Autonomous Position Location in Distributed, Embedded, Wireless Systems

William Merrill, Lewis Girod, Jeremy Elson, Kathy Sohrabi, Fredric Newberg, and William Kaiser

Sensoria Corporation
200 Corporate Pointe, Suite 100
Culver City, CA 90230
310-641-1331x212
williamm@sensoria.com

ABSTRACT

To take full advantage of the potential of distributed embedded systems, methods for locating the positions of nodes within these systems are needed. In many cases these systems must operate autonomously without reference input from an outside source. This paper describes the merits of three general methodologies for position location when applied in a distributed, embedded wirelessly connected environment. In addition specific details on one implementation, time of flight acoustic signals synchronized via RF signals autonomously distributed over multiple nodes is presented, with discussion of the accuracy achieved with this embedded, distributed, wireless system.

1. INTRODUCTION

While GPS is becoming ubiquitous for absolute position location in a wide variety of applications, in many systems alternative position location methods are desired due to GPS's sensitivity to jamming, its requirement for a clear view of the sky for operation, its limited resolution, and its cost. This paper provides an overview of alternative geolocation mechanisms that may be used by embedded systems that only require relative position location, with a detailed description of results from one implementation using acoustic signaling, building on the substantial body of work which has been published in this area to date [1-8].

Relative position location for embedded wireless distributed systems, unlike GPS, often does not require an external infrastructure, and may not need a global reference position. In this paper discussion of the relative merits of active RF and acoustic signaling to determine range and/or angles between embedded wireless nodes is provided, as well as an assessment of current technology capabilities. Particularly, a comparison is made between time of arrival, angle of arrival, and path loss modeling methods to determine the relative locations of embedded wireless nodes, both via RF and acoustic signaling. Integral to this is an assessment of the impact of environmental and multi-path errors within each methodology, and the capabilities required for the synchronization necessary in acoustic and RF time of arrival ranging. The severe impact of multi-path signal propagation and dependence of signal path loss on environmental variation generally dictates the use of a time of arrival or time difference of arrival based methodology, either alone or in concert with another technique, for effective geolocation.

To demonstrate the capabilities of a relative position location system for wireless embedded nodes, details are provided on an implementation of a hybrid acoustic RF ranging technology. This technology leverages an RF 2.4GHz wireless communications channel to provide inter-node synchronization, and coordination between nodes, while determining the distance between nodes through acoustic signaling. This system is similar in concept to the recently developed USC and UCLA [1,2], the active bat, [3], and the active cricket [4,5] acoustic location systems. It operates in a purely peer-to-peer system, as one component within the DARPA/ATO Self Healing Minefield prototype communication and control system [9]. The acoustic signal consists of chaotic sequence emitted from four speakers on each node and received on other nodes in the system through their four microphones. The time of arrival at each microphone, synchronized over the RF channel with the acoustic transmit time, enables a range measurement at each microphone, which is then used to triangulate the source position, or reception angle. Collaboration between nodes over the RF channel is also accomplished to ensure reception of enough range and angle measurements to characterize the position of each node to a desired accuracy. Details are provided on the accuracy of this robust distributed system, which determines both angle and range between wireless nodes autonomously, then uses this information to compute a relative position for each node. Details on the performance of this system in both indoor and outdoor environments are presented. Individual range accuracy of less than one meter over tens of meters for up to twenty nodes is shown.

2. COMPARISON OF POSITION LOCATION METHODS

Location methods, whether based on acoustic or RF signaling may be broken up into three broad categories. These are Time of arrival (ToA), Angle-of-Arrival (AoA), and signal strength measurement. Alternate position location methodologies include dead reckoning systems (measuring a change in position) and inferred location due to proximity to a known location such as investigated within the Bluetooth Local Positioning Working Group [6]. However, this paper will focus on methods to provide relative location between stationary nodes, without requiring external location references.

