A System for Tracking and Locating Emergency Personnel Inside Buildings

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Biography

Mr. Ilir F. Progri received his Diploma of Engineer Degree in Electrical Engineering from Polytechnic University of Tirana, Albania in 1994. He received his MS degree in Electrical Engineering from Electrical and Computer Engineering Department, Worcester Polytechnic Institute (WPI) in 1997. He is currently a graduate student of the Electrical and Computer Engineering Department, WPI, perusing his Ph.D. degree in Electrical Engineering with strong emphasis in carrier phase and signal processing, integrity monitoring, precision approach and landing, filter design and implementation, numerical methods and numerical linear algebra, software development and management.

Dr. William R Michalson is an Associate Professor in the Electrical and Computer Engineering Department at Worcester Polytechnic Institute, where he also directs the Satellite Navigation Laboratory. The majority of his research focuses on the development, test, and evaluation of GPS integrity monitoring algorithms, with an emphasis on integrity monitoring for sole-means navigation and precision approach. He is involved with the development of GPS systems for specialized applications. Previously, he was with Raytheon Company where he developed computer system architectures for space-based data and signal processors.

Abstract

One of the most hazardous jobs firefighters and other emergency personnel must do is to enter a burning building. In this situation, the building floor plan may be unknown (and may change), visibility is impaired, and the locations of other equipment and personnel may change. Combining this situation with a limited air supply and potentially obstructed escape paths results in an extremely dangerous environment. This paper will discuss a system that is currently in development that uses GPS and GPS-like technologies to provide navigation information to emergency personnel inside a building and situation awareness monitoring to personnel outside a building. The paper will present the system architecture and any relevant simulated or experimental results.

Introduction

Recent advances in information technology and integrated electronics provide a means for locating firefighters and other emergency personnel inside buildings. In this paper, an approach to integrating the technologies required to develop a location system are presented.

From the firefighter's point of view this system must have characteristics such as:

1. Small size – any equipment carried on the firefighter must be small enough to not interfere with normal activity. Further, it must be rugged enough to survive extreme environments.
2. Flexibility – the system must be useful in situations where there are no existing floor plans and where entry may occur in locations other than doors or windows
3. Communications – position, health and situation awareness information may be communicated to, or from, the firefighter.
4. Accuracy – the accuracy of the system must be such that an individual may be located under zero visibility conditions.
5. Reliability – the system must be reliable enough that firefighters are willing to entrust it with their safety.
6. Simplicity – the system must be easy to use in a distracting environment.

These characteristics form a minimal set of criteria for a system designed for use in the extreme environment of a burning building. In such an environment there are strict limits on the amount of time a firefighter may be inside due to limitations imposed by a limited air supply and on increasing fire and smoke intensity. Additional system challenges result as a consequence of the complete or partial falling of the building, which may result in the destruction of escape paths.

From the firefighter safety system point of view, a wearable device suitable for the environment must have the following additional characteristics:

1. Identify the current location (in three dimensions) to the incident command post outside the building under any circumstance.
2. Provide status (health and motion) information on each team member, and on the condition of the exit paths.
3. Provide emergency exit guidance (back-tracking) to each team member via synthesized voice commands, and to the incident command post
4. Provide "homing" signals to guide searchers in locating firefighters in trouble.

Preliminary System Design

Assume that the firefighter path(s) are those of figure 1 and figure 2.

