WPI Precision Personnel Location System: Rapid Deployment Antenna System and Sensor Fusion for 3D Precision Location

A. Cavanaugh, M. Lowe, D. Cyganski, R. J. Duckworth

BIOGRAPHY

Mr. Andrew Cavanaugh is a M.S. candidate in Electrical and Computer Engineering at WPI. Since completing his B.S. EE degree at The University of Rhode Island in 2008, he has served as a research assistant in the WPI Precision Personnel Location Laboratory. His research is focused on improving the accuracy of the WPI Precision Personnel Location system, using Bayesian methods to fuse diverse sources of information.

Mr. Matthew Lowe has been attending WPI since 2005, and is currently working towards his M.S. degree in Electrical and Computer Engineering in the Precision Personnel Location Laboratory. Mr. Lowe has done funded research in the areas of applied mathematics, signal processing, and is currently focused on developing the tools necessary to efficiently fuse information from pressure, inertial, magnetic, and other sensors for use in location solutions.

Dr. David Cyganski is Professor of Electrical and Computer Engineering at WPI where he performs research and teaches linear and non-linear multidimensional signal processing, communications and computer networks. 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. He is a member of IEEE and a member of ION.

Dr. R. James Duckworth is an Associate Professor in the Electrical and Computer Engineering department at WPI. He obtained his Ph.D. 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 fellow of the BCS, a senior member of the IEEE, and a member of ION.

ABSTRACT

An RF-based 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 and rapid deployment. The RF 3D location system, based on a recently developed multicarrier signal fusion algorithm, has previously demonstrated submeter positioning accuracy of a transmitter, even in difficult indoor environments with high multi-path, with all receivers placed outside the building. However, the current version of the system requires a set of 12 to 16 antennas be distributed outside three to four sides of the building in order to obtain the necessary diversity of information necessary to precisely resolve 3D location. This is undesirable as a practical application of a Precision Personnel Location (PPL) system requires rapid deployment of any antenna nodes at a time when almost all manpower at the fire scene is dedicated to rapid and safe entry into the building and fire suppression activities. Thus, the act of antenna deployment must be extremely fast, easy and forgiving. This paper reports on the development and evaluation outcomes of an approach that permits 3D location based upon deployment of two antenna arrays on any one face of the building.

The positioning performance of the PPL system with the new antenna system will be compared to performance from the previous incarnation of the PPL system with widely distributed antennas. In the case of the new antenna system, outcomes will be shown for both the cases of Bayesian inference based upon additional sensor information and without this sensor information. The previously described[1], [2], [3], [4], [5] WPI PPL system has demonstrated 3D accuracies of better than 1 m in indoor tests. We will show that the new version of the system does not perform at the level of precision as that with a diverse antenna distribution, however, at a level sufficient to still significantly aid in search and rescue missions.

INTRODUCTION:

WPI PRECISION PERSONNEL LOCATOR SYSTEM

The Worcester Polytechnic Institute(WPI) Precision Personnel Location(PPL) system, being developed at WPI, is an RF based system for locating first responders inside of a building. More specifically, the goal is to have a system that is accurate within +/- one meter, portable, rugged, and rapidly deployable with no site preparation or on-site calibration procedures[2]. In recent years, the system has been expanded to consider fire, police, military, and even robotic vehicles in both urban and wilderness settings.
Figure 1 is an artist’s rendition of the PPL concept. The locator units worn by personnel emit a Multi-Carrier Wide-Band(MC-WB) signal that is received by multiple antennas located outdoors, around the building at known positions. The receiving antennas are connected to our transceiver units, which send the spectrum of the received signal to a central computer through a wireless network. The computer processes the data from all of the received antennas, and calculates the location of the firefighter based on the time-difference-of-arrival(TDOA) like algorithm involving a signal fusion approach.

The following sections will describe the current WPI location algorithm(σART), pure RF signal based tests of both the unrestricted and rapid deployments, additional sensor information introduced in this paper, and the results of the rapid deployment system information fused with these additional sources of information.

**The WPI PPL System**

The Precision Personnel Location system currently employs the σART algorithm to solve for the position of our locator unit using multi carrier complex amplitude data from receiving antennas. Unlike traditional approaches, which use multi lateralization to determine a location solution, σART considers data from all receiving antennas to solve for a position[7], [8].