ToA methods utilize a signal's time of flight, and assumptions about the signals velocity to calculate range, and possibly angle between nodes. Measurements of one-way time of flight, two way time of flight (active and passive reflectors), and time of flight difference between sets of nodes all fall into this general category. In the broadest sense continuous wave methods, which measure the phase change of an analog signal can be included in TOA methods although digital, or pulsed signals are generally used to measure a signal's travel time. GPS is also a TOA methodology in that it uses the time difference of arrival (TDOA) of various satellite signals. The central idea behind these methods is the use of signal propagation time measurements to obtain the distance between points.

A second group of position location algorithms, which in some cases are closely intertwined with the first are the angle of arrival (AOA) methods. AOA methods fix a source through triangulation, based on signal direction. AOA methods pinpoint the direction of a signal using the angular resolution of the attached antenna or antenna array in conjunction with signal processing of the signals from multiple antennas or antenna apertures, or by comparing the arrival time of the signal at various points within an array (treated as a TOA method in this paper).

The third method is the use of a received signal's amplitude measurement in conjunction with a propagation loss model to determine a transmitter's distance. This method requires a prior knowledge of both transmit antenna and receive antenna characteristics within the environment (radiation pattern, and antenna efficiency in each environment) as well as knowledge of the propagation loss along each signal path.

Significant errors may be introduced in each of these approaches due to multi-path reflections, due to environmental variation in path loss and acoustic signal propagation velocity, and due to timing errors. Table 2 summarizes the impact of each of these errors for both acoustic and RF implementations of these methodologies and provides a list of references for each associated error.

Errors due to reception of multi-path signals can be very substantial for all three methods. By modeling the RF or acoustic wave propagation with a ray-tracing picture the idea of substantial errors in time, angle, or strength of an incoming signal is easily understood.

Significant work has been done on measuring and modeling both the delay spread and angular spread of microwave signals due to multi-path indoors [1-5,10-14], outdoors [7,8,11,15,16], and even underground [17]. These references illustrate the problems that multi-path errors cause for a position location scheme. For example with 5.2GHz RF measurements in [11] in four outdoor urban scenarios 17 multi-path ray clusters can be distinguished for environments were Line-of-Sight is available, increasing to 31 ray clusters for obstructed LOS environments. These ray clusters can be separated further into individual multi-path components by their delay spread increasing to 26 individual "rays" for LOS and to 54 individual "rays" for non-LOS if separated in both angle and time. These individual multi-path components are spread over all 360 degrees (spread evenly indoors as shown in [12]), vary in intensity over 50dB, and over a delay spread of up to 500ns (150m path difference). The scale of these variations is confirmed for outdoor and underground measurements, with wide variation in time of arrival, angle of arrival, and signal strength due to multi-path signals. Thus to effectively operate an RF position location system requires a method to separate out the impact of the LOS and non-LOS signals. This becomes difficult with available low-power electronics, or requires dedicated RF front-end hardware. The reason is that the signals overlap particularly at the time scales required for accurate RF location, requiring timing tolerances (~1ns to distinguish 30cm) comparable to a multi-megabit communication overhead, while available energy on battery operated nodes may dictate the use of much lower signaling rates.

Multi-path is a similar consideration for the acoustic signal, as particularly in comparison with Microwave frequencies, scatterer size in terms of wavelength is comparable for most acoustic signals. While multi-path errors will impact both RF and acoustic signaling schemes, in some cases RF systems may be more sensitive. For example in systems operating near the ground at spacing much larger than either antenna height, the wave traveling along a direct path is effectively canceled to the first order by the wave reflecting off the ground so that the power level of waves scattered off large obstacles can be comparably significant [18,19]. Since acoustic waves propagating in air only encounter higher impedance surfaces, the phase inversion seen for RF on reflection off the conducting ground does not occur, so that acoustic signals do not suffer this cancellation. In addition, due to the six orders of magnitude slower acoustic propagation velocity in air (~345m/s) when compared with RF, separation of multi-path components is simplified with available hardware, as it can be done in near real time on the digitally sampled signal with power efficient commercial off the shelf (COTS) components. However acoustic signals are much more environmentally dependent.