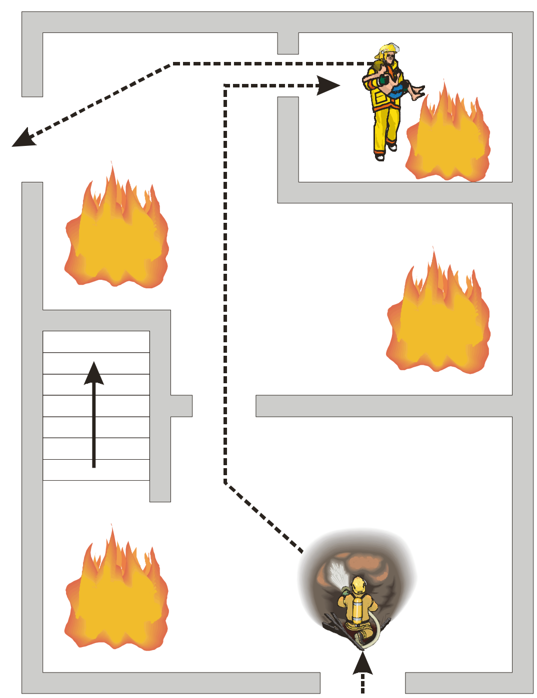

Figure 1: Firefighter scenario in a 2D area

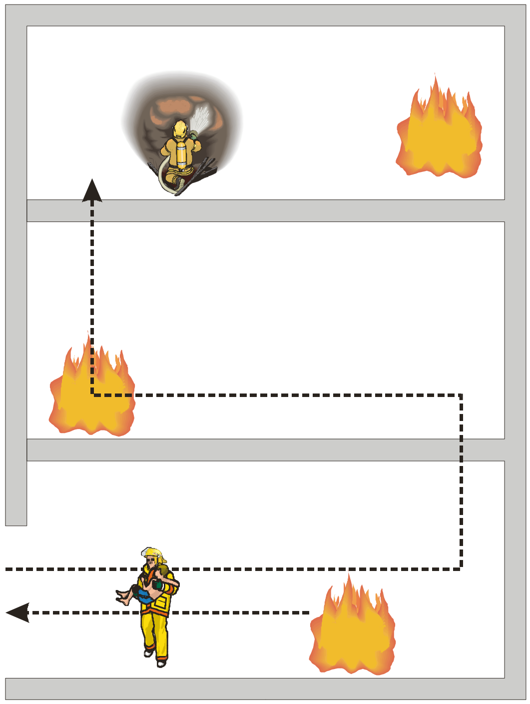

Figure 2: Firefighter scenario in a 3D area

Initially we assume that the itinerary (or path) of the firefighter inside the building is known with respect to a reference coordinate system, which can be either chosen inside or outside the building. We will also assume that the firefighter is equipped with a wireless transceiver capable of tracking a GPS-like signal and transmitting information to each team member and to the incident command post.

We will assume that pseudolites, or GPS-like signal emitters, can be utilized to accurately determine the location of the firefighter.

We will also assume that path along which the firefighter is moving is either:

1. Visible by a single fixed receiver
2. Visible by multiple fixed receivers
3. Visible by no fixed receivers

In the first two cases, navigation system design can be based on the double difference technique by using the measurements available from a common set of visible pseudolites [1]. Similarly, double differencing can be used in the second scenario case as well since it is reasonable to assume that the path has piecewise visibility to at least one fixed receiver located along the path. This technique is described in [1] in great detail.

The last case can be treated utilizing the single difference technique. Since the single difference technique has not previously been applied in this application, we will provide additional theoretical background for this technique as an alternative navigating means.

Single Differences – No fixed receivers

The analytical formulation of the carrier phase measurement between the f^{th} (firefighter) receiver and the j^{th} pseudolite, $\phi_f^j[k]$, is as follows,

$$\phi_f^j[k] = d_f^j[k] + c\left(\Delta t_f[k] - \Delta t^j[k]\right) + \lambda a_f^j[0] + \varepsilon_{j\phi}^M[k] + \varepsilon_f^\phi[k]. \quad (1)$$

The unknown quantities of expression (1) are defined in the following order:

$d_f^j[k]$ denotes the geometric distance between the f^{th} receiver and the j^{th} pseudolite.

$\Delta t_f[k]$ denotes the f^{th} receiver clock bias.

$\Delta t^j[k]$ similarly determines the j^{th} pseudolite clock bias.

$a_f^j[0]$ represents the number of unknown cycles between the f^{th} receiver and the j^{th} pseudolite at the initial moment of tracking.

$\varepsilon_{j\phi}^M[k]$ depicts the multipath error (see expression 12 of [1]) of receiving the signal from the j^{th} pseudolite from paths different than the LOS path.

$\varepsilon_f^\phi[k]$ denotes the carrier phase measurement error of the fth receiver.

k is the epoch index from the moment of tracking the carrier phase of the jth pseudolite.

$\lambda = c/f$ is also known as the wavelength of the carrier phase.

