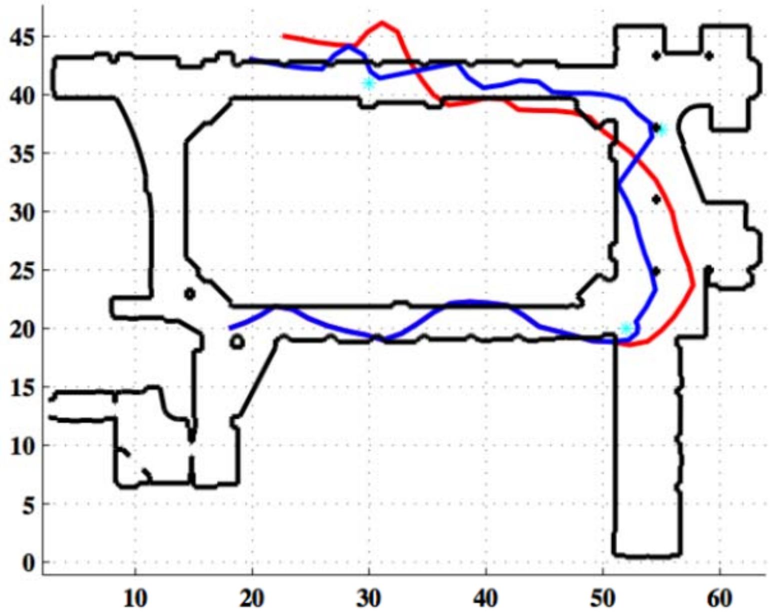


The results of EKF are also used to compute the vertical acceleration used to step detection. Each gait cycle begins with an initial contact, after which the body swings forward on a single foot. This is followed by the final contact, which marks the beginning of the double stance phase, during which both feet remain on the ground. To estimate the step length estimation initial contact each step needs to be identified by means of vertical accelerations, since gait cycles involve the rise and fall of the pelvis [9]. In this work the initial contact of each step is detected by using adaptive time windows, assuming that rescuers move slowly during mission.

The position estimated by the EKF in the prediction step is refined during RFID refinement. Upon tag detection, the reader receives data contained in the user memory. According to REFIRE protocol, the tag provides its own position, its orientation and its accuracy. Using these data, the position of the rescuer can be re-calibrated during long lasting missions. Since no ranging technique is adopted in this work, only the position of the rescuer is corrected, being the attitude is non-observable. When no information from tags is retrieved, the position is updated according PDR, since no correction can be performed.

Figure 4 provides a picture of the effectiveness of the estimation comparing those obtained using only the PDR algorithm (red line) with the RLA that also uses the presence of three RFID tags (cyan stairs) to correct the estimation (blue line). In the scenario the rescuer executed 60 steps with an overall distance travelled of 100 m. In the trials, the radiation is computed according to the results shown in Fig. 2, so the main radiation lobe is supposed to have a range r = 3 m.

Figure 3: Rescuer Localization Algorithm



Communication

Even though self-localization is an important aspect for the responder, it is more compulsory for the commander; hence the need to guarantee a constant communication among operators involved in rescue. Both wired and wireless communication techniques have different drawbacks. Cables used for wired communication dramatically reduce the mobility, while wireless devices are generally unable to penetrate large walls or underground structures.

In the REFIRE project, the MT is equipped with the capability of forwarding positioning information by means of 2G/3G/4G wireless networks (e.g., Public Land Mobile Networks (PLMNs) or Professional Mobile Radio (PMR), such as TETRA). Unfortunately, in severe test-bed scenarios, all of these solutions have been ineffective.

A different and promising solution is the use of a multi-hop strategy where a set of mobile antennas dynamically self-configure their positions to continuously guarantee communication amongst the rescue operator and a fixed base station. This kind of configuration is generally denoted as Mobile Ad-hoc NETwork (MANET) and has the peculiarity that each node operates both as a host and as a router. Therefore, any node can communicate directly with other nodes that are within its transmission range and, in order to reach a node that is out of its range, data packets are relayed over a sequence of intermediate nodes using a store-and-forward multi-hop transmission principle.