Environmental variations both over time and from environment to environment can impact the accuracy of both RF and acoustic locations methods. For RF the variation from environment to environment is most significant in reducing the effectiveness of signal strength methods, or in preventing the reception of a signal above the noise floor at the desired distance. For example empirical fitting of path loss data to a power law fall off with distance often results in exponents ranging form 1 to 6 [15-21], making anything but relative comparisons unwieldy (and due to spatial fading even complicating those). In addition acoustic signal propagation varies in velocity, strength, and even direction based on environmental changes in the propagating medium (wind, humidity, vertical temperature profiles, temperature changes along the signal path, etc.). This is a multifaceted problem in that both the turbulence and the temperature inhomogeneity of the air through which sound is passing will limit the time of flight accuracy and range. Particularly for systems that depend on phase comparison across multiple sensors in an array, as turbulence and varying temperature profiles of each path distort the coherence of individual rays, the errors can mount. For example in [22] coherence lengths of less then 2m in the transverse direction for measurements in a refractive shadow are shown. In addition the environment can significantly affect the distance over which the acoustic signal travels as temperature inversions (in the vertical air temperature profile) cause upward refraction and an artificial shadow boundary for low lying nodes. In conjunction with the velocity of sound variation with the square root of absolute temperatures, and more muted variation with humidity, this can cause significant environmental variation. These errors increase with the distance over which acoustic signals travel, thus they are manageable with intelligent processing of the data. However, they constrain the solution space.

In addition to multi-path and environmental considerations AOA methods require a size at least the order of the wavelength considered to separate phase variation, and electric or mechanical scanning of the antenna's reception or transmission direction. To differentiate a signal's direction, signal processing may take advantage of a smaller number of antennas than in a conventional phased array system (which are typically at least tens of wavelengths across) to differentiate signal phase or signal time of arrival at multiple antennas, and from that offset incoming signal angle. However even these methods require multiple antennas, preferably on the order of half a wavelength apart.

Amplitude measurement schemes are subject to the high degree of variability in propagation loss encountered by microwave and acoustic signals discussed earlier. In addition to the variation in signal fall off in different propagation environments [15-21] (which might be accounted for empirically through measurements in a local environment) there may be substantial variation in the antenna's characteristics [23]. First the non-isotropic nature of the antenna must be accounted for since even if the antenna is designed to radiate isotropically in the presence of the ground, different antenna characteristics are seen when the antenna flips over, or is near a tree for example. In addition to signal strength differences due to the radiation pattern, there will also be signal strength differences if the ground or near field scatterers detunes an RF antenna. This may cause variations on the order of tens of dB in similar propagation paths depending on the angle between the received and transmitted antennas and the matching of the antennas in their deployed environments

Like the other two method types TOA methods are subject to error due to signal multi-path. However, while multi-path may cause severe problems in certain environments (such as indoor areas) methods are available to alleviate it by time gating to acquire only the first received signal. In addition, the error induced in TOA systems by multi-path is generally smaller than that seen in both AOA methods and amplitude measurement methods. The key requirement in TOA methods is achieving the granularity of the time scale needed to measure the travel time between nodes (10ns to travel 3m for RF and 10ms for 3.5m acoustic). The required clock chip need not be this quick if the system can measure chip offsets as is commonly done with partial chip correlation in GPS systems. By comparing offsets between an incoming PN code and an internally generated code sub 1% accuracy chip offset can be obtained with a 10MHz chip rate (yielding a sub-nanosecond resolution).

As a result of the error analysis discussed above and illustrated in Table 2, the system we have implemented is based on acoustic time of arrival signaling, leveraging an RF synchronization method. This system is described in the following section.

3. EXAMPLE IMPLEMENTATION

SELF HEALING MINEFIELD

An implementation of a stand-alone position location methodology has been built into the nodes developed in DARPA/ATO's Self Healing Minefield (SHM) program [24]. The SHM system uses acoustic ranging in conjunction with broadcast RF synchronization [9,25,26] to obtain the range and angle between pairs of nodes in a local area. From this range and angle data a node builds a local coordinate system for surrounding nodes, then merges multiple local coordinate systems to create a field table on each node in the system. A system of twenty nodes has been demonstrated in operation in August 2002, with a sample prototype shown in Figure 1.

