WPI Precision Personnel Locator System – Evaluation by First Responders

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BIOGRAPHY

Dr. R. James Duckworth is an Associate Professor in the Electrical and Computer Engineering department at WPI. He obtained his PhD in parallel processing from the University of Nottingham in England. He joined WPI in 1987. Duckworth teaches undergraduate and graduate courses in computer engineering, focusing on microprocessor and digital system design, including using VHDL and Verilog for synthesis and modeling. His main research area is embedded system design. He is a senior member of the IEEE, and a member of the ION, IEE, and BCS and is a Chartered Engineer of the Engineering Council of the UK.

Dr. David Cyganski is professor of Electrical and Computer Engineering at WPI where he performs research and teaches in the areas of linear and non-linear multidimensional signal processing, communications and computer networks, and supervises the WPI Convergent Technology Center. He is an active researcher in the areas of radar imaging, automatic target recognition, machine vision and protocols for computer networks. He is coauthor of the book *Information Technology: Inside and Outside*. Prior to joining the faculty at WPI he was an MTS at Bell Laboratories and has since held the administrative positions of Vice President of Information Systems and Vice Provost at WPI.

Dr. William R. Michalson is a Professor in the ECE Department at the WPI where he performs research and teaches in the areas of navigation, communications and computer system design. He supervises the WPI Center for Advanced Integrated Radio Navigation (CAIRN). His research focuses on the development, test, and evaluation of systems, which combine communications and navigation. He has been involved with navigation projects for both civilian and military applications with a special emphasis on navigation and communication techniques in indoor, underground or otherwise GPS-deprived situations. Prior to joining the faculty at WPI, Dr. Michalson spent approximately 12 years at the Raytheon Company where he was involved with the development of embedded computers for guidance, communications and data processing systems for both space borne and terrestrial applications.

ABSTRACT

This paper describes the latest developments in the Worcester Polytechnic Institute (WPI) Precision Personnel Locator (PPL) project. The RF-based PPL system is being developed for tracking of first responders and other personnel in indoor environments. The system assumes no existing infrastructure, no pre-characterization of the area of operation and is designed for spectral compliance. Recent testing with wider bandwidth (150MHz) ranging signals has shown sub-meter positioning accuracy of a transmitter even in difficult indoor environments with high multi-path despite all receivers being placed outside the building

As part of the testing and evaluation, firefighters from the local Worcester fire department provided feedback on various systems aspects: the suitability of the locator devices worn by the first responders, the incident commander's display unit, the improvement in situational awareness, and the suitability for both search and rescue operations. The system has also been extended to provide basic physiological information from the users, and a preliminary evaluation is also included.

INTRODUCTION: WPI PRECISION PERSONNEL LOCATOR SYSTEM

This paper describes the outcomes of recent tests using new hardware enhancements of the Worcester Polytechnic Institute (WPI) Precision Personnel Locator (PPL) system which has been the subject of a series of papers tracking progress in this project [1-8]. The main hardware enhancements have been to change from a 60MHz wide RF ranging signal to a 150MHz wide ranging signal [9].

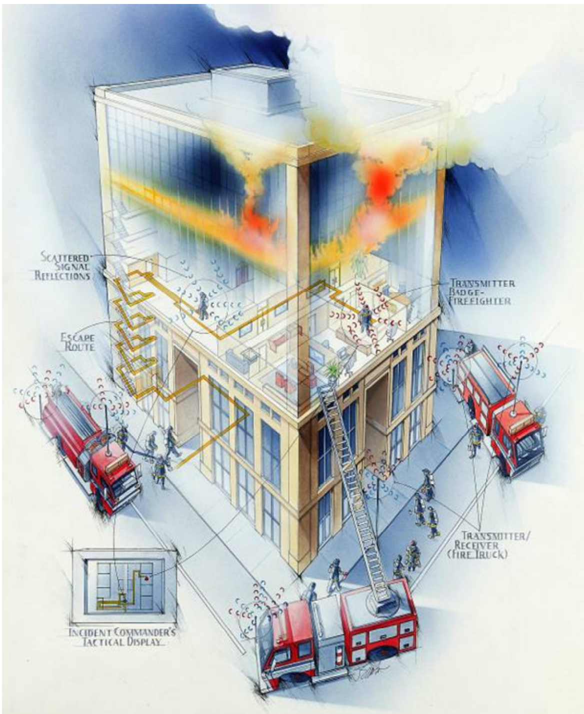

Fig. 1 Precision Personnel Locator system concept illustration.