A similar expression can be written for the carrier phase formulation between the firefighter receiver fth and the lth pseudolite as,

$$\phi_f^l[k] = d_f^l[k] + c\left(\Delta t_f[k] - \Delta t^l[k]\right) + \lambda a_f^l[0] + \varepsilon_{l\phi}^M[k] + \varepsilon_f^\phi[k]. \quad (2)$$

Taking the difference between the quantity (1) and (2) yields,

$$\phi_f^{j-l}[k] = d_f^{j-l}[k] + c\Delta t^{j-l}[k] + \lambda a_f^{j-l}[0] + \varepsilon_{j-l\phi}^M[k] + 2\varepsilon_f^\phi[k]. \quad (3)$$

Assuming that for very short duration of time the quantity $c\Delta t^{j-l}[k]$ remains unchanged or changes very slowly then we can include this part in the ambiguity quantity as (known as modified ambiguities)

$$\lambda\tilde{a}_f^{j-l}[0] \cong c\Delta t^{j-l}[k] + \lambda a_f^{j-l}[0]. \quad (4)$$

Similarly, we can include the remainder of the multipath effect into the effect of noise

$$2\tilde{\varepsilon}_f^\phi[k] \cong \varepsilon_{(j-l)\phi}^M[k] + 2\varepsilon_f^\phi[k]. \quad (5)$$

Combining the result of (4) and (5) into (3) produces,

$$\phi_f^{j-l}[k] = d_f^{j-l}[k] + \lambda\tilde{a}_f^{j-l}[0] + 2\tilde{\varepsilon}_f^\phi[k]. \quad (6)$$

Let M be the number of independent measurements. We can write (6) in vector/matrix notation as,

$$\ddot{\mathbf{O}}[k] = \mathbf{d}[k] + \lambda\tilde{\mathbf{a}}[0] + 2\tilde{\mathbf{e}}[k]. \quad (7)$$

Therefore, assuming that the filter states are the position and velocity of the firefighter receiver and modified single difference ambiguities we obtain the following measurement (observable) vector/matrix equation,

$$\ddot{\mathbf{O}}[k] \cong \mathbf{H}[k]\mathbf{s}[k] + 2\tilde{\mathbf{e}}[k]. \quad (8)$$

Where, $\mathbf{H}[k]$ denotes the measurement matrix relating the state vector to the observable vector of the single difference accumulated carrier phase. Assume that the system dynamics can be modeled as a Kalman filter; thus, for a transition matrix **T**[k] the propagation state vector is formulated with the help of the following expression [2],

$$\mathbf{s}[k+1] = \mathbf{T}[k]\mathbf{s}[k] + \mathbf{w}[k]. \quad (9)$$

The process noise $\mathbf{w}[k]$ is assumed white sequence with known covariance **Q**[k] and uncorrelated with double carrier phase measurement noise, **R**[k].

Eliminating the intermediate steps, we present here the final solution of the Kalman (recursive) filter in two major phases,

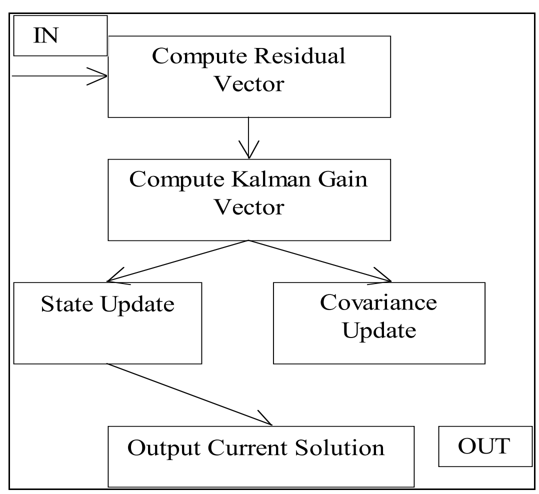

Figure 3: Kalman filter state update

- **State update (see figure 3)**

We seek to update the state in accordance with,

$$\hat{\mathbf{s}}[k] = \hat{\mathbf{s}}[k]^- + \mathbf{G}[k]\left(\ddot{\mathbf{O}}[k] - \mathbf{H}[k]\hat{\mathbf{s}}[k]^-\right)$$

$$= \hat{\mathbf{s}}[k]^- + \mathbf{G}[k]\mathbf{z}[k]. \quad (10)$$

In equation (10), $\hat{\mathbf{s}}[k]^-$ presents the state vector in the *a priori* estimate, $\mathbf{z}[k]$ is defined as the residual vector; and the matrix G[k] denotes the Kalman gain matrix which in its optimal form is written as,

$$\mathbf{G}[k] = \mathbf{C}[k]^- \mathbf{H}[k]^T \left(\mathbf{H}[k]\mathbf{C}[k]^- \mathbf{H}[k]^T + \mathbf{R}[k]\right)^{-1}. \quad (11)$$

