A Novel First Responders Location Tracking System: Architecture and Functional Requirements

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***Abstract*—The aim of the SAFESENS (Sensor Technologies for Enhanced Safety and Security of Buildings and its Occupants) project is to obtain earlier and more reliable fire detection, along with accurate occupancy detection and first responders' health condition and indoor location monitoring. In this paper, an analysis of the requirements requested by the tracking system is shown, together with an overview of the exploitable technologies and the current state-of-the-art. A novel system architecture, mainly based on UWB, inertial sensors, barometer and Bluetooth Low-Energy (BLE), is proposed also showing some preliminary results regarding the chosen technologies. The final system will be shown in several real-case applications on successful completion of the project.**

Keywords—Ultra-wideband; Inertial sensors; Localization; Firefighters

I. INTRODUCTION

The inhalation of smoke and toxic gases due to indoor fires affects more than 100,000 people in Europe every year. Some of these gases are undetectable by humans and may cause long-term injures. Many of the existing fire safety systems are designed to detect and respond only to smoke and heat. However, these elements are mainly present during the latter stages of the fire cycle when the silent gas killers have been already released. In addition, current fire cells are based on expensive optical detectors, have large form factor and do not provide information about the location of people in the flaming building. Nonetheless, firefighters constantly put their lives at risk. Hence, these workers should be equipped with reliable, wearable personal health monitors, which are able to detect multiple hazardous gases at low concentrations, monitor person's health conditions and track its indoor locations.

SAFESENS (Sensor Technologies for Enhanced Safety and Security of Buildings and its Occupants) is an ENIAC JU project [1] whose goal is to obtain earlier and more reliable fire detection, along with accurate occupancy detection and first responders monitoring, by co-integrating new multiple (wearable and not) gas sensor, presence detection technologies (i.e. micro-bolometer), and personal health/tracking monitors.

This concept is illustrated below in an indoor fire situation:

1. A home and building automation sensor node is able to early detect fire due to its multiple gas sensing means.
2. Gas and presence sensor data is processed by data fusion algorithms able to intelligently interpret the current safety risk levels.
3. System-level algorithms provide an accurate safety risk assessment of the building by means of fire propagation and people occupancy maps.
4. Fire and occupancy data are real-time updated at the central alarm centre for continuous safety risk monitoring.
5. First responders are able to safely evacuate the building as wearable electronics constantly monitor their vital signs and indoor locations.

Tyndall National Institute, as part of the SAFESENS consortium, is developing a first responders monitoring system, i.e. the estimation of the activity performed (such as, lying, running, climbing stairs etc…) and of their location in indoor environments. The paper considers the potential technologies usable in the project, the requested requirements, the system architecture, some preliminary results and, finally, an overview of the current state-of-the-art.

II. REQUIREMENTS FOR INDOOR LOCALIZATION SYSTEMS

Requirements behind first responding monitoring are usually tight due to the intrinsic characteristics of the job. To understand end-users requirements, an online survey and a workshop have been organized with firefighters and relevant authorities. The outcomes of those activities outlined several requirements that need to be met by a tracking system.

The first requirement is that the first responders do not want to carry extra equipment. Wearing more items (like wristbands) is time-consuming. Moreover, the placement of the monitoring unit (or tracking system) is not preferred on the arm. The arm is in many cases located close to the ground. In other cases, the arms and hands are also frequently used to protect the head or face against debris from above, in which case a wristband will need to cope with possible strong impacts. Similarly, boots have been discouraged as a possible placement location, as they work closely with oil, petrol, dust, corrosive materials, heat, and are typically used to thrust doors or windows.

A second aspect that needs to be considered is the extreme conditions in which the personal safety monitor needs to be operated. Shocks were already mentioned, but most importantly the temperature may be high (up to several hundred degrees) and the air may be polluted with fine particles and dust. For all the mentioned reasons, the monitoring unit, worn by each first responder involved in the operations, needs to be light-weight (< 1 kg), unlikely most of the equipment currently used (such as, self-contained breathing apparatuses - SCBA which can be up to 13 kg), power-efficient (battery life-time > 6 hours, thus more than the average time expected for search & rescue operations), low-cost, and high-temperature resistant. The location on which the mobile tracking device is attached should not hamper normal operations or to be considered as an extra device, which means that the monitor has to be small, robust and embedded into the equipment already adopted (such as, into the straps of the SCBA) given that the chest represents the most stable and protected position for placing sensors.

