ZeroKey's Quantum RTLS Indoor Positioning System

Dr. Christopher Leskiw, Dr. Guojiang Gao, and Matthew Lowe

Abstract- ***Many*** **Indoor Positioning Systems (IPS) are emerging to meet the needs of industries that are looking to track personnel, autonomous vehicles, manual workflows, and assets in order to dramatically improve worker safety and process efficiency. To date the disclosed IPS system is the only solution that can demonstrate consumer-ready three-dimensional positioning accuracy at millimetre-level across very large environments. This paper provides an overview of ZeroKey's first generation IPS, Quantum RTLS, and introduces the laboratory testing performed to verify performance. A brief outline is provided of the types of deployment scenarios that are currently active. The positioning problem is described. mathematically, and the traditional solution is presented. Ranging performance of the proprietary implementation is shown to be comparable to that of geodetic-grade optical instruments (e.g. total stations) and that multidimensional positioning performance is best-in-class achieving accuracies down to the millimetre. Real world trials show millimetre-level performance (sub-centimeter in the worst case) across large industrial environments such as warehouses, factories, and logistics hubs. The technology's flexible form-factors allow for daisy chained permanent installations or agile battery powered deployments. Accompanying software provides a flexible user experience that readily interfaces with equipment spanning from conventional computing hardware to the latest virtual and augmented reality platforms.**

Index Terms- **indoor positioning, ultrasonic time-of-flight, multilateration, Kalman filter, acoustic ranging**

I. Introduction

GLOBAL Navigation Satellite Systems (GNSS) and Indoor Positioning Systems are two of the key technologies sharing center stage in today's navigation and positioning revolution. While GNSS is a robust 3-dimensional, geolocation technology providing civilian-use positioning accuracy on the order of 4 metres RMS [1], the dependence on line-of-sight signals from satellites limits reliable use to outdoor and clear sky environments. As such there is a growing landscape of solutions to deliver reliable positioning in indoor environments. Just as a multitude of new goods and services were made possible due to an accurate outdoor positioning system (i.e. GPS), similar economic opportunities await solutions to the exponentially growing indoor positioning market. Estimates predict the market opportunity to be on the order of $10 billion per year by 2024 [2].

There is a heterogeneous collection of technologies delivering IPS, spanning radio frequency-based solutions such as cellular 5G networks, Wi-Fi networks, ultra-wideband (UWB) transceivers, and Bluetooth Low Energy (BLE) devices, to optical solutions using cameras or lasers.

Most non-camera based IPS solutions operate fundamentally by determining the distance of a tracked object to a known reference device. This is accomplished by relating received signal power or time-of-flight to a distance. In the case ofBLE and Wi-Fi solutions, localization of objects relies upon the Received Signal Strength Indicator (RSSI), and offers positioning accuracy on the order of meters (e.g. 70 cm to 20 m) [3][4]. Ultra-wideband systems have better accuracy by measuring the time-of-flight (TOF) of an Electro-Magnetic (EM) wave from an object to several receivers (anchor nodes), achieving measurements accurate to tens of centimetres [5]. Camera-based computer vision provides accuracies ranging from 15 cm to 1 m [6], depending on the environment and lighting conditions. Similar to UWB, ultrasonic systems utilize a TOF method for range finding, however due to the relatively slow speed of sound when compared to EM waves, can provide significantly improved localization accuracy, generally within 2 cm [7][8], and in the case of ZeroKey's Quantum RTLS implementation within 2 mm.

TOF based positioning is similar to TOF imaging, i.e., medical sonography, where energy in the form of waves is transmitted into an area to be recovered by an array of receivers. The time-of-flight is measured and converted to a distance in order to calculate a position. In the case of imaging, the distance will represent the distance to a reflector that redirected

C. Leskiw Ph.D., P.Eng., is a member of IEEE and APEGA, working as a principal engineer at ZeroKey Inc., Calgary, Alberta (e-mail: cleskiw@zerokey.com).