Figure 1: SHM node, which includes a stand-alone autonomous position location system shown next to a pen.

The SHM node includes within a 12cm diameter 4.4cm tall cylinder four Kingstate KDS-27008 micro-speakers and electrolet condenser microphones, a SH4 7751 microprocessor, and dual AC97 CODECs to support separate processing and transmission on each of the four speaker and microphone channels at a rate of 48k samples/s.

The SHM node incorporate a self-assembling network [9,27], which leverages broadcast time synchronization [9,25,26] to provide an infrastructure of nodes with a common time base each equipped with four independent speakers and microphones. These speakers and microphones are used, in a TDMA scheme through coordination over the RF channel via the self-assembled network [7,27] to determine the acoustic time of flight between their individual speakers and the microphones on surrounding nodes. Within this paper focus will be given to the acoustic ranging capabilities of the SHM node, with further details on the platform operation provided in [9].

The acoustic ranging (AR) module of the SHM node leverages the inter-cluster synchronization provided by the link monitoring software module. The heartbeat provides synchronization over RF [9,25,26]. Utilizing this synchronization each node can determine the range to other nodes based on a one way acoustic time of flight. In the current system each node that has an RF modem operating as an RF base also synchronizes all acoustic signaling within a local area in a TDMA cycle with the RF remotes.

The AR module sends a different BPSK coded 1024 bit length chaotic sequence out of each of four speakers on a single SHM communication unit. The signals are coded at a chipping rate of 10kHz, centered at an acoustic carrier frequency of 12kHz. The signals are received by each of the nodes expecting a signal, and correlated for each of the expected chaotic sequences. In doing this correlation the sampled data (on each of the four microphones) is also evaluated to determine a representative noise level. Then based on the correlated signal level, a signal-to-noise ratio is assigned to each of the sixteen microphone and speaker pairs, between two nodes. This SNR is then used to determine whether to use the sampled data or not. First the speakers are compared, and the speaker with the highest SNR values chosen to use for all processing (giving an indication that this speaker is pointed towards the receiving node and reducing the influence of multi-path). Then the four microphones sampling the signal sent by this speaker are compared (if they have a large enough SNR) to provide both a range between nodes (the weighted average) and an angle between nodes, determined from the weighted time of flight differences between each microphone pair. The transmission of these acoustic chaotic sequences is scheduled by each cluster's RF base. Thus each node within an RF cluster attempts to get the range and angle to every other node in the cluster.

The base in the RF cluster then collects the range and angle data calculated between each pair of nodes, evaluates this based on comparing two way paths and associated SNR, and requests re-ranging as appropriate. These range and angle values are then used as input and to compute an initial guess for a least squares multilateration optimization described in [28], to determine a relative coordinate system for the list of nodes in the range table.

To expand the multilateration table on to include the nearest fifty or so neighbors the multilateration from each base is communicated [9,27] to the fifty or so nearest neighbors. Each node then contains a collection of multilateration tables that are merged to provide a field table. To minimize error nearest each node, the merging is accomplished by starting with the largest multilateration table that contains the node in question, then averaging in each multilateration table with this one based on the largest common node set. Merging is accomplished independently on each node to provide a field table with the node on which it resides at the origin.

Updates to the field table are provided as needed by sending around updates to the multilateration tables. These updates are then merged into each node's field table whenever a change in the system requires re-ranging (such as node movement).

4. EXPERIMENTAL RESULTS OF SHM IMPLEMENTATION

The SHM communication unit and ranging system has been tested both indoor and out. Discussion of the results for these experiments is provided below.

The accuracy of determined positions from seven SHM nodes operating outdoors on top of a parking garage is shown in Figure 2. Within this figure the measured locations (ground truth) for each node is shown in blue (accuracy of ±25cm) and the field table reported locations shown in red. Accuracy is seen in this case to be within the ±25cm ground truth accuracy at the coordinate system level.