In principal our Multi-Carrier Wide-Band(MC-WB) signal divides our bandwidth of operation B Hz into a collection of N discrete, unmodulated sub-carriers, spaced at B/N Hz [2]. In practice, hardware limitations keep us from placing sub-carriers near the upper and lower limits of our allotted bandwidth. Typically we employ approximately 100 sub-carriers spaced over a 150 MHz bandwidth. The carriers are spaced evenly, except where deletions have been made to avoid interfering with existing services in the range from 608 to 614 MHz, over our FCC allocated 550-700 MHz experimental band.

At a particular antenna, the signal measured at the output of a receiver may be written in the frequency domain, sampled at the transmitted sub-carrier frequencies \( \omega_k = 2\pi f_k \),

\[
X(\omega_k) \cdot H(\omega_k) \cdot \sum_i a_i e^{-j\omega_k t_i} \tag{1}
\]

where \( H(\omega_k) \) is the transfer function of the receiver and \( X(\omega_k) \) is the transmitted signal. Assuming these two terms are known, what remains is the channel response containing information about the direct and multipath signal components, each of which is a sinusoid:

\[
V(\omega_k) = \sum_i a_i e^{-j\omega_k t_i} \tag{2}
\]

where \( a_i \) is the amplitude for the \( i \)-th signal and \( t_i \) determines the periodicity of each signal with respect to \( \omega_k \) and is the propagation delay of the \( i \)-th signal. The σART algorithm assembles the measured channel responses from all antennas to the poor geometry this presents for 3D precision location within the context of the present TDOA-like multicarrier solution technique and especially when challenged within the high multipath indoor environment, large errors in the direction perpendicular to the antenna plane are experienced. To ameliorate this degradation of location precision, a new data fusion system has been developed that uses Bayesian inference to introduce additional, not necessarily precise or low variance information, to obtain a refined global solution. The flexible Bayesian inference engine allows additional information to be obtained from sources as diverse as low-cost inertial sensors and simple radio ranging sensors.

The goal of the WPI precision personnel location project is development of a system appropriate for use by first responders incorporating no pre-installed infrastructure, rapid deployability, medium (not ultra-wide) bandwidth, flexible and spectrally compliant signals, and low cost personnel tags[2]. Previous papers have described: development and performance of new signal processing and location techniques for the amelioration of the extreme multi-path conditions such as found in typical commercial and industrial structures[1], [2], [3], [4], [5], which usually frustrate all attempts to achieve precision location; incorporation of physiological monitoring sensors and real time display; automated solution of outdoor sensor positions for rapid deployment; synchronization technology for wirelessly connected transceiver nodes[6]. This paper describes a next generation of the PPL fast-deployment antenna system and requisite sensor and algorithmic support for solution of 3D indoor location from antennas located on only a single side of a building. An approach has been developed in which signals are captured from antennas mounted on two extension ladders that can be transported easily by fire truck and then quickly extended and leaned against a building face. However, due to the extreme multi-path conditions such as found in typical commercial and industrial structures, which usually frustrate all attempts to achieve precision location; in-
into a signal matrix $S$ whose columns are the channel response (2) measured at each antenna,

$$S = \begin{pmatrix} V_1(\omega_1) & \cdots & V_n(\omega_1) \\ \vdots & \ddots & \vdots \\ V_1(\omega_k) & \cdots & V_n(\omega_k) \end{pmatrix} = D + M. \quad (3)$$

Considering direct-path signal energy, the elements of $D$ correspond to phase changes due to line-of-sight propagation at the speed of light:

$$D = a_n e^{-j\omega_k t_n} = \begin{pmatrix} a_1 e^{-j\omega_k t_1} & \cdots & a_n e^{-j\omega_k t_n} \\ \vdots & \ddots & \vdots \\ a_1 e^{-j\omega_k t_1} & \cdots & a_n e^{-j\omega_k t_n} \end{pmatrix} \quad (4)$$

