An Enhanced Indoor Positioning System for First Responders

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***Abstract*—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 knowledge for incident commander. In this work both localization and tracking for rescuers are addressed in the framework of REFIRE project. The designed positioning system is based on the well-known prediction-correction schema adopted in field robotics. Proprioceptive sensors, i.e., inertial sensors and magnetometer, mounted on the waist of the rescuers, are used to form a coarse estimation of the locations. Due to the drift of inertial sensors, the position estimate needs to be updated by exteroceptive sensors, i.e., RFID system composed by tags embedded in the emergency signs as exteroceptive sensors and a wearable tag-reader. In long-lasting mission RFID tags reset the drift by providing a positioning having room-level accuracy.**

***Keywords*—Situation aware tracking algorithms, Hybrid sensor fusion, Systems integrating Inertial Measurement Units (IMU), Step length estimation, RFID waypoint guidance**

I. INTRODUCTION

Team localization and tracking in rescue scenarios open new prospects both to increase safety and also to decrease mission time: localized rescue personnel can be better coordinated, commanded and guided. Moreover a reliable localization system reduces the possibility of disorientation and failure to locate victims, which are contributing factors to rescuer deaths.

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 [17]. In the same year, in US six firefighters were killed for the same reason in the Worcester Cold Storage Warehouse fire [23]. 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 underlying 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 [10] and [11]:

- 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 a emergency responder body worn integrated electronics system as first issue for the industry in its R&D priority report. This system should integrate enhanced communication capabilities, locations and tracking capabilities, situational awareness and environmental sensing capabilities, physiological status monitoring capabilities.

In this paper the localization and tracking problems for first responders are addressed in the framework of REFIRE project [16]. The designed Rescuer Localization Algorithm (RLA) is based on the well-known prediction-correction schema adopted in field robotics. Pedestrian dead reckoning using inertial measurement is used to form a rough estimate of rescuer position. To improve the results of the prediction step, a deep analysis of the devices used is carried out. Specifically to reduce the drift in the estimate, an accurate calibration based on IEEE standard is performed on IMU. Using bias and scale estimated in the calibration, the heading, represented by quaternions of the rescuer is recursively computed by an Extended Kalman Filter. The step is detected by an online learning algorithm based on Rayleigh oscillator and able to identify a gait-cycle: once a gait cycle is isolated, the length of the step is computed. Although some promising results have been retrieved using the proposed pedestrian dead reckoning, the position estimate degrades in time due to the remaining drift that affect the inertial sensors. Hence, in long-lasting mission it is mandatory the use of the pre-deployed RFID tags: they reset the drift providing a positioning having room-level accuracy.

The paper is organized as follows: Section II provides a literature review on personnel localization; Section III sketches the framework of REFIRE, the accuracy of the devices used for localization is discussed in Sec. IV; the positioning system is detailed in Sec. V; the results of the proposed algorithm for indoor localization are reported and in Sec. VI; finally, some conclusion remarks are collected in Sec. VII.

II. Related Works

Firefighters have developed navigation practices for use in poor visibility. All these methods tend to be simple and practical, exploiting low-tech and robust equipment. Although these simple and practical methods become more effective with training, they are prone to fail. To this end, researchers have built location systems around a variety of technologies.

The Personal Navigation System (PeNa) [20] of the PeLoTe projects [7] is designed to be a stand-alone high-tech localization system. The position estimate is achieved by dead reckoning and map-based localization. The PeNa is a fully portable system, built around a standard hiking backpack. The total weight of the system is approximately 14 kg without the laptops and represents a proof-of-concept: PeNa hardware is incompatible with both rescuer equipment and indeed operating conditions.

More recently Globe developed WASP, a Wearable Advanced Sensor Platform [22]. This body-worn system integrates physiological monitoring and location tracking into a single system that collects, transmits, and displays user data to a command station. The Physiological Status Monitoring (PSM) system tracks in real time firefighter heart rate, respiration, activity levels and other physiological factors. The PSM sensor is on a strap housed within a fire resistant T-shirt. The location tracking system is worn on a belt under the firefighter's turnout gear. The accuracy of the localization system is not available.

A different approach comprises Wireless Sensors Networks (WSN) to track rescuer in deep indoor environment. In the FIRE project a WSN called SmokeNet [26] is adopted to track first responders while operating in large building incidents, and supply key information to all parties involved. The FIRE rescue architecture provides also several additional features. The information retrieved by SmokeNet are shown on a head-mounted display and sent to the incident commander. Localization is performed by exploiting beacon devices that constantly broadcast static information. Personnel carry a first responder device that listens for beacon transmissions and computes its position by fingerprinting.

The Precise Personnel Location System is a localization system based on radio frequency signals and inertial sensor supplementation. The system assumes no existing infrastructure and no pre-characterization of operation area. To be tracked, first responders and other emergency personnel carry a transmitter emitting a multi-carrier wide-band signal, which is sensed at receiving stations fixed upon emergency response vehicles. The receiving stations are deployed outside the emergency area in order to form an ad-hoc network.