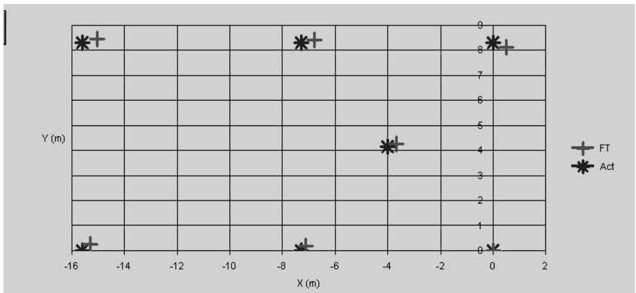

Figure 2: Node generated map for 7 nodes. Note agreement between location map (+) and ground truth locations (*).

Similar to Figure 2, the reported results compared with the ground truth locations of a twenty-node test in Missouri in mid August near the middle of the day are shown in Figure 3. This figure also displays the RF network used by the SHM nodes (colored lines for those monitored directly over Ethernet) to determine their position. In this figure the grid lines are at one-meter intervals over a 40m by 30m area, and the center of each rectangle corresponds to a node's reported position.

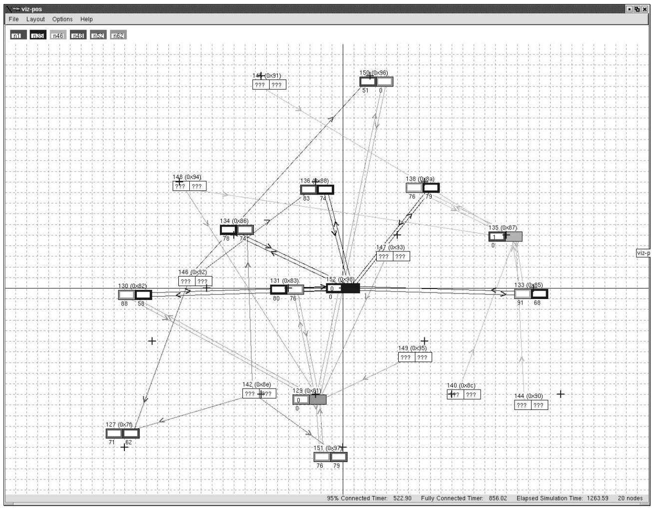

Figure 3: Twenty-unit SHM reported field table, compared with ground truth locations (blue +).

To assess the repeatability and accuracy of the acoustic ranging distance and angle measurements, a suite of measurements have been compared. These measurements were taken indoors in an office environment with LOS paths existing between each node pair, but in close proximity to walls, the ceiling and cubicle boundaries. These measurements for range and angle are shown in Figure 4 and Figure 5. For comparison the angles and ranges between the nodes are given in Table 1.

A	B	A to B	B to A	Separation
84	81	85°	265°	285cm
84	89	45°	225°	480cm
84	87	70°	250°	415cm
84	83	55°	235°	1040cm
84	88	55°	235°	865cm

Table 1: Ground truth angles and ranges corresponding to Figure 4 and Figure 5.

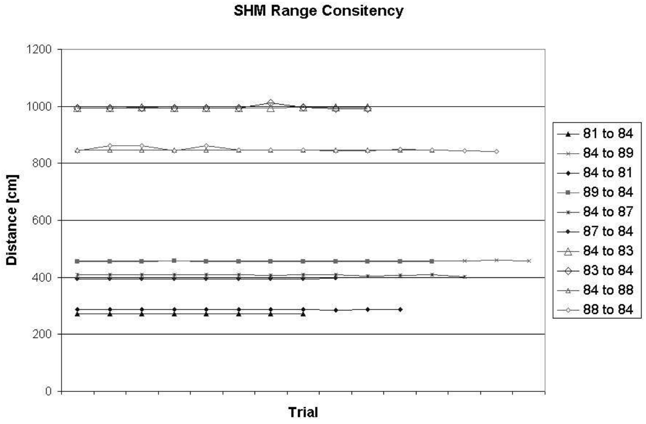

Figure 4: Range consistency between nodes during acoustic ranging testing.