Fig. 1 provides an overview of the envisioned precise personnel locator system being developed. The goal of the PPL system is to provide a robust real-time location tracking system which does not require any pre-existing infrastructure. Emergency vehicles and first responders would carry Multi Carrier – Wide Band (MC-WB) based transmitters. PPL equipped emergency vehicles arriving at the scene execute a calibration phase during which an ad hoc network and a relative coordinate system is established amongst the vehicle-fixed units. This relative position information may be optionally fixed to a known layout or to GPS reference coordinates.

Using the coordinates established by the vehicles, the signals received at the vehicles are then used to calculate the relative positions of personnel and/or equipment in and around the building.

The location of each first responder is then sent to a command and control display located at a command post base station which would display position information on its display console. This device displays the current position of all transmitters with respect either to the auto-generated coordinate system, or to a user preferred coordinate system. This may be registered to electronic building floor plans if such plans are available and/or may be GPS registered if GPS signals are available at the command console. The command console may also provide other services such as displaying the tracks of all locators so that a map of available pathways in the building may be automatically generated by the movements of personnel and used in lieu of building plans to increase the commander's knowledge about the internal building structures and path obstructions on the fireground. Commanders can then apply this information for emergency-exit guidance and for assisting rescue of first responders in trouble.

The requirements for such a wireless personal tracking system are high accuracy (better than one meter) position location and tracking in 3 dimensions. In addition the system should provide; health and vital sign information, environment and temperature monitoring, be able to simultaneously track a minimum of 100 users, provide emergency exit guidance (back-tracking) and 'homing' signals [2].

Our location system is based upon a novel method developed by WPI for deployable operations-scale 3-D RF location. This zero-infrastructure, self-calibrating system tracks wearers of locator devices within buildings with respect to reference (receiver) units placed outside (or inside) buildings. The system design emphasizes low cost, size and weight, compatibility with FCC spectrum allocations, and simple, robust operation.

Any system which solves the 3-D location problem depends upon acquisition of distance fixes with respect to several reference points. In GPS the mobile units take a passive role, receiving signals transmitted by satellites with well known locations. In our approach, the mobile locator units are active, transmitting a signal which is received at the reference points. This approach is better suited to an interior environment, where GPS signal reception is very poor, and where a premium is placed on the low cost and low power drain of mobile units owing to the economic and logistic factors peculiar to first responder operations.

System Architecture

The WPI PPL system consists of three components:

- Locator transmitters worn by each first responder or individual to be tracked;
- Reference Unit receivers that define the operational geometry and communicate with each other, the Locators, and the Base Station; and
- Incident commander's Base Station which displays results in an operationally useful manner.

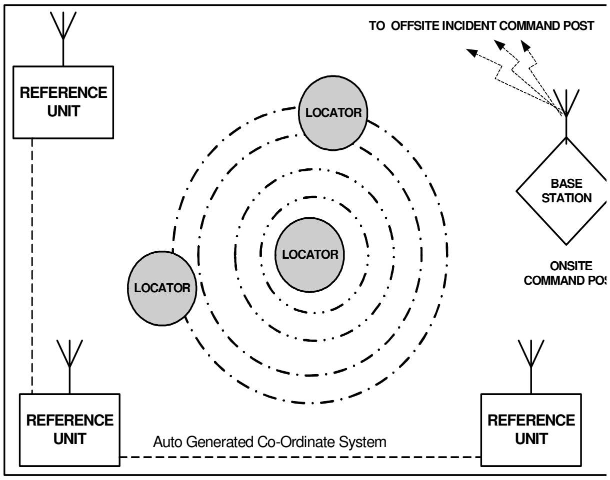

Fig. 2 PPL system overview.