G. Gao has his Ph.D. specializing in GNSS and is head of algorithm development at ZeroKey Inc. (e-mail: guojiang@zerokey.com).

M. Lowe is the originator of the IPS solution and CEO at ZeroKey Inc. (e-mail: matt@zerokey.com).

the wave to receivers that are typically located near the transmitter as complimentary components of the same imaging device. However, in the context of a positioning system there is a separation between the transmitter and each receiving device such that the computed ranges represent the separation distance between the devices. With an array of receivers producing an array of ranges, the transmitter's location can be determined using a multilateration method, assuming the locations of the receivers are known.

The separation between the transmitter and receiver complicates the range calculation as the receiver and transmitters do not share a common clock, a requirement to measure the time-of-flight of a signal. In the case of imaging, because the transmitter and receivers are co-located, the clock is shared within the same device.

To overcome the challenges imposed by unknown time information, one of two solutions are typically employed. One solution requires the receivers (or transmitters) to have synchronized clocks such that the time-difference-of-arrival (TDOA) can be used to recover the clock information [9]. A second solution employs two way ranging where a round trip signaling exchange is used to transmit TOF information to the originating device, which maintains a single clock shared across its transmitting and receiving components [9]. Unfortunately, in either case, errors in timing from clock drift or system latency Are significant and are multiplied by the wave of propagation

speed. In the case of EM waves, even a small timing error results in very large range errors due to the extremely fast

propagation speed, i.e., the speed of light (2.99×10^8 mis). In GNSS this problem is addressed through the use of highly accurate and synchronized atomic clocks, which are a key component of every GNSS satellite. Such an approach is feasible for systems with such a limited number of satellites, however for indoor systems where reference devices may number into the thousands, it is clearly infeasible to include an atomic clock in every device.

II. HYBRID IMPLEMENTATION FOR ACCURATE IPS

An accurate range measurement between the target (also herein called the mobile) and reference device (also herein called an anchor) is the limiting factor for accurate 3D positioning. ZeroKey's solution merges the most reliable and accurate ranging techniques. The large propagation speed differential between ultrasonic and EM waves permits the use

of the EM wave as a time reference while taking advantage of the slower ultrasonic wave for the distance measurement [10]. The main advantage ultrasonic waves offer over their EM counterparts is the increased time allotted for signal samples to be collected between the transmission and reception of the acoustic wave. Range error is inversely proportional to wave propagation speed and for a point-to-point transmission is determined by:

$$\delta r = dT \times c \qquad (l)$$

where Or is the range error in meters, c is the wave propagation speed in mis, and dT is the timing error in seconds. For precise positioning, the smallest achievable Or is desired. It is apparent. that if timing error is determined by the quality and cost of the hardware, it can then be assumed to be consistent across devices within the same product class. Thus, to achieve the smallest Or the much lower propagation speed of acoustic waves (-343 mis) is desirable over that of EM waves (2.99×10^8 mis).

A second advantage of using acoustic signals for ranging is the improved multipath characteristics, i.e. the manner in which the wavelength of the wave dictates how the energy is absorbed, reflected, and diffracted off of objects in the environment. For example, the reflections off a nearby moving forklift or a storage rack, are specular for high frequency EM waves yet diffuse for ultrasonic waves. Specular reflections are a problem since they arrive as overlapping time-shifted copies of the transmitted signal, corrupting the original signal and the calculated range [11]. In the case of diffuse reflections, the transmitted energy is scattered in multiple directions, ultimately presenting as a lower level of multipath noise at the receivers.