The update equations for the covariance matrix $\mathbf{C}[k]$ in its sub-optimal and optimal form are:

$$\mathbf{C}[k] = (\mathbf{I} - \mathbf{G}[k]\mathbf{H}[k])\mathbf{C}[k]^- (\mathbf{I} - \mathbf{G}[k]\mathbf{H}[k])^T$$

$$+ \mathbf{G}[k]\mathbf{R}[k]\mathbf{G}[k]^T, \quad (12)$$

$$\mathbf{C}[k] = (\mathbf{I} - \mathbf{G}[k]\mathbf{H}[k])\mathbf{C}[k]^-. \quad (13)$$

Equations (10) through (13) form the heart of the Kalman filter state update phase. State update is followed by state propagation also known as time update or time propagation phase,

- **Time update, state or time propagation (see figure 4)**

One equation of the state or time propagation is obtained by modifying expression (9),

$$\hat{\mathbf{s}}[k+1]^- = \mathbf{T}[k]\hat{\mathbf{s}}[k]. \quad (14)$$

The state error covariance changes in accordance with,

$$\mathbf{C}[k+1]^- = \mathbf{T}[k]\mathbf{C}[k]\mathbf{T}[k]^T + \mathbf{Q}[k]. \quad (15)$$

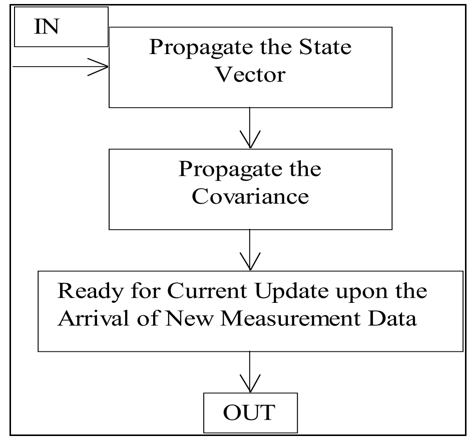

Figure 4: Kalman filter state propagation

Simulation Description **and Results**

Using the simulator developed in [1] a set of scenarios was developed for a firefighter moving in a building such as that depicted in figure 5. In this situation, the firefighter moves in 2 dimensions. The movement was arbitrarily selected to move the firefighter first to the east, then north, and then southwest.

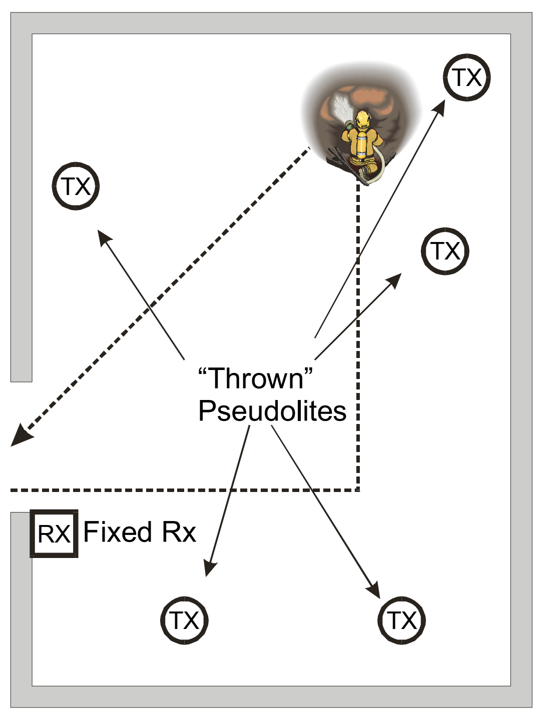

Figure 5: Simulated 2D tracking

In the simulation, as the firefighter enters the building, a fixed receiver is placed at near the point of entry. This establishes an arbitrary, but stationary, reference point that will be used to establish a basis for mapping and for locating people and equipment inside the building.