A similar approach is assumed in EUROPCOM project [5]: base units, mounted on emergency service vehicles and equipped with Global Navigation Satellite System (GNSS) receivers provide a reference network; mobile units, carried by rescuers, determine their own position within the building and send the information to the control unit. To prevent the lost of connectivity, emergency personnel carries additional dropped units to be released during mission.

Ultrasound beacons deployed by rescuers are used in LifeNet system [6], which provides the functionality of a traditional lifeline. The remaining elements of LifeNet implementation are a wearable computer able to receive positioning information from the beacons integrated with the boots and a micro-display integrated in the breathing mask to present navigational information.

Self–deployable passive beacons are considered in EU Project LIAISON [19]. While progressing indoor, the first responders deploy passive RFID tags that are used to correct the large errors affecting MEMS performances by Bayesian filter. The first team of first responders attaches tag each time it passes a door. RFID are also placed when changing floor, both at the beginning and at the end of the stairway. Upon installation, the geographical coordinates of the tag are associated with the tag ID. The second team of rescuers benefits from the deployed RFID tags. The first responders need only to be equipped with an RFID reader. A similar approach can be found in [28], where a robotic team exploring a disaster area is considered. The exploration is conducted in two phases. In the first step, the robots autonomously explore an unknown cellar environment while successfully deploying RFID tags. In the second step, the robots explore again to explore the same environment, taking advantage of the previously deployed tags.

The Hybrid Rescue Teams Localization System (HRTLS) [14], [15] considers rescue team composed by both human operators and robots. The localization module of the system is based on Flipside [8] proposed by the US National Institute of Standards and Technology (NIST) [9]. Hybrid team uses pre-deployed RFID tags embedded in emergency signs, extinguishers, and emergency lamps to correct dead reckoning. PDR is performed using commercial smartphone equipped with inertial sensors. The RFID tags are static, while first responders and robots wear the mobile readers. The reader range and the distance between tags are the key parameters: a long range will give only approximate locations, but a short range will miss tags. To validate the approach tags providing information in about 2 m range is considered. The deployment effort is negligible, with a considerable cost in map maintenance. The localization system, however, is reliable, since it is based on an Bayesian adaptive filter able to solve both localization and Simultaneous Localization And Map building problem (SLAM) when changes occur in the environment. The main goal of HRTLS is to create location awareness for both the supervisor and the rescuers inside the emergency area. HRTLS provides also several additional features: redundant communication channels are sketched in the architecture to share information between the hybrid team and the supervisor; inertial sensors are used to identify rescuers in distress. The major limitation of HRTLS stems in the implementation: it has been tested only by simulation and still needs to be validated in a real emergency situation.

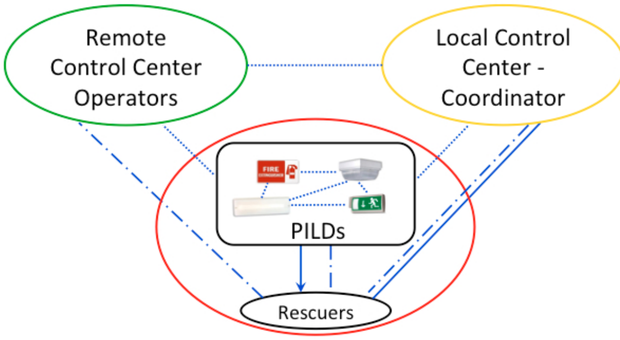


Fig. 1. Communication between REFIRE users according to the implementation levels: lines represent redundant links.

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 during emergencies due to the 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 these environments, indeed, localization fail 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 these researches 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 different devices. Interoperability is indeed guarantee only by adopting a highly standardized protocol and devices. The definition of those standards is the main focus of REFIRE project.

III. REFIRE FRAMEWORK

Most of the proposed solutions for localization and tracking in GPS-denied environment are based on proprietary infrastructures deployed in the environment. These different proprietary systems cannot interoperate with the specific devices used by the rescuers; hence, there is a strong need to develop standard communication and localization protocols. To this end, the target of the REFIRE project is to define an interoperating localization protocol to anticipate the proliferation of unfitting proprietary localization systems. The main outcome of REFIRE is a proof-of-concept implementation, referred to as *reference implementation*. Moreover, a first set of industrial prototypes will be developed and tested, in order to validate the commercial viability of the protocol set out by the project. The validation of both the reference implementation and the pre-industrial prototypes in complex trials should further demonstrate the effectiveness of the approach, eventually boosting an early adoption of integrated tools and devices at European level.

The overall 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 pre-installed 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. Outside the emergency area the operators of the Remote Control Centre (RCC) support and coordinate the mission.