While Fig. 1 illustrates these pieces of equipment as they may be deployed in an operational environment, Fig. 2 provides a simplified depiction of the overall Precision Personnel Locator System architecture to support the following discussion. The system design (summarized below and in detail in [8]) enables the Locators to be small, and inexpensive to produce in large quantity. They transmit a repetitive broadband ranging signal as well as a narrowband identification and control signal. They also contain a data receiver for the control channel.

As indicated above, upon arrival at the incident site, reference units are placed near and around the location in which operations will take place. To perform 2D location three or more, and for 3D location, four or more receive points must be deployed. There are valuable gains in SNR and other contributing factors to be obtained from additional reference points. As was described in [8] we exploit an antenna multiplexing strategy that allows us to reduce the cost and complexity of the system by limiting the number of receivers needed. These antennas and the supporting reference units may be mounted on several vehicles or can be deployed manually from one or more transport vehicles.

First responders will wear the mobile locator units which continuously transmit the MC-WB signals that are received by the reference units. Employing time difference of arrival (TDOA) techniques and a novel multi-lateralization algorithm to be described in a future paper, the reference units determine the position of the locator with respect to the auto-generated coordinate system.

Precision Location Approach

At the center of the RF precision indoor location problem is the means selected for precise ranging (distance estimation) between one or more base stations and a mobile locator device. Similar ranging technology is the basis for GPS technology in which satellite base station transmitters permit establishment of the location of mobile receivers and is also applied in cell phone location systems in which tower located base-station receivers estimate the location of mobile hand-held cell phone transmitters. However, several factors which are particularly exacerbated in the indoor environment have obstructed direct application of past solutions which are familiar from these other applications: insufficient signal strength, lack of precision and small-difference multipath degradation.

The difficult multi-path problem can be ameliorated with ultra-wideband ranging signals, however spectrum non-compliance issues have limited the applicability of this solution – furthermore failure of simple pulse distortion models in actual through-building and multi-path propagation conditions presents a significant challenge as well. In contrast, work to date on the proof-of-concept system described here has demonstrated means to provide these capabilities within the bounds of practical constraints.

The WPI PPL system is based upon the use of a multi-carrier wideband signal, similar to that used in OFDM communications, such as DSL broadband, and super-resolution range estimation algorithms similar to those employed in advanced radar systems. Multiple discrete carriers are combined to form a wideband signal. Super-resolution processing results in a system that has several especially noteworthy properties that distinguish it from both impulse based and spread spectrum based ultra-wideband systems. Each carrier has nominally zero bandwidth and hence may be woven in between channels of existing services without interference, providing significant levels of spectral compatibility. The smaller overall bandwidth (compared to UWB) also reduces antenna complexity and size while increasing efficiency, and reduces the problems introduced by frequency dependence of the signal paths due to material properties in a building.

This signal structure and signal processing approach together provide for the simplicity of the mobile locator units which comprises a simple periodic signal transmitter with no time synchronization requirements. This simple structure translates into a very low cost and low power consumption unit. The reference receiver architecture also benefits, as this moderate bandwidth signal structure allows a simplified "software-radio" implementation architecture that is amenable to system-on-chip design. This implementation approach has already been beneficial in the prototype stage as it has allowed us to implement many experimental software and firmware upgrades with no change in hardware and will likewise permit maintenance upgrades in any future commercial realization.

Over the course of this project we have developed prototypes that have generated the OFDM-like MC-WB ranging signal with a range of frequencies spanning bandwidths from 25 to 150 MHz. In all cases, the signal consists of N unmodulated sub-carriers spanning the bandwidth of operation B Hz, and (in the simplest implementation) spaced at B/N Hz. The regular spacing implied above is not necessary, and in fact these sub-carriers can be made to fall at arbitrary points in the spectrum chosen to avoid other-service interference and fulfill regulatory requirements without compromising the ranging technology we are using.