As the firefighter enters the building, additional pseudolite transmitters are literally scattered in arbitrary locations. These transmitters provide the additional signal sources needed for navigation. The transmitter positions need not be known *a priori* as they will be determined by the system (using the firefighter and the fixed receiver as a reference).

Scenario 1 – moving east

For this scenario we picture a firefighter who moves 3 m on the east direction as shown in figure 6.

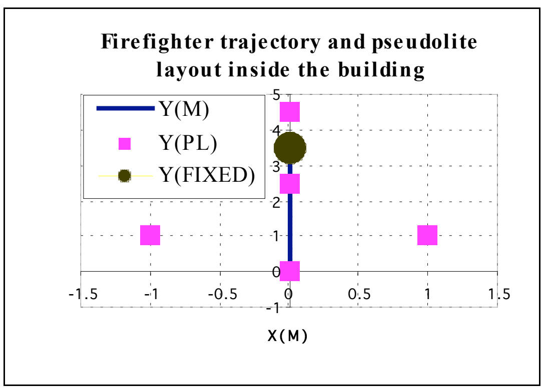

Figure 6: Firefighter moving in the east direction

The pseudolites are denoted with squares and the fixed receiver is presented with a circle. The firefighter moves in the east direction at 10cm per sec. The simulation results for this scenario are obtained by processing all the measurements that are obtained from the receiver (pseudorange, carrier phase, and Doppler).