In conjunction with the RF range testing, acoustic ranging accuracy at distance of operation has been recorded based on outdoor measurements on an open field. These measurements were conducted at temperatures around 40°F during mid-day, first at the corners of a 3m, 6m, and 12m square, and then to ensure RF communication by raising each SHM node 20cm onto cardboard boxes at the corners of a 18m, 24m, and 36m square. Figure 6 shows the error between measured node spacing and that calculated by the node's acoustic ranging. In this figure the errors at a spacing of 24m and 36m are magnified, given that the node spacing were not measured individually, rather the nodes were set out along a marked 3m grid, which for comparison had errors when comparing the measured distances at 6m, 12m, and 18m of up to 70cm. Figure 7 provides the errors seen in the angles for this same set of measurements. The errors are within ±1m in range and generally within ±30°, with one angular measurement off by 180 degrees

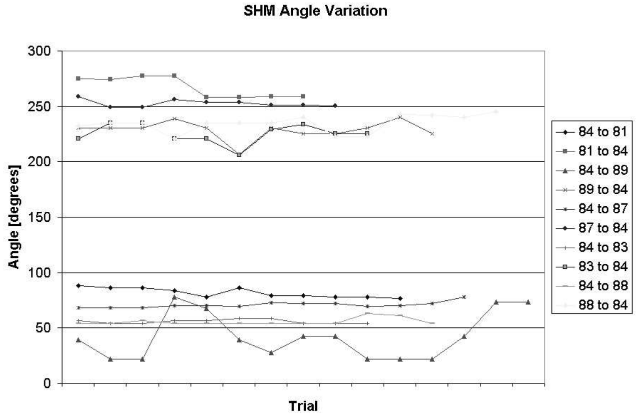

Figure 5: Angle consistency between nodes during acoustic ranging testing.

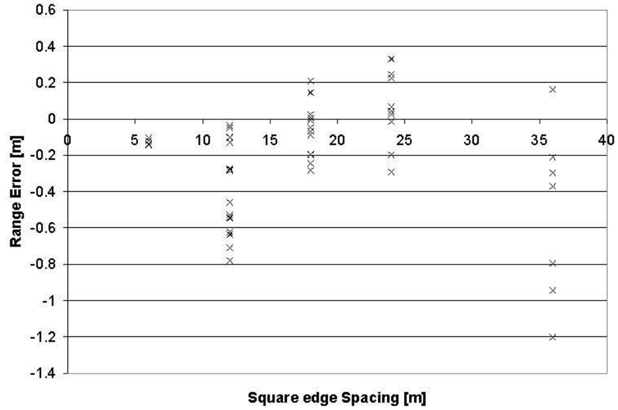

Figure 6: Error seen in outdoor range measurements. Included at each spacing are measurements along the square edges and the square diagonals.

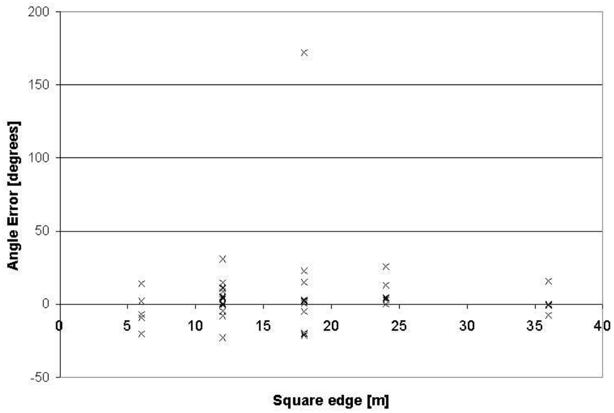

Figure 7: Error seen in outdoor angle measurements. Included at each spacing are measurements along the square edges and the square diagonals.