The localization system 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. To this end, the MT is connected to an RFID reader: this is the flipside of the typical RFID applications, which envisages mobile tags and fixed readers, as suggested in [8]. The MTs should be able to provide a room-level accuracy localization during extended missions and to forward positioning information to the CC by means of 2G/3G/4G wireless networks (e.g., Public Land Mobile Networks (PLMNs) or Professional Mobile Radio (PMR), such as TETRA). In such a way, the CC can collect and process positioning-data in order to track and guide rescuers during missions involving indoor or unknown locations, hence improving situational awareness so as to enhance rescuers safety and rescue efficiency. The same information can be sent to the RCC.

The REFIRE localization system is designed to reduce the dependence on wireless links to external data sources by exploiting the capability of RFID tags to store critical up-to-date building information for local retrieval. The main objective of the REFIRE project is then to identify the minimal set of information to be exchanged between the RFID tags and the MTs during emergency operations and build a standard protocol around it. At the moment, the first release of the standard is available. According to it, the REFIRE message is encoded in the user memory of the RFID tags. The standard message is divided in two parts: a *fixed* one and a *variable* one.

The fixed part, that is compulsory, includes six fields, while the variable part is still to be defined and is optional. Binary coding of information is adopted to save user memory space. The six fields of the fixed part of the REFIRE message are: *REFIRE identification*; *Geographical coordinates* (provided adopting the WGS-84 standard for cartography, geodesy, and navigation); *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 effectiveness of this version of the standard is currently under evaluation. In these tests, passive UHF RFID tags and wearable readers have been evaluated. An industrial implementation, the RLA, has been developed using the prediction - correction schema of robotic localization. To this end proprioceptive sensors, i.e., an Inertial Measurement Unit, is used to track rescuer. The position is refined by exteroceptive sensor, represented by REFIRE PILDs. Some preliminary results on localization have been obtained and have to be investigated to provide inputs for the second release of the REFIRE standard.

TABLE I. iNEMO SPECIFICATIONS

Gyroscopes	
Range Roll, Pitch, Yaw [deg/s]	± 300 [deg/s]
Resolution [deg/s]	<0.05 [deg/s]
Accelerometers	
Range X/Y/Z	± 2 [g]
Resolution	<0.25 [mg]
Magnetometers	
Range X/Y/Z	±8 [G]
Resolution	<0.25 [mG]
Physical	
Size	4×4 [cm]
Weight	30 [g]
Update Rate	100 [Hz]

IV. DEVICES FOR POSITIONING SYSTEM

The localization system used in the industrial implementation of REFIRE project is based on several technologies. Accelerometers, gyroscopes and magnetometers determine the position and the heading of a moving rescuer. To this end an Inertial Measurement Unit (IMU) is considered. It consists of 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). MEMS devices offer potentially significant cost, size, and weight advantages, which have resulted in a proliferation of the applications where such devices can be used in systems. Apart from the consumer and automotive sectors, that represent the principal market, MEMS inertial sensors can also provide navigation solution in different environments (i.e., forestry roads, town centers and tunnels). If there is no doubt that MEMS technologies represents an interesting turning point for low cost inertial based sensors and applications, nevertheless it is mandatory to deeply investigate the behavior of these MEMS sensors by test calibration.

According to the robotic approach, the positioning provided by IMU can be further improved by means of exteroceptive sensor, able to provide information from the surroundings. In our positioning system these sensors are represented by passive tags (i.e., the PILDs) deployed in known location in the environment. To evaluate the effectiveness of the approach, some tests have been carried out in order to estimate the accuracy of the wearable RFID reader.

A. Inertial Measurement System

In this work the iNEMO STEVALMKI062V2 platform has been considered as part of MT unit. It combines accelerometers, gyroscopes and magnetometers with pressure and temperature sensors to provide 3-axis sensing of linear, angular and magnetic motion, complemented with temperature and barometer/altitude readings. In this work only accelerometers, gyroscopes and magnetometers have been exploited. The specifications of these sensors in iNEMO platform are summarized in Tab. I.

All those sensors have been involved during the experiments, estimating the random walk component following the IEEE Std 952–1997 procedures [1]. For both accelerometers and gyroscopes, the largest errors are usually bias instabilities (measured in deg/s for the gyro bias drift, or mg for the accelerometer bias), and scale factors. Bias and scale factors

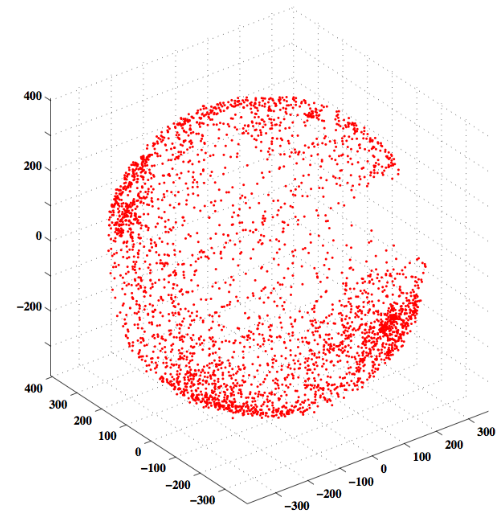


Fig. 2. Magnetometer ellipsoid.