The firefighters tracking system needs to be real-time self-configurable/self-organizing (i.e. no time for configuration), and rapid to deploy, which involves impossibility to place base stations/anchors outside the building during operations. Moreover, indoor mobile infrastructure cannot be deployed by first responders in order not to interfere with their working protocols. On the other side, line or battery-powered pre-deployed infrastructure in buildings, equipment or on fire trucks is instead acceptable. However, the system must not be vulnerable to environmental and system factors, and to be adaptive and resilient in case pre-deployed infrastructure will stop working (due to fire, or other reasons).

The whole tracking system has to be intuitive, easy to use (both for first responders and command centre), and be able to guarantee an overall room-level accuracy (~ 5-10 m) and correct estimation of floors and rooms where the firefighters are. Reliability, availability, robustness and consistency in all contexts and scenarios are further important features that will be addressed. Finally, given the consideration that a typical rescue team usually includes 2-4 first responders, but several teams may be needed in case of "special fires", the system has to guarantee scalability as well.

The opportunity to transmit possible warnings, alerts in case of downed first responder or frequent feedback so that the first responders may auto-control their effort is also recommended. First responders' locations, identification, accountability, and related vital signs will be displayed at the command centre (ideally, a tablet on a firefighter's truck) through an intuitive and easy to understand graphical representation also including context data about the building (e.g. maps, occupants' location, fire location, first responders' health status and position). Firefighters' information will be transmitted to the command centre at a low-communication rate (~ 0.1 Hz).

III. Potential Technologies

It is evident how only one technology would not be capable of meeting all the requirements mentioned in paragraph II, and, therefore, a multi-sensor approach is the solution generally adopted. Although GNSS provides global coordinates and is considered as the best solution for outdoor cases, its application indoor can still result in large errors. Infrared systems are characterized by high cost and possible interference from sunlight, while ultrasounds require line-of-sight. Cameras or night-vision are small and low-cost, and represent a good alternative when maps are not available. However, their adoption may be problematic in case of low-visibility scenarios or dynamic environments.

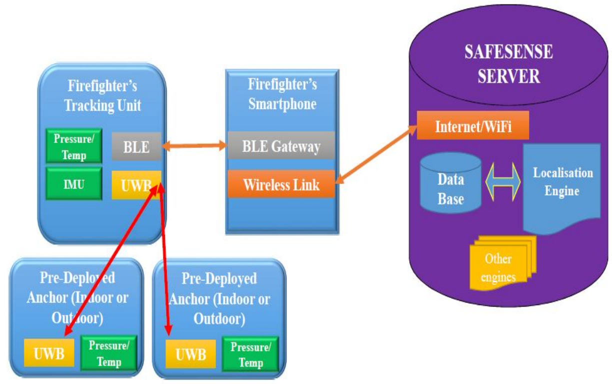

Fig. 1. System architecture scheme

Radio frequency (RF) technologies, such as WIFI, Radio Frequency Identification (RFID), Bluetooth Low-Energy (BLE), ZigBee, Ultra-Wideband (UWB), are more suitable for indoor positioning as radio waves can penetrate through obstacles more easily than ultrasounds, and thus guaranteeing a larger coverage area, operating in non-line-of-sight (NLOS) conditions. Theoretically, every RF technology could realize positioning. However, the overall performance varies according to the signal bandwidth and the signal-to-noise ratio (SNR) in line-of-sight (LOS) areas. Therefore, among all the RF technologies, UWB, with its large signal bandwidth (≥ 500Mz), and consequent high time resolution property, represents one of the most promising technologies for ranging and indoor positioning, with an accuracy in the order of decimetres. Moreover, UWB technology exhibits additional benefits, including ultra-low power operation, high data rates, enhanced multipath immunity when compared with other RF technologies, robustness to jamming, and low electromagnetic (EM) interference allowing UWB to coexist with other wireless devices. However, despite the abovementioned advantages, UWB implementations are still prone to reduced performance due to multipath effects, particularly in NLOS conditions. Indeed, these effects are most prominent while tracking moving objects or persons.