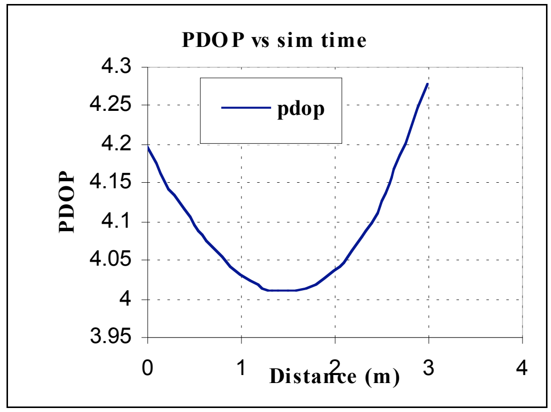

Figure 7: Firefighter PDOP

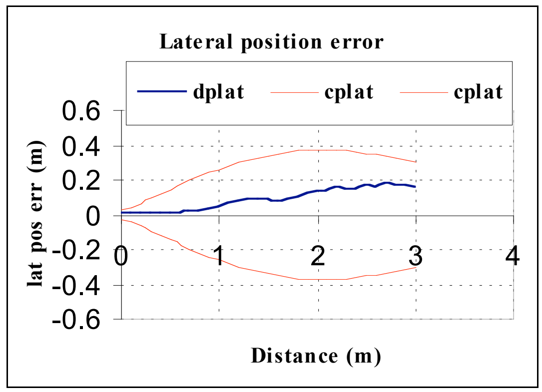

Figure 8: Firefighter lateral position error

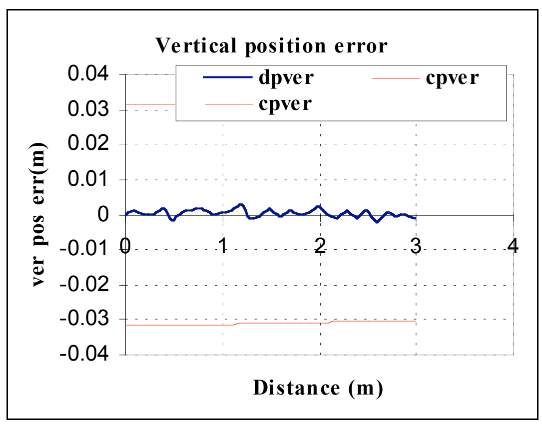

Figure 9: Firefighter vertical position error

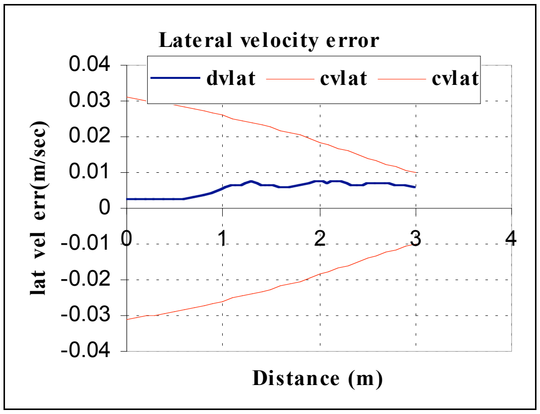

Figure 10: Firefighter lateral velocity error

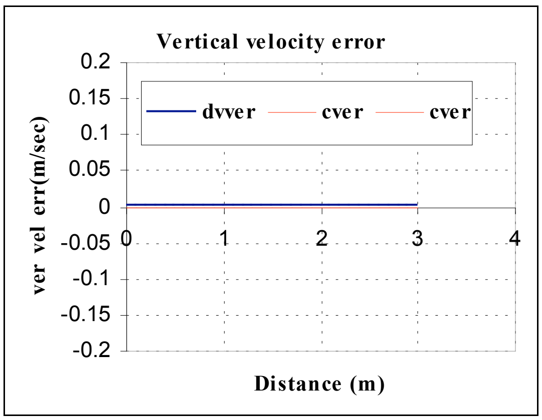

Figure 11: Firefighter vertical velocity error

Scenario 2 – moving north

For this scenario we picture a firefighter who moves 6 m on the north direction as shown in figure 12.

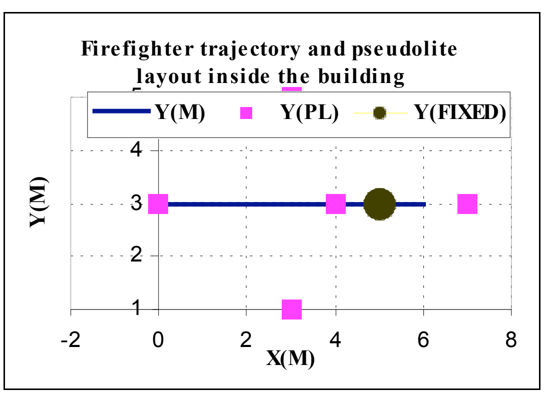

Figure 12: Firefighter moving in the north direction

The pseudolites are denoted with squares and the fixed receiver is represented with a circle. The firefighter moves in the north direction at 20cm per sec. The simulation results for this scenario are obtained by processing all the measurements that are obtained from the receiver (pseudorange, carrier phase, and Doppler).