TABLE II. BIAS AND SCALE FACTORS FOR ACCELEROMETERS AND GYROSCOPES

Parameters	Accelerometer	Gyroscopes
Bias x	-0.67 [mg]	-0.003 [deg/s]
Bias y	-8.03 [mg]	0.005 [deg/s]
Bias z	4.72 [mg]	-0.002 [deg/s]
Scale Factor x	0.01%	0.01%
Scale Factor y	.001%	0.01%
Scale Factor z	0.01%	0.01%

can be estimated by the well known six-position static test method [1]. This method requires the inertial system to be mounted on a leveled table with each sensitive axis pointing alternately up and down. For a triad of orthogonal sensors this results in a total of six positions. The bias b_i^j can be computed as

$$b_i^j = \frac{\hat{m}_{i\uparrow}^j + \hat{m}_{i\downarrow}^j}{2} \tag{1}$$

where $\hat{m}$ is the mean value of the measurements retrieved from sensor $j \in \{a, w\}$ along the i-th axis ($i \in \{x, y, z\}$), upward ($\uparrow$) downward ($\downarrow$). Scale (S) factors can then be calculated according to the following equations:

$$S_i^j = \frac{\hat{m}_{i\uparrow}^j + \hat{m}_{i\downarrow}^j - 2K}{2K}$$

where the value K is a known reference signal. For accelerometers, K is the local gravity constant and for gyroscopes it is the magnitude of the earth rotation rate at the given latitude. It is worth mentioning that the earth rotation rate can only be used for navigation and tactical grade gyroscopes, since low grade gyroscopes such as MEMS suffer from bias instability and noise levels that can completely mask the earth reference signal. To further improve the estimation of scale factors for gyroscopes, also the angle rate test has been performed using a professional record player as turntable. The scale factor can be retrieved by rotating the table through a defined angle rate ω in both the clockwise $\omega_{i,cl}^w$ and counter clockwise $\omega_{i,ccl}^w$

$$S_i^w = \frac{\hat{\omega}_{i,cl}^w + \hat{\omega}_{i,ccl}^w}{2\omega}$$

The results of these tests are reported in Tab. II.

TABLE III. TAG AND READER SPECIFICATIONS

Tags	
Frequency	$860 \div 960$ [MHz]
Temperature	$-40°C \div +65°$[C]
EPC	96 [bits]
User Memory	512 [bits]
Reader	
Transmission power	500 [mW]
Frequency	867.6 [MHz]
Temperature	$-20°C \div +60°$[C]

The six-position calibration accuracy depends on how well the axes are aligned with the vertical axes of the local level frame: this standard calibration method can be used to determine the bias and scale factors of the sensors, but cannot estimate the axes misalignments (non-orthogonalities). To estimate the non-orthogonalities, not considered here, an improved six-position test can be performed which takes into account all three types of errors.

The main sources of magnetic distortion are scaling and bias, wide-band noise, hard/soft iron bias. As shown in [24], a calibration procedure is able to alleviate the effects of these disturbances. The magnetometer calibration problem can be recast into a unified transformation parametrized by a rotation R, a scaling S, and an offset b. Consequently, it can be shown [24] that, for all linear transformations of the magnetic field, the magnetometer readings will always lie on an ellipsoid manifold (see Fig. 2). A maximum likelihood estimator can be used to find the optimal calibration parameters which maximize the likelihood of the sensor readings. The calibration algorithm is derived in the sensor frame and does not require any specific information about the magnetic fields magnitude and body frame coordinates. This allows for magnetometer calibration without external aiding references.

B. RFID system

The tags adopted in this work are UHF passive Omni-ID Ultra Long Range RFID tags [12], the reader is he RFID CAEN A528 OEM UHF multi-regional compact Reader [2]. The tag are designed for outdoor applications: they are installed inside an ABS chassis so can be directly mounted. 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. Finally, the reader can receive the tag code if enough power is detected by its antenna. In such a case, the communication between the reader and the tag is successfully performed. Thus, main parameters to depict the RFID system are the distance d between the reader and a tag, the azimuth θ, and elevation angles φ.

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. 3: 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, the azimuth and the elevation. The percentage of successful readings is depicted.

The performed test pointed out that the main radiation lobe of the RFID system has a range $r = 3$ m and an angle $\alpha = 120°$.

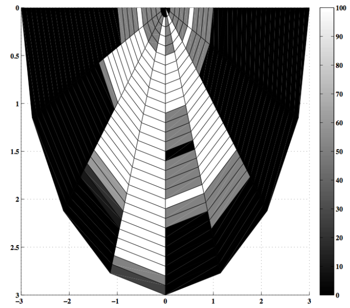


Fig. 3. Percentage of successful readings.