Given knowledge of the antenna positions $\vec{p}_n$, and frequencies $\omega_k$, the received signal may be re-phased for a hypothetical source location $\vec{x}$. This is done by calculating the appropriate delays from every point in the search space to each antenna; these pre-computed delays are then removed from the received data when computing the metric on the corresponding scan grid point:

$$D(\vec{x}) = a_n e^{-j\omega_k t_n} e^{j\omega_k ||\vec{p}_n - \vec{x}||/c} \quad (5)$$

where $c$ is the speed of light. Thus the matrix of received signals with propagation delays $t_n$ from a transmitter, re-phased to $\vec{x}$ can be written as

$$D(\vec{x}) = a_n e^{-j\omega_k t_n - \Delta t_n} \quad (6)$$

illustrating how the re-phasing adjusts the time delay content of the received signal. At the true transmitter location $\vec{x}_s$ (subscripted with $\star$), the delays removed by re-phasing are the same as the delays imparted by line-of-sight propagation, and the column vectors in $D$ become linearly dependent,

$$S(\vec{x}_s) = D(\vec{x}_s) + M(\vec{x}_s) = a_n e^{-j\phi_n} + M(\vec{x}_s) \quad (7)$$

and thus $D(\vec{x}_s)$ is rank one. As the re-phasing operation preserves total signal energy (the Frobenius norm of $S$), the rank structure, as described by the singular values (obtained via singular value decomposition [9]) of $S(\vec{x})$

$$U^H S(\vec{x}) V = \Sigma = \text{diag}(\sigma_1, \sigma_2, \ldots, \sigma_n) \quad (8)$$

reflects the distribution of received signal energy among the linearly independent basis vectors of $S(\vec{x})$. Assuming that the receivers are not overwhelmed by multipath signal energy, the first singular value $\sigma_1$ measures the strength of linear dependence between the re-phased direct path signal components and is maximized at the transmitter’s location. This is the $\sigma$ART metric or likelihood function[7] an example of which is shown in Fig. 2 for the case of an unrestricted deployment test at the site used in the current work and described below. The location of a firefighter is determined by exhaustively scanning the entire search space and then selecting the point where the $\sigma$ART likelihood function is maximized.

**ORIGINAL SIGNAL/ALGORITHM TEST RESULTS**

The test site chosen for our new rapid deployment method was the WPI Campus Ministry building. This site consists of a three story wooden house, on a typical urban house lot. To make the comparison between the previous and new deployment methods more meaningful, the new results will be compared with an older test performed at this same site. The test conditions are not identical; logistical constraints, such as furniture reconfiguration, off-limits rooms, and time limitations forced us to create a different set of truth points in the rapid deployment test. Although the points are different, we consider the overall test conditions to be equivalent, since both sets of points represent a large number of diverse locations throughout the house, which is assumed to have the same gross RF characteristics in both cases.

**Unrestricted Antenna Deployment**

In March of 2008, the PPL system was tested at the WPI Campus Ministry building. Antennas were placed on all sides of the building with various heights, as shown in Figure 3. The spatial diversity of the antennas in this configuration improves the solution by providing a sensor geometry with low geometric dilution of precision.

Figure 4 shows the error vectors from the unrestricted-deployment test. The XY mean absolute error is 0.93 m while the Z mean absolute error is 0.95 m.

**Rapid Deployment**

In July of 2009, the PPL system was again tested at the WPI Campus Ministry building. This time, flat panel receiving antennas were attached to aluminum extension ladders that were quickly moved into place on the right side of the house. In this case all of the antennas were approximately coplanar and parallel with the side of the house. For nearly coplanar antennas the position solution suffers a geometric dilution of

1Each ladder took two students less than 1 minute to deploy.
precision perpendicular to the plane. This increased ambiguity is seen as pronounced ambiguity in the X direction of the $\sigma$ART likelihood function, seen in Fig. 6, resulting in the positioning errors seen in Fig. 7 which depicts the error vectors from the rapid-deployment test. Owing to this large GDOP, the XY mean absolute error has degraded to 6.43 m while the mean absolute Z error is now 1.51 m. If we double the number of ladder-arrays employed, we find that the XY mean absolute error improves to 3.95 m while the mean absolute Z error becomes 0.82 m.

**ADDITIONAL SOURCES OF INFORMATION**

**Complementary RF-Ranging**

In the original system the mobile unit had transmit-only capability; for the new system under test, the mobile units have been given transceiver capability which was used to collect TOA information. The range between the mobile locator and each receive antenna is computed using a round-trip TOA based method. This range information is easily corrupted by RF propagation velocity changes that occur when the signal passes through walls, and other obstructions and/or is reflected.
To use these ranges to our advantage, we assigned a likelihood function to each of them using the estimated range as the mean of the likelihood function. This likelihood function is then used in the fusion algorithm to be described below.