Another promising solution is the inertial technology based on small, low-cost Micro Electro-Mechanical Sensors (MEMS). The adoption of a stand-alone inertial sensor approach (accelerometer, gyroscope and magnetometer – or IMU) for navigation has long been established. Typically, the current position and orientation are estimated by accumulating movements measured using the on-board sensors. However, even though inertial data present regularity and independence from any existing infrastructure, accurate position tracking is provided only for short periods of time, being prone to drift for longer timescales. Finally, barometers represent an excellent complement to IMU and GPS technology with regards to height information, even though they may be dependent on weather condition, wind, temperature, etc…

In summary, the best solution seems to rely on a fusion of IMU, barometer, and UWB which will overcome the limitations of each individual technology.

IV. System Architecture and Preliminary Results

The system architecture (Fig. 1) consists of several parts, as follows:

- Pre-deployed anchors;
- Monitoring units;
- Command centre.

Pre-deployed anchors may be placed indoors (integrated into gas sensors and/or micro-bolometers) and outdoors (on first responders' vehicles). Such anchors consist of UWB transceiver, barometer (as a reference for height), and GPS (for global reference) in case of outdoor anchors. Given the fact that first responders' vehicles are usually parked in accordance to fire tactics (typically, one after the other) and not around the building to cover the entire perimeter, and that this protocol cannot be changed to provide more coverage for RF communication, the possibility to extend the number of anchors in particular scenarios, by integrating nodes also into a rope typically adopted by first responders when performing rescue operations, will be considered.

Monitoring units, worn by each first responder into the straps of SCBA, consist of a board with IMU, barometer, UWB transceiver and BLE, and a smartphone carried on by the worker. The board transmits all the inertial, pressure, and ranging information to the smartphone through BLE. The ranging data are given by UWB by measuring the range among the monitoring unit and the nearby anchors. It is worth mentioning that the smartphone may collect data via BLE also from wearable gas sensors and physiological sensors (e.g. oxygen levels, heart rate, etc…) worn by the first responder.

All the data gathered on the smartphone are then transmitted to an external command centre, where a server will process them in real-time and visualize the outcome on a device (e.g. tablet), in order to support the commander in chief.

The firefighter position is estimated on the server through a robust tracking algorithm, which may be based on different approaches, such as least squares, Kalman filter, particle filter, and so on. Each of those methods have different advantages and drawbacks with regards to accuracy, computational complexity, fast output response and so on, and a trade-off analysis will be performed to implement the optimal solution.

The tracking algorithm can be based on

- UWB ranging data (firefighter-to-anchors);
- UWB ranging data (firefighter-to-anchors) combined with inertial sensors from the firefighter;
- UWB ranging data (firefighter-to-anchors) combined with inertial sensors from the firefighter, and with firefighter-to-firefighter UWB ranging data.

The last approach will provide the opportunity to perform cooperative navigation in order to increase accuracy and availability of the system, and make it more robust in case of destruction of pre-deployed anchors due to fire.

In order to avoid designing an ad-hoc UWB transceiver, which will affect form factor, power consumption, and wearability of the monitoring unit, a small, low-cost, long-range, accurate, IEEE 802.15.4-2011a complaint wireless transceiver based on ultra-wideband techniques, produced by Decawave [2], will be adopted. An example of the UWB transceiver performance is shown in Table I. Two UWB transceivers have been considered in three different scenarios: outdoor LOS, indoor LOS and indoor NLOS. The actual distance between the nodes was 20 m, 25m, and 10 m, respectively, which is consistent with the distances in real case scenarios. The mean error was included between 2 and 20 cm, which is significantly promising, also because the error standard deviation is limited as well. However, those test considered two static nodes, and more test need to be carried out in dynamic contexts. Furthermore, the localization performance of the UWB transceiver have been tested in real scenario. Three anchors have been placed indoor, with two of them under moderate NLOS (a 10cm concrete wall between anchors and tag) and the remaining one under heavy NLOS (3 concrete walls in-between). Fig. 2 shows the cumulative distribution function of the tag position calculated through a least square method. Under mixed NLOS environments the system can achieve 90% of the times an error lower than 1.5 m, with an average error equal to 72 cm. This encouraging result can be further improved with additional signal processing techniques. Moreover, the barometer has been tested in a real-case scenario (Fig. 3). The test evaluated the height information extrapolated from a pressure sensor worn by a subject walking upstairs at moderate speed. The error range is between 0.1 and 0.4 m, which is significantly promising. Finally, activity monitoring (e.g. the discrimination among walking, running, crawling, climbing stairs, etc…) can be estimated from IMU data (by means of machine learning, or other approaches), providing information on the firefighters' activity and still enhancing the system performance.