On the base of the preliminary results in [6], a specific MANET can be arranged by means of a platoon of mobile robots equipped with a wireless device (that we will call antennas) able to dynamically adapt their configuration to realize an ad-hoc network to support communication from a responder and a fixed base station.

Due to the complexity of the task, any centralised solution appears unable to manage the complexity of this mission, thus imposing the need to develop a full-decentralised solution. In other terms, the mobile robots have to autonomously form a virtual chain with each one performing a small set of elementary tasks. In [6] this goal is obtained exploiting the Null-Space-Based Control (NSB) which is a peculiar form of the behaviour-based approach. In this framework, managing a mission involving several robots with simultaneous multiple tasks, the overall mission is decomposed into elementary responsibilities (e.g., the behaviours are solved as if they were working alone and, finally, the outputs of the single tasks are combined in order to obtain the motion command for each robot).

As discussed in [12] the NSB uses a geometric, hierarchy based composition of the tasks' outputs to obtain the motion reference commands for the robot that allows the system to exhibit robustness with respect to eventually conflicting tasks. Specifically, each robot has the following elementary tasks:

- ✓ **Obstacle avoidance**. It allows avoidance of any impact of the vehicle with fixed or mobile vehicles. This task always has the highest priority;
- ✓ **Keep in communication with the next antenna**. This task keeps the antenna sufficiently close to the next one in the virtual chain. Notice that the responder represent the first antenna;
- ✓ **Keep in communication with the previous antenna**. It keeps the antenna sufficiently close to the previous one in the virtual chain;
- ✓ **Keep clear the agent path**. It allows in keeping clear the path of the agent eventually coming back toward the antennas

Except for the Obstacle Avoidance, the priority of the tasks can be dynamically arranged. The NSB allows the fulfilment of the task with highest priority, and in doing so avoids conflict with the other behaviours. Specifically, it implements only the components of the low priority tasks that are in the null space of the Jacobian of the high priority task (for more details see [6] and [12]).

The main advantage of such a distributed solution is its ability to manage unpredicted situations; such as the failure of one antenna and/or the introduction of obstacles. The robots, as experimentally illustrated in the video http://webuser.unicas.it/lai/robotica/video/MANET_SIM.avi, automatically reconfigure the chain in order to manage the updated situation. A snapshot of the video is reported in Fig. 4, where antenna number 6 faults in the third picture and becomes an obstacle, but does not affect the overall performance of the chain.

This solution has been successfully experimentally tested in a large indoor environment, illustrating the capability to create an ad-hoc network able to cover a distance of about 100 meters. Fig. 5 reports one snapshot of a mission execution with a team of five mobile robots moving in a building environment.