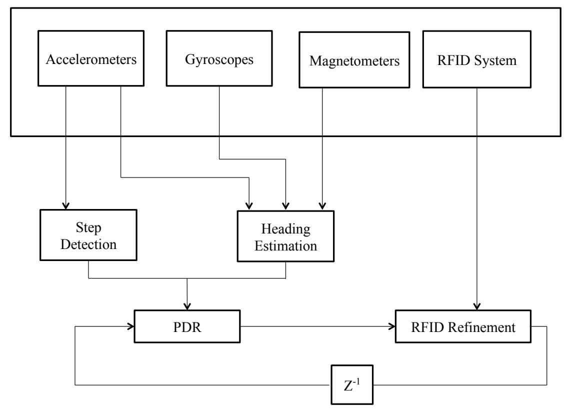


Fig. 4. Rescuer Localization Algorithm.

V. RESCUER LOCALIZATION ALGORITHM

The Rescuer Localization Algorithm (RLA) exploits both iNemo and RFID data to estimate the position of a rescuer. As required by Firefighter National Corp, the RFID reader is fixed on the chest and the iNemo 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. 4. Measurements provided by the sensory systems are pre-processed according to the results of the calibration step described in the previous section. 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, that is corrected by RFID measurements when available. In the followings the Pedestrian Dead Reckoning (PDR) and the RFID refinement are detailed.

A. Pedestrian Dead Reckoning

The PDR provide the location and the heading of the rescuer in a reference frame describing the environment. The heading is computed by an Extended Kalman Filter; the attitude of the rescuer is described by means of quaternions, as proposed in [21]. In the prediction step, the control input u_k is obtained by gyroscopes measurements and the state transition is computed as follows

$$\hat{x}_{k|k-1} = f(\hat{x}_{k-1|k-1}, u_k) = \hat{x}_{k-1|k-1} \otimes r_k \tag{2}$$

where x_k is the quaternion and r_k represents the spatial rotation during the quaternion space in the sampling interval $[k-1,k]$. The covariance matrix of the prediction step is computed as

$$P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k \tag{3}$$

where F_k is the Jacobian of the state transition map and Q_k represent the process noise.

The observation vector is represent by the measurements from both magnetometers and the accelerometers. The expected measurement from accelerometers can be computed according to the following equations

$$a = h_a(\hat{x}_{k|k-1}) = K_a \mathbf{R}(\hat{x}_{k|k-1}) g \tag{4}$$

where $a = [a_x, a_y, a_z]^T$ represents the acceleration in the body frame, K_a is the scale factor matrices, $\mathbf{R}$ is the rotation matrix from body frame to reference frame, and g is the gravity.

The expected measurement from magnetometers can be computed according to the following equations

$$m = h_m(\hat{x}_{k|k-1}) = K_m \mathbf{R}(\hat{x}_{k|k-1}) h \tag{5}$$

where $m = [m_x, m_y, m_z]^T$ represents the magnetic field in the body frame, K_m is the scale factor matrices and h is the Earths magnetic field.

It is worth underlying that data from accelerometers can be used only when the rescuer is still, otherwise the gravity cannot be compensated. Moreover a validation gate based on Mahalanobis distance [13] is set up to discharge magnetometers outliers due to soft or hard iron distortions.

The correspondent covariance matrix is given by

$$S_k = H_k P_{k|k-1} H_k^T + V_k \tag{6}$$

where H_k is the Jacobian of $h(\cdot) = [h_a^T(\cdot), h_m^T(\cdot)]^T$ and V_k is the covariance matrix of the measurements. The estimate update in the correction step is given by

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k[z_k - h(\hat{x}_{k|k-1})] \tag{7}$$

where $K_k = P_{k|k-1} H_k^T S^{-1}$ is the Kalman gain and the covariance is

$$P_{k|k} = (I - K_k H_k) P_{k-1|k}. \tag{8}$$

The output of the heading EKF is 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 identify by means of vertical accelerations, since gait cycle involves the rise and fall of the pelvis [27]. In this work the initial contact of each step is detected by using adaptive time windows, assuming that rescuers move slowly during mission. Finally the step length is computed as

$$l = \beta \sqrt[4]{a_M - a_m} \tag{9}$$

where a_M and a_m are the maximum and minimum vertical acceleration during gait cycle and β is a parameter depending on the rescuer that has to be set experimentally [25].