The moderate bandwidth requirements of the MC-WB signal also yields significant benefits with respect to antenna design. The current mobile transmitter unit exploits the benefits of compact patch antennas which can be tuned to admit the required bandwidth [9, 10, 11, 12].

Precise and multi-path compatible location is obtained by applying novel multi-carrier range recovery techniques derived in past work at WPI as described in [1, 3, 4, 7] based upon state space estimator approaches to modern spectral analysis first outlined in [13]. Fusion of these range outcomes was previously conducted by using standard multi-lateralization techniques [14] but has now been replaced by a new approach to be described in a future paper.

PRECISION PERSONNEL LOCATOR SYSTEM TEST RESULTS

In an earlier paper [8] we described the success of the current PPL system in a difficult indoor environment using a 60 MHz wide ranging signal centered at 440 MHz. More recently in [9] we described the substantial re-design of the RF and digital hardware in our system to allow us to work with a 150MHz wide signal. This section describes location results using this wider ranging signal. In each case we demonstrate location performance of less than 1 meter of mean absolute error. All of these experiments involve locating a free-standing transmitter (battery powered with no cables to the rest of the system) inside a structure without any previous training or introduction of any information about the structure into the location system.

The transmitter, also referred to as the locator module, that contains the RF ranging signal and data communication channel is shown in Fig. 3 below:

Fig. 3 Locator tracking module carried by first responders.

The electronic devices inside the module can be seen in Fig. 4. The board on the top left is the 900MHz radio used for command and control and data communication. Below this is the digital RF ranging signal generator consisting of an FPGA and DAC. On the bottom right is the wideband RF transmitter producing a 150MHz wide signal from 550 to 700MHz. The board on the top right holds the rechargeable battery, on-off switch, and the Polar receiver module used for heart-rate information. All of these customized electronic circuit boards were developed by students and faculty at WPI. The whole assembly weighs approximately 23 oz with the batteries.

Fig. 4 Locator module electronics

Fig. 5 shows the locator module and the 150MHz wide-band PIFA attached to the air tank assembly. In a later design it is expected the antenna will be integrated with the rest of the electronics inside the locator module plastic housing.

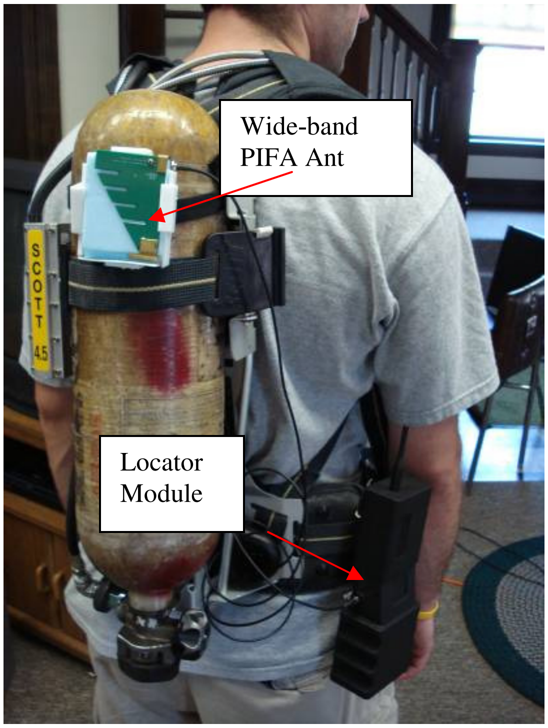

Fig. 5 Locator Tracking System attached to the air tank assembly.

We used the same three-floor wooden building as for earlier tests. This building is the WPI Religious Center, a formerly residential house, and is shown in Fig. 6. While not as seemingly daunting, residential fires, owing to their larger numbers, lead to a significant number of fire fighter fatalities. According to a congressional testimony "Statistics also show that among all structure fires, it is those in residential homes that are most dangerous, accounting for over 70 percent of all fire deaths each year" [15].