Figure 4: Snapshots of the simulation test in indoor-like environment

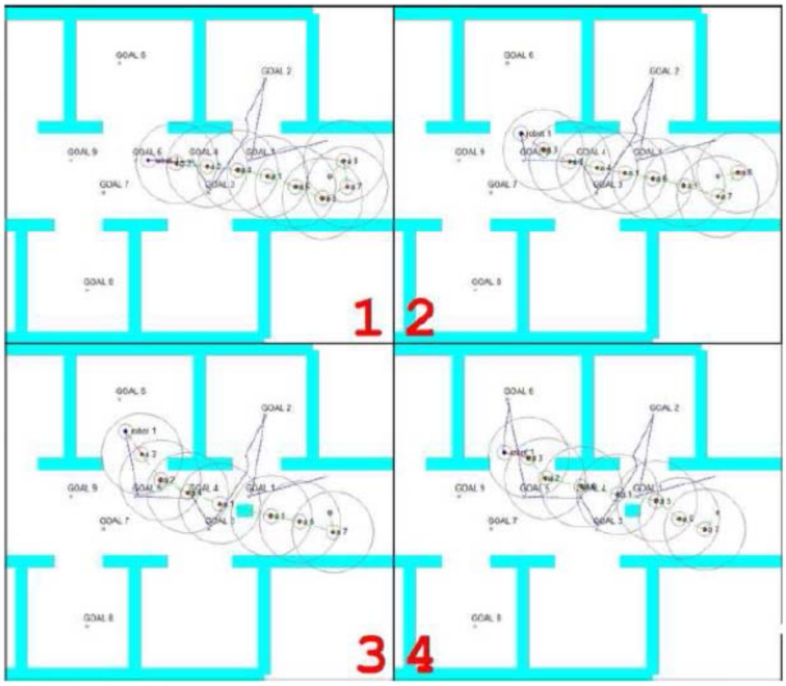
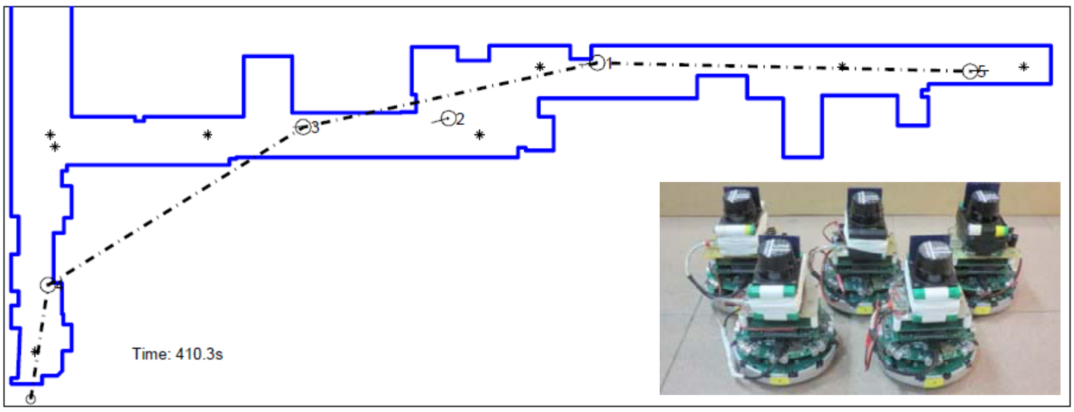


Figure 5: Snapshot of the experimental test in indoor-like environment



Discussion

To cope with the problem of localization of responders inside an emergency scenario, we propose a solution which merges the approach developed inside the REFIRE project with use of a platoon of robots, developed in the framework of the NECTAR project, able to perform autonomously an ad-hoc network which affords constant connectivity between responder and commander. This solution seems very attractive considering preliminarily experiments have demonstrated its effectiveness. To date, the main limitation is the low speed of the robot platoon, which imposes a severe constraint to the mobility of the responders.

Another important aspect to highlight is that the design of our robot was meant to carry out a different role. Indeed, in our schema, the robot represented an autonomous entity that cooperates directly with the responder inside crisis scenarios. Even if the robot is still unable to substitute the human operator, we think that the next step involves overcoming remote telecontrolled robots in order to take advantage of autonomous platforms able to support (possibly in a transparent way) the responder in performing his/her duties.

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Federica Pascucci received the "Laurea" degree in Computer Science from the University of "Roma Tre" and the Research Doctorate degree in Systems Engineering from the University of Rome "La Sapienza" in 2000 and 2004 respectively. She is with the Department of Computer Science and Automation of the University of "Roma Tre", where she is an Assistant Professor since 2005. Her research interests are in the field of industrial control systems, robotics, sensor fusion and critical infrastructure protection (CIP). Several published papers, in the robotics field, are in the area of mobile robotic localization in unstructured environment. Many techniques derived from Fuzzy Logic, Bayesian Estimation, and Dempster-Shafer Theory have been developed and applied to the problem of mapping building and vision based localization. More recently, she has been interested to search and rescue localization in highly dynamic environment using sensor networks.

Roberto Setola (1969) obtained his Master of Science in Electronic Engineering (1992) and PhD in Electronic Engineering and Computer Science (1996) from The University of Naples Federico II. Currently, he is a professor of Automatic Control at University CAMPUS BioMedico and head of the COSERITY Lab (Complex Systems & Security Lab). He is also the director of the Master's program for 'Homeland Security, Systems and methods and tools for security and crisis management'. Formerly a member of the Italian Prime Minister Office (1999-2004), Mr. Setola was the coordinator of the working-group on Critical Information Infrastructure Protection established by the Italian Prime Minister (2003-2004). Since 1992, , in collaboration with several universities and research centres, he has performed studies on modelling, simulation and control of complex networks and systems and the protection of critical infrastructures. He has co-authored 3 books, edited 3 books, been a guest editor of 3 special issues on international journals, and co-authored roughly 130 scientific publications.