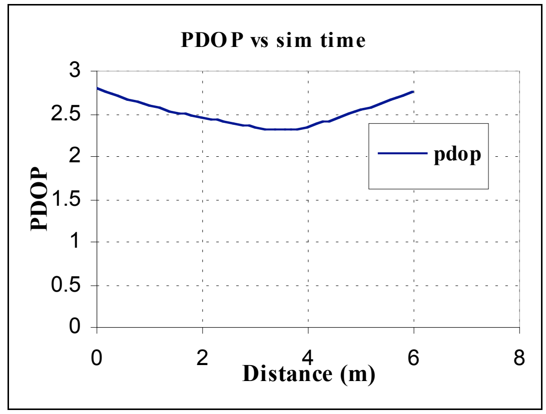

Figure 13: Firefighter PDOP

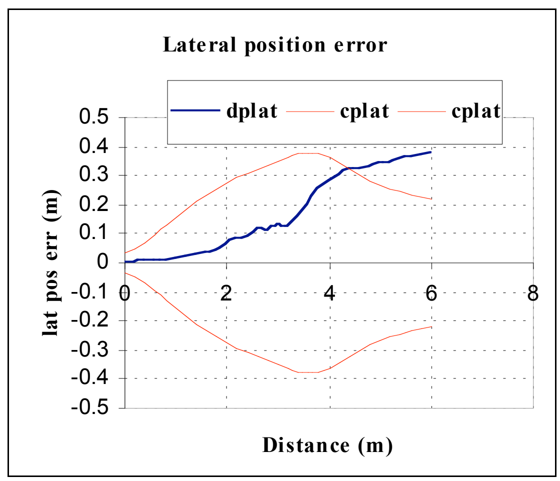

Figure 14: Firefighter lateral position error

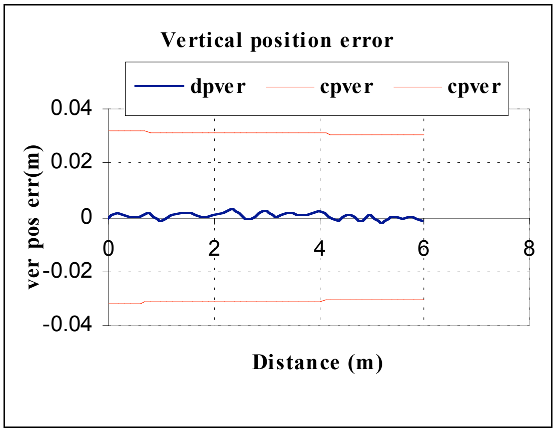

Figure 15: Firefighter vertical position error

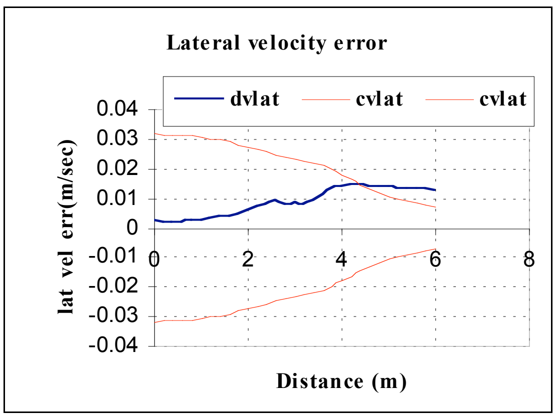

Figure 16: Firefighter lateral velocity error

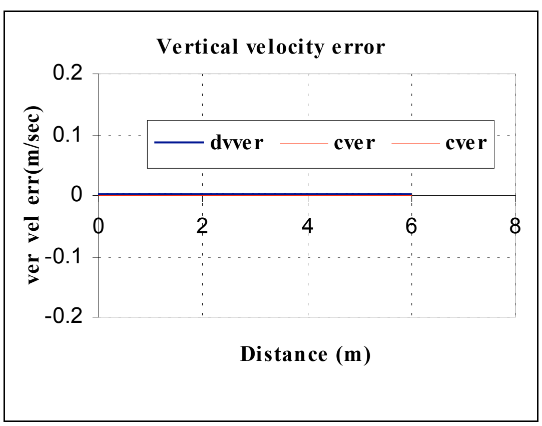

Figure 17: Firefighter vertical velocity error

Scenario 3 – moving southwest

For this scenario we picture a firefighter who moves about 13 m on the southwest direction as shown in figure 18.

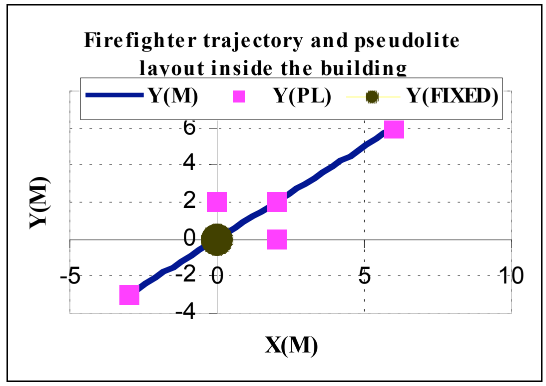

Figure 18: Firefighter moving in the southwest direction

The pseudolites are denoted with squares and the fixed receiver is represented with a circle. The firefighter moves in the southwest direction at $30\sqrt{2}$ cm per sec. The simulation results for this scenario are obtained by processing all the measurements that are obtained from the receiver (pseudorange, carrier phase, and Doppler).