Fig. 6 Exterior view of WPI Religious Center test location.

While this testing location presented a less challenging multipath environment than other steel-structured buildings we have used for earlier experiments, even wooden structure buildings contain significant amounts of metal plumbing, wiring, window frames/screens, appliances, fireplace and furnace ducts, etc., that contribute to the multipath environment.

For this test our receiver antennas were all placed outside of the building, at the approximate height of the first floor. They were staggered in height to provide 3D location information. The transmitter was placed at various surveyed locations inside the house, both on the first and second floor.

The position estimation results for the transmitter locations on the first floor are shown in Fig. 7. The actual mobile transmitter locations are shown by the blue boxes. The receiver antenna locations are shown by the circles. The red arrows indicate the magnitude and direction of the location error from the transmitter detected position relative to the actual position. The average absolute distance error for these locations was 0.68 meters or approximately 2 ft. It is interesting to note that the locations with the larger errors (right part of the house) were in the kitchen area that had large metal structures such as a fridge, oven, and metal ducting.

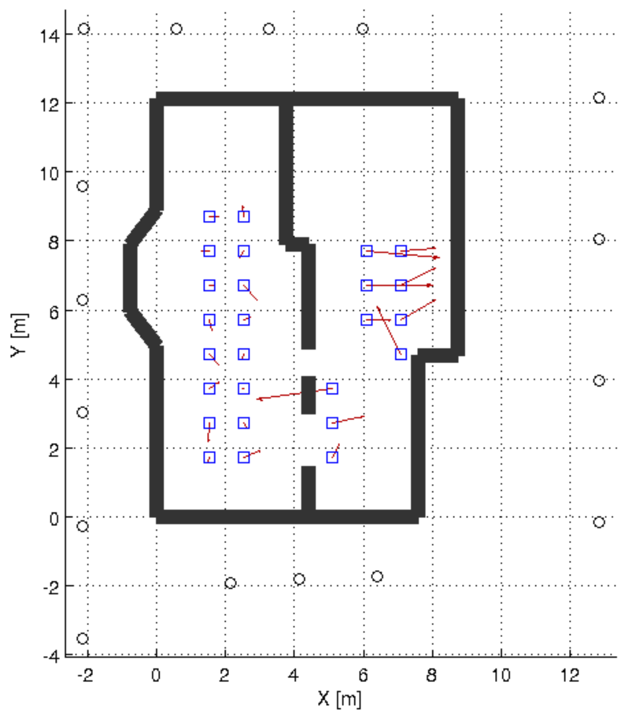

Fig. 7 First floor error plot – mean error 0.68m

In a similar manner Fig. 8 graphically depicts the position estimation performance for transmitter locations on the second floor. The average absolute distance error for these second floor locations was 0.3 meters or approximately 1 ft.