V. State-of-the-Art of Indoor Localization Systems for First Responders

Tracking rescuing personnel within buildings in emergency situations and providing reliable communications among them is a problem which has attracted considerable attention in recent years. A number of solutions (products/prototypes) have already been proposed in literature or on the market. Some of the best known examples are the following ones:

- Precision Personnel Locator [3] of the Worcester Polytechnic Institute;
- POSCOMM [4] from NAVSYS;
- NAViSEER [5] from SEER Technology;
- Harris GR-100 [6] from Harris Corporation;
- Personnel Navigation, Locating and Tracking [7] from ENSCO;
- TRX Sentrix Systems [8];

TABLE I. UWB TRANSCEIVER PERFORMANCE

Test	Error Mean [m]	Error Standard Dev. [m]	Experiment Range [m]
Outdoor LOS	0.02	0.15	20
Indoor LOS	0.08	0.07	25
Indoor NLOS	0.20	0.10	10

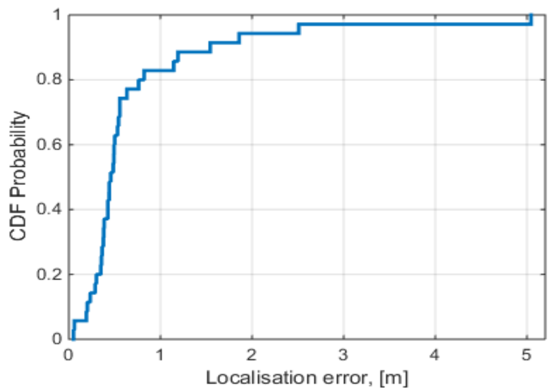

Fig. 2. Cumulative distribution function of error localization

- GLANSER [9] from Honeywell, TRX Systems, and Argon ST;
- FLARE [10] from Q-Track;
- EUROPCOM [11] project involving Thales UK, Delft University of Technology, Graz University of Technology, and IMST GmbH.

While GLANSER represents the most complete product in terms of technologies adopted and features provided, the system is still bulky and heavy to carry for firefighters (2"x4"x6" per 2 lbs). EUROPCOM, instead, is based on an ad-hoc UWB solution. Also in this case, the device may be too large to be easily worn by first responders (16 x 8 x 3.5 cm), and the system requires the workers to drop anchors in specific points inside the building during rescue operations, which is not practical for real scenarios.

VI. CONCLUSIONS AND FUTURE WORKS

This paper presents a monitoring system for first responders involved in rescue operations, as part of the SAFESENS project. An overview of the requirements requested for such a system, along with an analysis of the possible exploitable technologies has been provided. A novel system architecture has been proposed, and some preliminary results regarding UWB and barometer proved to be reliable and helpful as for the localization goal. The tracking algorithm will be implemented on a server with the aim of providing a good trade-off between accuracy and complexity. Moreover, first responders' motion analysis will be part of the work. The final system will integrate novel gas sensors, physiological sensors, and presence detection technology to enhance the current system, and will be shown in several real-case applications on successful completion of the project.

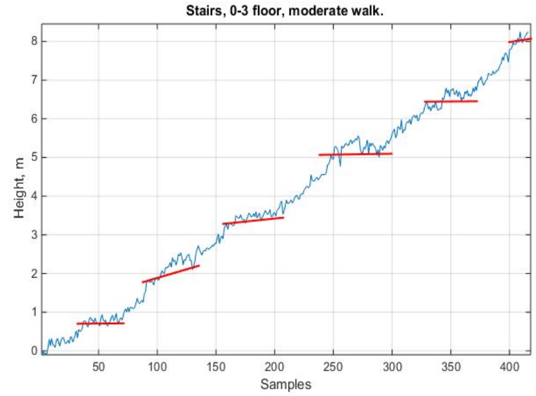

Fig. 3. Barometer performance in a real-case scenario

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