B. RFID refinement

The position estimated in the prediction step is refined during RFID refinement. Upon tag detection, 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 mission. Since no ranging technique is adopted in this work, only the position of the rescuer is corrected, being the attitude non-observable. When no information from tags are retrieved, the position is updated according PDR, since no correction can be performed. If a rescuer is in the main radiation lobe, the reader receives information from tag and the position is updated according to different strategies encoded in the following rules:

Rule 1 *Condition:* PDR estimates the position of rescuer near the main radiation lobe and the tag reader perceives the tag i;
Action: the position is re-calibrated on the edge of coverage area and the values on the leading diagonal of the covariance matrix is slightly decreased;

Rule 2 *Condition:* PDR estimates the rescuer is inside the main radiation lobe of a tag i and the tag reader continuously perceives the tag i;
Action: the position $\hat{p}_r^c$ is updated according to the following equation

$$\hat{p}_r^c = \gamma \hat{p}_r^p + (1-\gamma) p_i \tag{10}$$

where p_r^p is the position of the rescuer during prediction, p_i is the center of the main radiation lobe of tag i and $\gamma \in [0, \dots, 1]$ is a weight determined by the prediction covariance;

Rule 3 *Condition:* PDR estimates the rescuer is inside the main radiation lobe of q tags and the tag reader perceives r tags;
Action: the position $\hat{p}_r^c$ is updated according to the following equation

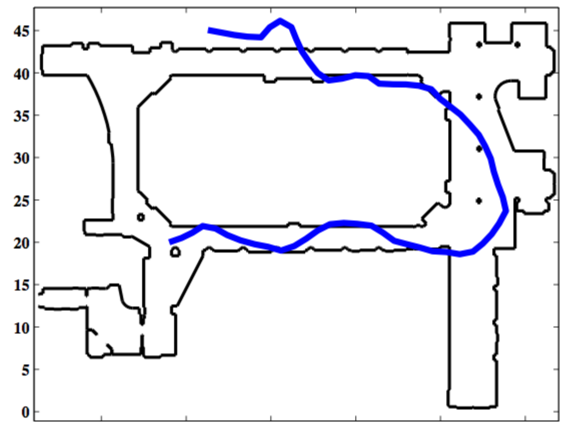
$$\hat{p}_r^c = \gamma_0 \hat{p}_r^p + \gamma_1 p_i^1 + \dots + \gamma_r p_i^r \tag{11}$$

where γ_i are weights so that $\sum_{i=0}^r \gamma_i = 1$ and are determined by the prediction covariance and the accuracy of the tags;

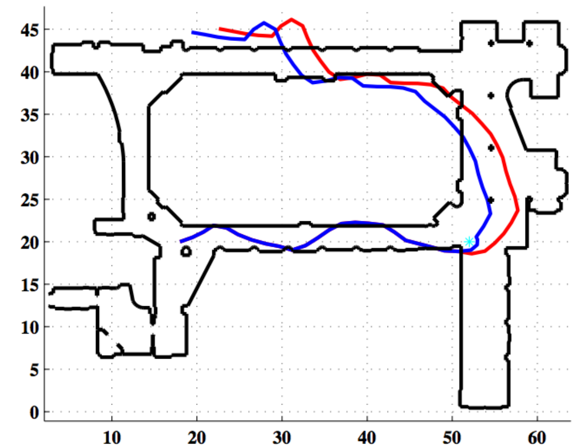
Rule 4 *Condition:* PDR estimates rescuer is far from the main radiation lobe of a tag i and the tag reader perceives the tag i;
Action: the position is reset on p_i and the values on the leading diagonal of the covariance matrix is slightly decreased.

VI. Experimental Results

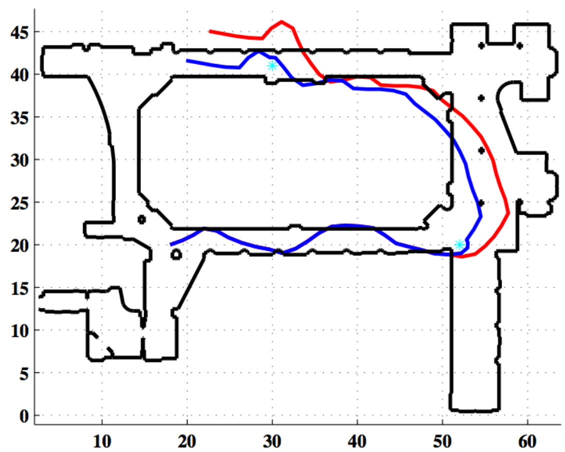
Several experimental tests have been carried out to prove the effectiveness of the RLA in REFIRE framework. Specifically we consider an office like environment compose by a long corridor. During the experiment, the rescuer is equipped with a waist-worn iNemo device connected to a laptop PC by high speed USB. The CAEN RFID reader is connected to the same laptop via Bluetooth. The sampling frequency of the iNemo is 100 Hz, the one of RFID reader is 5 Hz, and a



(a) Path estimated by PDR.



(b) Paths estimated by PDR (red) and path corrected (blue) by 1 tag (cyan star).



(c) Path estimated by PDR (red) and path corrected (blue) by 2 tags (cyan stars).