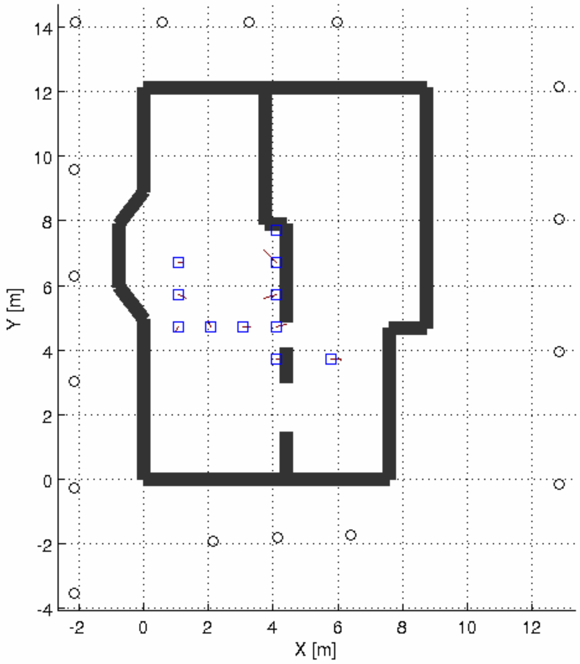

Fig. 8 Second floor error plot – mean error 0.3m

In addition to placing the transmitter at known locations throughout the building in order to obtain the error plots shown above, we also conducted real-time testing. The wearer of the system would walk through the building while the position was updated in real-time on the computer display. We also conducted some tests in which the wearer would crawl (as shown in Fig 9) at various places in the building to ensure there was no degradation due to transmitter antenna orientation.

Fig. 9 Crawling tests to provide different antenna orientation

EVALUATION BY FIRST RESPONDERS

While developing the Precision Personnel Location and Tracking system we have attempted to always keep in mind the requirements of ultimate users who will be using such a system. We have been fortunate to be able to work closely with the Worcester Fire Department and other first responders to better understand the special requirements for their needs.

For example, the Worcester Fire Department reviewed the prototype system operation and commander's display. The general display is shown in Fig 10 with more detail shown in Fig 11. They thought it was generally good, and easy to understand. We had attempted to try to display a 3D visualization through various means, such as wire frames and perspective drawings, but had abandoned these as being too confusing. For example, on a wire frame grid it is difficult to perceive what floor a person was actually on.

Fig. 10 Display showing real-time location and tracking of personnel inside building behind

We eventually decided to display the height of the transmitters using a vertical bar as shown in the center part of the display in Fig. 11, and this was found to be particularly intuitive. The vertical bar provides useful summary information showing the heights of all the firefighters, the user can then select different floors to show 2D location information for the people at that elevation.

One criticism of the screen and layout was the lack of information related to the orientation of the building relative to the command display. At an incident site the side of the building facing the incident command station (usually located in the commander's truck or jeep) is always designated side 'A'. The other sides of the building are then designated 'B', 'C', and 'D' in a clockwise direction around the building. This is important information used by all personnel at the incident site to convey their position or to direct operations. For example a team may be directed to go to "second floor, B side".

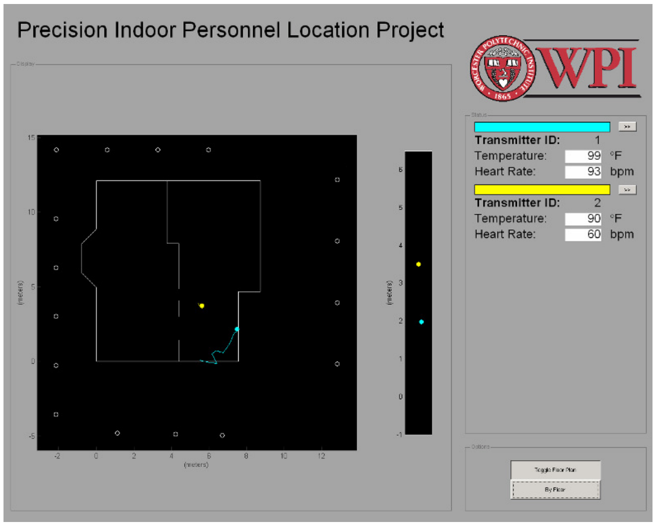

Fig. 11 Display showing tracking and location of two transmitters (blue and yellow) along with environmental and vital signs

The ability to turn on and off historical track information was also noted as being useful. Normally the tracks would be turned off so only the current position of the first responders would be shown. However, in a rescue mission, the tracks could be turned on to show the path taken by the person to be rescued, to help provide the best way to their location.

The ability to selectively display people by team or operation was also noted as important. There could be as many as 20 or more people in a structure and it should be possible to show all the individuals belonging to a particular company (ladder truck #5 for example) by highlighting them by flashing their position or tracks, or by a different color. In some cases the positions of groups of individuals could also be turned off to better focus on a particular individual or group.