A. Implementation Overview

When two signals with different propagation speeds are sent from a mobile device to a fixed anchor, the distance between them can be determined by:

$$r = \frac{c_{rf} c_a \Delta t}{c_{rf} - c_a} \qquad (2)$$

where r is the distance between the mobile and the anchor, Crt is the propagation speed of the first signal, Ca is the propagation speed of the slower signal and M is the difference between the arrival times of the two signals [10]. Once a range is determined between the mobile and the anchor, it is possible to relate the range to a position of the mobile device, depending on the desired dimensionality of the position and the number of available ranges. With an increasing number of ranges available it becomes possible to localize the device to an increasingly specific position as depicted in Fig. 1. below:

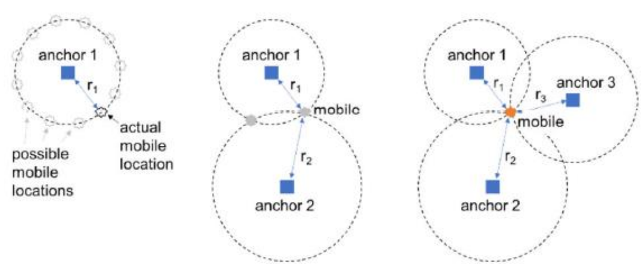

Fig. 1. The location of the mobile is determined by a multilateration. method

Conveniently, the mobile only needs to send out one EM and acoustic signal pair for all anchors to detect, i.e., each anchor does not need to be individually addressed, and therefore the multiple correlated ranges can be calculated simultaneously.

Due to environmental noise and other noise sources, there will be accuracy impairments in the calculated ranges which adversely affects the calculated position. Modem GNSS techniques to estimate the mobile position (i.e. Kalman filter, Bayesian estimator, least squares method, etc.) also apply to the

Quantum RTLS system and are utilized to derive the best estimate of the mobile position. Fig. 2 (right) illustrates the solution ambiguity arising from range measurements corrupted with error, as opposed to the case where the calculated ranges are exact as shown in Fig. 2 (left).

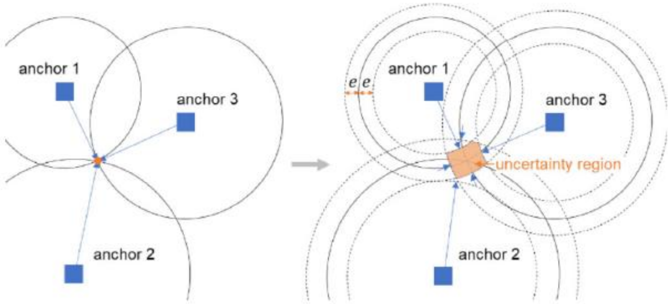

Fig. 2. Multiple range measurements are used to narrow the location estimate of the mobile, the ideal position (left) is resolved to an uncertainty region (right) due to measurement errors

B. *Error Minimization*

In order to derive the best estimate of the mobile's position from a collection of imperfect ranges, an expression for the position error is investigated:

$$e = \sum_{i}^{N} (r_{m_i} - r_i)^2$$

where e is the sum of the squares of the individual range errors, r_{m_i} is actual range between the mobile and anchor i, and r_i is the calculated range based on the transmitted and received signals. Minimizing the error becomes a well-known mathematical optimization exercise. The straightforward approach takes the derivative of (3) and sets it to zero. This requires the expanded versions of the components that make up e:

$$r_n = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2 + (z_m - z_n)^2} \tag{4}$$

$$e_i = \left(r_{actual} - \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2 + (z_m - z_n)^2}\right)^2 \tag{5}$$

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where x_m, y_m, z_m represent the unknown coordinates for the mobile, x_n, y_n, z_n represent the known coordinates for anchor n, r_n is the calculated range to anchor n based on the TOF measurement. Therefore, a solution for an over determined linear system of equations exists in the form:

$$\boldsymbol{R} = \boldsymbol{A}\boldsymbol{m} \tag{6}$$

where in this case:

$$\boldsymbol{m} = \begin{bmatrix} x_m \\ y_m \\ z_m \\ \sqrt{{x_m}^2 + {y_m}^2 + {z_m}^2} \end{bmatrix}, \tag{7}$$

$$\boldsymbol{A} = \begin{bmatrix} -2x_1 & -2y_1 & -2z_1 & 1 \\ -2x_2 & -2y_2 & -2z_2 & 1 \\ \vdots & \vdots & \vdots & \vdots \\ -2x_n & -2y_n & -2z_n & 1 \end{bmatrix}, \tag{8}$$

and

$$\boldsymbol{R} = \begin{bmatrix} r_1 - {x_1}^2 - {y_1}^2 - {z_1}^2 \\ \vdots \\ r_N - {x_N}^2 - {y_N}^2 - {z_N}^2 \end{bmatrix}. \tag{9}$$