(d) Path estimated by PDR (red) and path corrected (blue) by 3 tags (cyan stars).

Fig. 5. Indoor results in office like environment.

step is detected at 1 Hz. To this end, a synchronization step is performed to align data on time.

Here, the results of a penetrating mission along the corridor are presented: data collected during the experiment have been post-processed using MatLab. The rescuer execute 60 steps overall distance traveling up to 100 m.

The results of the experiment are shown in Fig. 5. Specifically, figure 5(a) shows the path of the rescuer computed without RFID corrections. It can be noticed that PDR is not suitable by itself for deep indoor localization. The positioning errors grow along the path and at the end of the experiment the accuracy is highly downgraded: the rescuer is located in a room nearby the corridor and this information can compromise his safety.

To understand the impact of RFID corrections, several configurations have been examined. Specifically, an increasing number of RFID tags deployed in the environment is considered. In these trials, the radiation is computed according to the results shown in Fig. 3, so the main radiation lobe is supposed to have a range $r = 3$ m. At the beginning of the path, no RFID tags are available, so the localization is obtained by PDR accumulating drift and errors. This error is removed by tag 1, however in Fig. 5(b) the position estimate is not suitable, since the maximum positioning error (5 m) does not allow room level accuracy. The performance suitably increase using 2 tags (see Fig. 5(c)), however the maximum positioning error (4 m) is still to high to be exploited in emergency scenario. Adding the last RFID tags, the target performance is achieved, as shown in Fig. 5(d). It is worth noticing that RFID tags are located in crossway (tags 1 and 2) or nearby doors (tag 3), as expected using tags embedded in emergency signs. Moreover, the emergency signs deployed in the corridor are more than the subset considered in this experiment, so the accuracy of the RLA can be further improved.

VII. Conclusion

This paper proposes the localization and tracking systems for first responders in the framework of REFIRE project [16]. The designed positioning system borrows its key idea from robotic localization, since it is based on the well-known prediction-correction schema. Proprioceptive sensors, i.e., an IMU and a triad-magnetometer are used to form a rough estimate of rescuer position in the prediction step. Exteroceptive sensors, i.e., RFID tags and readers, are used in the correction step.

Specifically to reduce the drift in the prediction estimate, an accurate calibration based on IEEE standard is performed on IMUs. Using bias and scale provided by the calibration, the orientation of the rescuer is retrieved by using Extended Kalman Filter based on quaternions. An online learning algorithm based on time windows and able to identify a gait-cycle detects the step: once a gait cycle is isolated, the length of the step is computed. The obtained results are not suitable for rescuer positioning, since the position estimate degrades in time due to the remaining drift that affect the inertial sensors. Hence, in long-lasting mission it is mandatory the use of the pre-deployed infrastructure able to bound the estimation drift of PDR. The pre-deployed network allows to achieve room level accuracy using a limited number of tags, as experimentally shown.

Future works will be devoted to improve the pedestrian dead reckoning in different ways: first of all non-orthogonalities have to be considered in the calibration of IMU; the step detection needs to be improved, since time windows are prone to fail in face of irregular movements, moreover there is the need to include the detection of different activities (i.e., running, ascending/descending stairs, standing still, etc.). In the correction step, the use of semi-passive and active tags has to be deeply analyzed to exploit the feature of these devices.

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REFERENCES

[1] P. Aggarwal, Z. Syed, X. Niu, and N. El-Sheimy, "A standard testing and calibration procedure for low cost mems inertial sensors and units", *The Journal of Navigation*, 61:323336, 3, 2008.

[2] CAEN A528 OEM UHF multiregional compact reader datasheet. Available: http://www.caenrfid.it/rfid/syproduct.php?fam=sread&mod=A528#

[3] M. Carli, S. Panzieri, F. Pascucci, "A joint routing and localization algorithm for emergency scenario", *Ad Hoc Networks*, Elsevier, 2012.

[4] R. J. Duckworth, "WPI Precision Personnel Location (PPL) System", *Proc. of the Fifth IEEE Consumer Communications & Networking Conference*, 2008.

[5] D. Harmer, M. Russell, E. Frazer, T. Bauge, S. Ingram, N. Schmidt, B. Kull, A. Yarovoy, A. Nezirovic, L. Xia3, V. Dizdarevic, and K. Witrisal, "EUROPCOM: Emergency Ultrawideband RadiO for Positioning and COMmunications", *Proc. of the 2008 IEEE Int. Conf. on Ultra-Wideband*, 2008.

[6] M. Klann, "Tactical Navigation Support for Firefighters: The LifeNet Ad-Hoc Sensor-Network and Wearable System", *Mobile Response*, Springer, 2009.