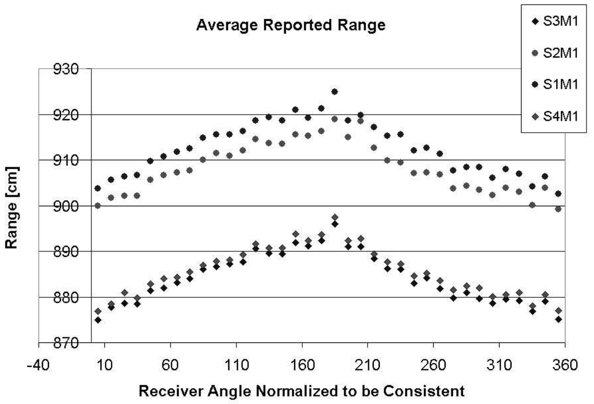

Figure 8: Range measured based on four different speakers on an SHM node as the sending node was rotated through a full circle.

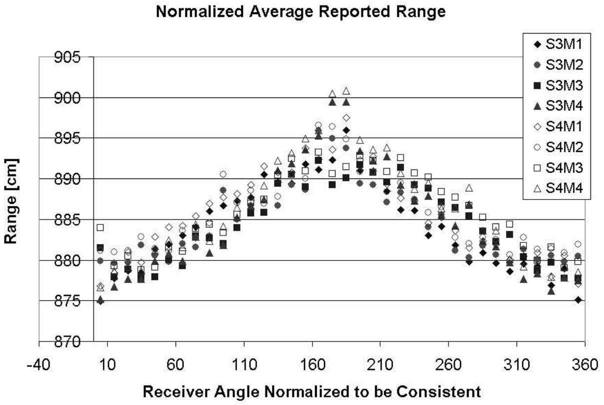

Figure 9: Range reported at four different microphones on a node based on two different speakers at a distance of 914cm.

To continually assess the performance of the SHM system, the directionality of each speaker and microphone has also been assessed. For example shown in Figure 8 is the range reported for two SHM nodes 30ft (9.1m) apart at each of the four speakers on the node as the receiving node was rotated through a circle. In this figure to assist comparison the rotation angle for each microphone is shifter by 90°, and the two CODEC outputs are shifted by20cm to more easily distinguish speakers one and two (S1 and S2) from speakers three and four. The reported range consistency across microphones (M1 through M4) for the signals sent from speakers one and two is shown in Figure 9.

In addition to the relative ranges seen at each microphone based on different speakers, the ratio of the signal correlation peak the correlation to the noise background was also measured as the SHM nodes were rotated. This measurement is shown in Figure 10 where significant impact of the microphone directivity is seen on the correlation peak. For reference the current system requires a correlation confidence factor of 10 to utilize the acoustic measurement. In addition to the pattern testing, the range of the acoustic ranging system between two nodes on the ground was tested at Kenneth Hahn Park in Los Angeles on a cloudy afternoon with gusty wind conditions. Acoustic ranging results measured out to 55m with an average correlation confidence factor of 7.2 (maximum of 19.5) over ten trials between the speaker and microphone facing one another, and an average of 4.4 on the diametrically opposed speaker and microphones.

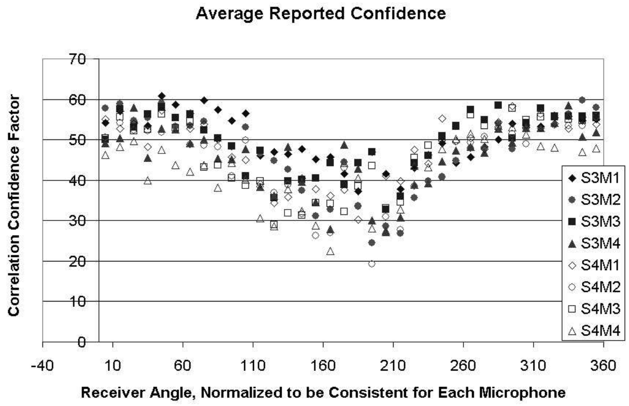

Figure 10Correlation Confidence as an SHM node is rotated at a distance of 914cm.