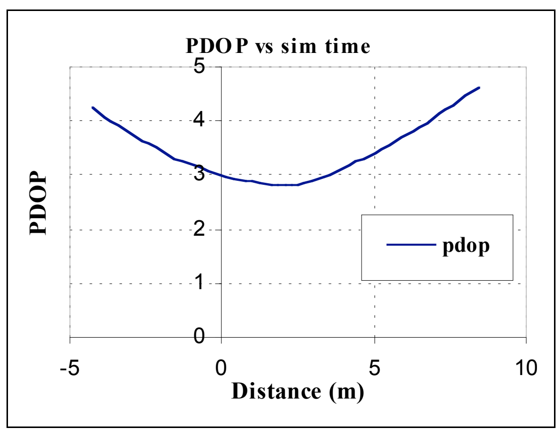

Figure 18: Firefighter PDOP

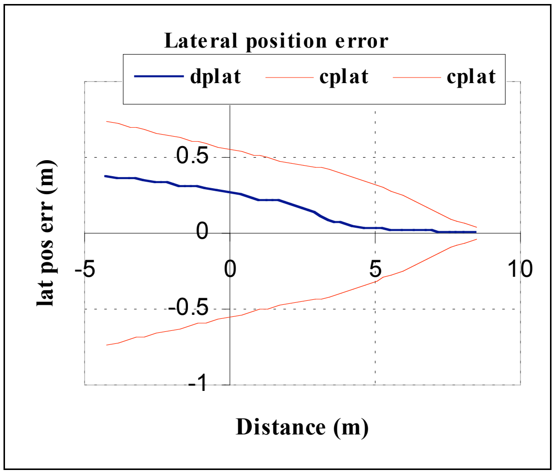

Figure 20: Firefighter lateral position error

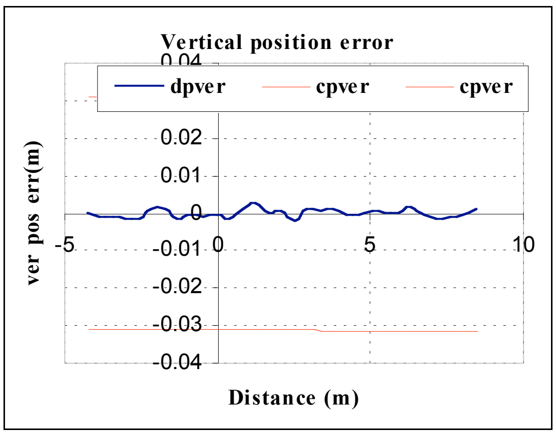

Figure 21: Firefighter vertical position error

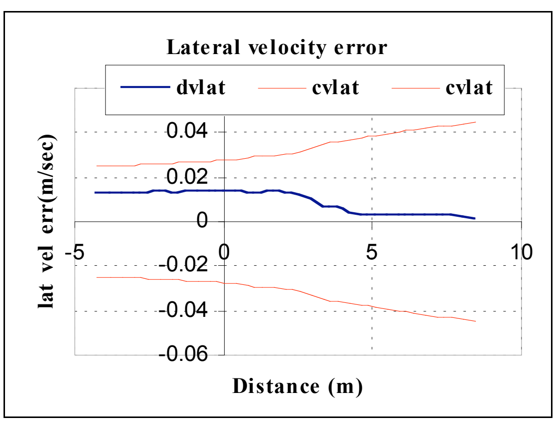

Figure 22: Firefighter lateral velocity error

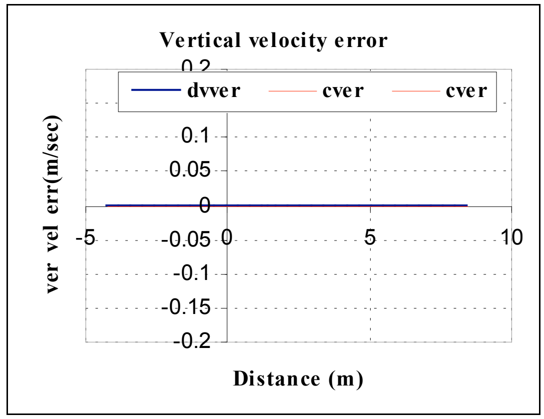

Figure 23: Firefighter vertical velocity error

Conclusions and Future Considerations

The work presented here represents a first step towards realizing a system that is capable of providing the real-time location of emergency workers inside structures. The basic concepts of GPS are exploited in a way that allows 3D positioning without access to the GPS satellites.

Several variations on the system presented are possible, and additional work to refine the overall system architecture is ongoing. Nevertheless, the simulations presented thus far suggest that sub-meter location of workers is possible.

References

1. *W. R. Michalson and I. F. Progri.* "Assessing the Accuracy of Underground Positioning Using Pseudolites." *Proceedings of the 13th International Technical Meeting of the Satellite Division of the ION, ION GPS-2000, September 19-22, 2000, Salt Lake City, Utah.*

2. *R. G. Brown and P. Y. C. Hwang.* Introduction to Random Signals and Applied Kalman Filtering. *Copyright © 1997, John Wiley & Sons, Inc. 1997*