[7] M. Kulich, J. Kout, L. Preucil, R. Mazl, J. Chudoba, J. Saarinen, J. Suomela, A. Halme, F. Driewer, H. Baier, K. Schilling, N. Ruangpayoongsak, and H. Roth, "PeLoTe a Heterogeneous Telematic System for Cooperative Search and Rescue Missions", *Proc of the 2004 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, 2004.

[8] L.E. Miller, "Indoor Navigation for First Responders: A Feasibility Study", *tech. report, US Natl Inst. Standards and Tech.*, 2006.

[9] L. E. Miller, P. F. Wilson, N. P. Bryner, M. H. Francis, J. R. Guerrieri, D. W. Stroup, and L. Klein-Berndt, "RFID-Assisted Indoor Localization and Communication for First Responders", *Proc. of the First European Conference on Antennas and Propagation*, 2006.

[10] NIOSH, "Fatality Assessment and Control Evaluation Investigation Report # F2007-19", available at *http://www.cdc.gov/niosh/fire/pdfs/face200619.pdf*, June 2007.

[11] NIOSH, "Fatality Assessment and Control Evaluation Investigation Report # F2007-18", available at *http://www.cdc.gov/niosh/fire/pdfs/face200718.pdf*, February 2009.

[12] Omni-ID Ultra Long Range RFID Tag datasheet. Available: http://www.rfidtags.com/documents/product/Omni-ID-Ultra-RFID-Tag-DataSheet.pdf

[13] S. Panzieri, F. Pascucci, and R. Setola, "Simultaneous Localisation and Mapping of a Mobile Robot via Interlaced Estended Kalman Filter",*Int. Journal of Modelling Identification and Control (IJMIC)*, 2008.

[14] F. Pascucci, R. Setola, "An Adaptive Localization System for First Responders", *Proc. of the 1st Int. Conf. on Wireless Technologies for Humanitarians Relief (ACWR)*, 2011.

[15] F. Pascucci, R. Setola, "An Indoor Localization Framework for Hybrid Rescue Teams", *Proceedings of the 18th IFAC World Congress*, 2011.

[16] F. Pascucci, S. Panzieri, R. Setola, G. Oliva, S. Marsella, M. Marzoli, U. Delprato, G. Borelli, M. Carpanelli, "A REference implementation of interoperable indoor location & communication systems for First REsponders: The REFIRE project", *IEEE Int. Symp. on Safety, Security, and Rescue Robotics (SSRR)*, 2012

[17] PSCE Secretariat, "Report PSCE Conference in Rome 2012", available at: http://www.heli4rescue.eu/downloads/, 2012.

[18] L. Preucil, J. Pavlicek, R. Mzl, F. Driewer, and K. Schilling, "Next Generation Human-Robot Telematic Teams", *AAAI Spring Symposium: Multidisciplinary Collaboration for Socially Assistive Robotics*, 2007.

[19] V. Renaudin, O. Yalak, P. Tom, and B. Merminod, Indoor Navigation of Emergency Agents, *European Journal of Navigation*, Vol. 5, No 3, 2007.

[20] J. Saarinen, S. Heikkila, M. Elomaa, J. Suomela, and A. Halme, "Rescue personnel localization system", *Proc of IEEE International Workshop on Safety, Security and Rescue Robotics*, 2005.

[21] A.M. Sabatini, "Quaternion-based extended kalman filter for determining orientation by inertial and magnetic sensing", *IEEE Tran. on Biomedical Engineering*, 2006.

[22] D.L. Smith, J.M. Haller, E.M. Hultquist, W.K. Lefferts, and P.C. Fehling, "The Station Uniform Shirt : Does it play a role beyond appearance?", *Firehouse magazine*, 2013.

[23] U.S. Fire Administration, Abandoned Cold Storage Warehouse Multi-Firefighter Fatality Fire Worcester, USFA-TR-134, 1999.

[24] J.F. Vasconcelos, G. Elkaim, C. Silvestre, P. Oliveira and B. Cardeira, "A Geometric Approach to Strapdown Magnetometer Calibration in Sensor Frame", *Proc. of the IEEE Int. Conf. on Robotics and Automation (ICRA)*, 2008.

[25] H. Wienberg, "Using the ADXL202 in Pedometer and Personal Navigation Applications", *Analog Devices AN-602 application note*, 2002.

[26] J. Wilson, V. Bhargava, A. Redfern, and P. Wright, "A Wireless Sensor Network and Incident Command Interface for Urban Firefighting", *Proc. of the 4th Ann. Intl Conf. Mobile and Ubiquitous Systems: Networking & Services*, 2007.

[27] W. Zijlstra, "Assessment of spatio-temporal parameters during unconstrained walking", textitEuropean Journal of Applied Physiology, vol. 92, pp. 39–44, 2004.

[28] V.A. Ziparo, A. Kleiner, B. Nebel, and D. Nardi, "RFID-Based Exploration for Large Robot Teams", In *Proc. of the IEEE Int. Conf. on Robotics and Automation (ICRA)*, 2007.