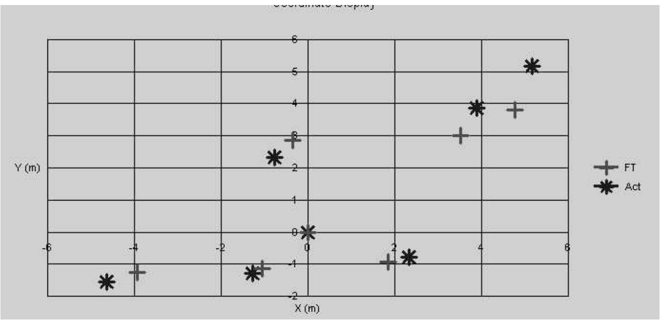

Figure 11: Comparison of reported (red +, FT) and ground truth coordinates (blue *) for a seven node test indoors.

In addition to the results shown in Figure 2 a reported field table for seven nodes operating is shown in Figure 11. In this table both ground truth (measured with ±25cm accuracy) and reported positions are shown. This test was conducted within a small open office suite with the seven nodes placed atop of cubicles. All nodes had LOS with other nodes, and were within 1m of the ceiling and in some cases within 1m of a wall.

5. CONCLUSIONS

Within this paper the relative merits of three position-location methods has been discussed with focus on the impact of multi-path and environmental variation on relative location accuracy. In addition a description of, and results from the operation of a hybrid acoustic RF position location technique within the prototype SHM communication nodes developed by the SAIC team under the direction of the DARPA/ATO has been provided. These results demonstrate operation both indoors and outdoors, and present results on system performance in these environments.

6. ACKNOWLEDGEMENTS

This work was partially supported by DARPA/ATO contract DAAE30-00-C-1055. In addition we would like to acknowledge the substantial guidance and advice provided by Thomas Altshuler with the DARPA/ATO office, and to Glenn Rolader, and John Rogers both at SAIC.

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Error Source	ToA	AoA	Signal Strength
RF Multi-path	Non-LOS signals can significantly delay the signal. [10-17] First arrival gating can compensate for this to some extent with dedicated hardware.	Non-LOS signals mean signals may come from any direction. [10-17]	Large variation in strength in multi-path signals. [10-17] Particularly, in near ground environments were path loss varies as the fourth power of distance. [18-21]
RF Environment	If LOS signal exists, minimal impact at ranges less then a few kilometers Influences the strength of LOS versus multi-path. [10-21]	If LOS signal exists, minimal impact at ranges less then a few kilometers Influences the strength of LOS versus multi-path. [10-21].	Substantial variation due to environment, spatial fading can cause significant errors. [10-21]
RF Synchronization	Speed of light requires high synchronization for TOA, or stable turn round time for round trip timing [7,8,29,30].	Stringent if phase comparisons of different receivers are used to calculate angle, particularly if done in digital post processing.	NA, as the time scale of fading is very long compared to that of propagation.
Acoustic Multi-path	Non-LOS signals can significantly delay the signal. [33-34]. First arrival gating can compensate for this. Simplified in comparison to RF due to slower signal velocity.	Non-LOS signals may come from any direction. [33-34]	Substantial variation in strength in multi-path signals. [33-34]
Acoustic Environment	Wide dependence on both environmental scatterers and varied propagation velocity dependent on the medium. [32-34] In addition wind and air turbulence can cause additional error [22,31,32].	Wide dependence on both environmental scatterers and varied propagation velocity dependent on the medium. [32-34] In addition wind and air turbulence can cause additional error [22,31,32].	Substantial environmental variation both within an environment (weather) and between environments. [22,31-34]
Acoustic Synchronization	Simplified in comparison with RF [25,26]	Wind and air turbulence can cause significant error if using beam forming [22].	Fast fading can complicate distributed combinations of multiple measurements.

Table 2: Significant Error sources for different position location methods.