The above discussion focused on the display of location and tracking information. Our system also provides system status information, such as battery voltage, the temperature of the environment, and if the distress button built into the locator module was pressed. If the distress button is displayed then a warning message is immediately and prominently displayed on the screen and the location of that trasnmitter highlighted.

The battery voltage is an example of a parameter that normally does not need to be displayed, it should only provide an alert condition when the battery needs to be recharged or replaced. The environmental temperature information is a similar parameter – only if an unsafe temperature is measured should an alert be made. This could then be used to indicate that the individual should be moved out of the area as soon as possible. Alternatively if the individual had been working in an elevated temperature location for an extended period then the alert may be elveated, resulting in a flashing warning on the display with possible audio alarms too. In our current system the environmental temperature is just continually displayed. More work is needed to decide how to best implement the warning options for the various environmental and system parameters.

PHYSIOLOGICAL INFORMATION

The system also monitors the heart rate of the person being tracked. A Polar heart rate monitor was used to determine the heart rate. This monitor consists of two parts, a strap like device worn around the chest that detects hear beats and transmits the information through a low-power, short-range radio, to a receiver unit. We integrated the receiver unit into the locator device so it could send this information back to the base station.

The Worcester Fire Department noted that this was great information to have access to. The number of deaths as a result of heart attacks during firefighting operations is actually greater than those caused by being lost or trapped in a structure. Having physiological information available may help to determine who is in imminent danger of suffering from problems caused by heat related stress or overexertion and could then be removed from the building or incident site in order to recover.

However there are a number of potential problems with adding physiological information. The first is related to information overload. It would be impossible for a commander to try to continuously monitor physiological information (such as heart rate, respiration, body temperature, oxygen saturation, etc) from all his personnel to try to determine if someone was in trouble. The commander will be busy directing operations related to the fire or other incident. Ideally the system should only display an alert condition if a problem is detected; otherwise the display should just show 'green' for example.

The second problem is related to determining what specific measurement values constitute a potential alert condition. It is not simple to even determine what an abnormal heart rate is. Age, weight, physical condition, can vary greatly from one person to another resulting in what may be considered a dangerously high heart rate in one individual to be perfectly acceptable in another.

One simple measurement technique used commonly in exercising is to calculate a maximum heart rate threshold based on the person's age. The maximum heart rate can be obtained by subtracting the age of the individual from 220. For example, a 40 year old would have a maximum desired heart rate while exercising of 180. This technique may provide a very simple threshold to determine whether the individual is OK 'green condition' or maybe needs checking 'orange or red condition'.

In the system we demonstrated to the fire department we just displayed the heart rate on a continuous basis without attempting to classify any alert levels. If respiration, body temperature, or oxygen saturation is also added in then acceptable ranges and limits need to be determined for each of these, both individually and maybe in combination.

As part of the ongoing research funded by a new fire safety and research award we will be adding in additional physiological information to our system by replacing the Polar heart rate monitor with a system from Foster Miller. This vest-based system provides heart rate, skin temperature, respiration rate, activity level, and orientation. We will further supplement this system with a pulse oximeter device developed at WPI to provide oxygen saturation levels.

CONCLUSIONS

This paper documents significant progress towards the important goal of precise (sub-meter) three-dimensional personnel tracking in the indoor environment with no pre-installed infrastructure. We have demonstrated approximately 1 m accuracy in three dimensions in a multi-storey structure with a 150 MHz wide signal.

The system operation has been demonstrated to the Worcester Fire Department and other first responders for their evaluation as regards ease of use and improving situational awareness at the incident site. We have obtained some valuable feedback which we will be using to improve our system.

We also described initial attempts to provide basic physiological information in the form of a heart rate monitor. This allows the incident commander to not only know the location and tracking of personnel inside a structure but also their physiological condition.

ACKNOWLEDGMENTS

We would like to thank Chief Dio and the Worcester Fire Department for their time and help with the design and evaluation of our Precision Personnel Location and Tracking System. The support of the National Institute of Justice of the Department of Justice is also gratefully acknowledged.

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