Barometric Sensor

To obtain an additional independent source of height information, we measured the air pressure difference between our locator and a reference unit outside, at ground level. The ambient pressure can change in time frames on the order of minutes from natural weather conditions, and wind gusts can have effects that cause changes on the order of seconds in duration. The differential pair is used to cancel the effects of these pressure changes. To account for pressure changes in the building that result from HVAC equipment would require another reference unit indoors. This is not a technical challenge, but logistical constraints may make this second reference infeasible.

The barometric sensors are also significantly affected by temperature, which presents a problem when one unit is indoors and the other is outside. We calibrated the pressure sensors with experimental data. The design of the current locator units themselves introduce some error because the temperature sensor is not exactly co-located with the pressure sensor; this will be corrected with our next hardware version.

Every pressure sensor is assumed to have a constant bias as well as a linear temperature dependence. To remove these effects we conducted several experiments in which we measured the units at constant heights under varying temperatures. This data was then processed to estimate the required correction parameters. The resulting bias and temperature constants are shown for four units in Table I.

### Rapid Deployment Antennas with Bayesian Fusion

The Bayesian algorithm that we developed allows multiple data sets to be fused together to generate a single location solution. This algorithm considers information from the $\text{\sigma ART}$ likelihood function, barometric sensors, temperature sensors, and RF based TOA ranges. This algorithm allows us to enhance our accuracy in the challenging rapid deployment configuration. The Bayesian solution is obtained from an a priori distribution, which in our case is based on the assumption that the correct location is uniformly distributed over a search space corresponding to a 3-D region slightly larger that that which encloses the house.

The likelihood that the correct location is at a given point is:

$$\max_{x,y,z} P(\text{position}|M_{\text{\sigma ART}}, M_{\text{TOA}}, M_{\text{Barometric}})$$

Where $M_{\text{\sigma ART}}, M_{\text{TOA}}, M_{\text{Barometric}}$ denote the measured data. The likelihood metric is evaluated at every point on the scan grid, and the location estimate is given as the point where the metric is maximized. We found that the X,Y solution was relatively insensitive to values of Z assumed during the likelihood optimization process when these were restricted to the range of values consistent with barometric height estimates for a given floor. Thus, to increase solution speed, we scanned only the plane that was located at the height corresponding to the barometric measurement. This effectively changed the assumed prior distribution into a uniform distribution over the truncated horizontal plane consistent with the barometric height estimate, rather than a 3D space. Applying the remaining RF data to calculate the metric for every point on the plane gave us a 2D likelihood function whose maximum was our location solution.

The fused results, shown in Fig. 8, demonstrated an improved XY mean absolute error of 2.49 m in the 2 ladder case, and 3.07 m in the 4 ladder case. The Z error was 0.47 m in both cases. In both cases there is still noticeable GDOP in the X direction. The results of this evaluation compared to that of the previously described configurations and algorithms are shown in Table II.

### Conclusions

The importance of precision indoor positioning with no pre-installed infrastructure is well understood, and this paper presents significant progress toward that goal. Previously this research group constructed a system using RF-only technology with diversely distributed antennas which successfully demonstrated the concept of the new positioning approach while realizing that deployment requirements of the fire fighting environment and severe deployment restrictions would additionally need to be addressed. This paper explained these deployment requirements, the problem posed by them, the solution implemented, and the performance of a system enhanced by fusion of information from three sources.

While the Rapid Deployment/Fusion outcomes are less precise than the unrestricted deployment approach, the floor is always correctly identified (with half meter precision). The floor occupied by the subject to be rescued is considered, by firefighters, to be the single most valuable piece of information to promote timely rescues. The Y direction information has approximately 2 meter maximum error (4 ladder case), which
can be probed with classic swinging firefighter’s “pike” or ax handle. The larger (2-4 meter) X direction errors can be accommodated with rapid linear search, which is faster than searching the circular area swept by this same distance. Thus this paper documents what must be considered a successful demonstration of firefighter location technology with a rapid deployment system.

The new hardware (with mobile transceiver capability) which enabled the tests described in this paper also unlocks other opportunities that surpass in potential the basic fusion system just described. We are continuing active research aimed at further improving the precision of X,Y and Z estimates in the rapid deployment configuration.

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REFERENCES