Since $\boldsymbol{m}$ contains the unknowns (6), the equation is rewritten to isolate them:

$$\boldsymbol{m} = \boldsymbol{A}^{-1}\boldsymbol{R}. \tag{10}$$

In most cases $\boldsymbol{A}$ is not square and therefore not invertible. The matrix is multiplied by its transpose to obtain an invertible square matrix. After applying the transpose to both sides of the equation:

$$\boldsymbol{A}^{\intercal}\boldsymbol{R} = \boldsymbol{A}^{\intercal}\boldsymbol{A}\boldsymbol{m}, \tag{11}$$

and

$$\boldsymbol{m} = (\boldsymbol{A}^{\intercal}\boldsymbol{A})^{-1}\boldsymbol{A}^{\intercal}\boldsymbol{R}. \tag{12}$$

The $\boldsymbol{A^1A}$ term is invertible [12]; thus $\boldsymbol{m}$ can be solved. The solution is the least squares solution as the resulting position is the one that minimized the square of the differences between the actual and measured ranges.

C. *Timing Correction*

Minimizing the error in the ranges also requires proper detection of the moment of arrival of the incoming signals. The receiver often takes the form of an energy detector [13] that detects energy levels above a certain threshold.

To determine the range precisely, ZeroKey has developed proprietary methods to provide industry leading performance as shown in the following section.

III. IMPLEMENTATION PERFORMANCE

ZeroKey's solution consists of one or more mobile sensors, several anchors and one or more USB or Ethernet connected gateway modules. Two performance metrics are the focus of system verification: ranging accuracy, and 3D positioning accuracy.

For range verification, the system aims to be as accurate as conventional laser rangefinders that have accuracies within+/- 2 mm. To test the performance, a mobile device is attached to a robotic rail car that carries the mobile and a laser rangefinder along a rail while measuring the distance between the car and a fixed anchor. The setup is depicted in Fig. 3. At each desired distance the range is measured by the laser and by the ultrasonic mobile-anchor pair whilst noise is injected to mimic real-world conditions. Fig. 4 graphs the results for a typical experimental run for ranges between 0.4 m and 3 m. Typical results are within the ranging accuracy of the laser ranger when there is a clear line of sight path between the mobile and the anchor.

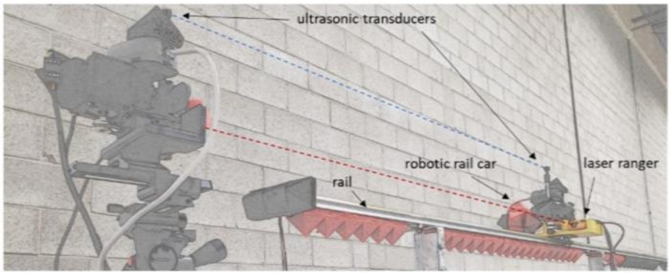

Fig. 3. A mobile device's ranging performance is characterized against a laser ranger with 2 mm accuracy at multiple distances along a rail

Verification of 3D positioning accuracy requires a system with a mobile, gateway, and multiple anchors. A Faro Platinum Arm is used as a ground truth system to hold and accurately report the position of the mobile to within 0.073 mm. Six anchors are placed in static locations on the ground. The arm's probe is coupled to the mobile device and is relocated multiple times in 3D space. The reported positions from the measurement arm and the ZeroKey system are recorded and compared. Fig. 5 contains the 3D positioning results as well as the errors for each cartesian axis over the duration of the test. Despite individual ranging accuracy being on the order of 2 mm, after Kalman filter fusion of 6 ranges from all anchors, the final estimated position error is on average better than+/- 1 mm.

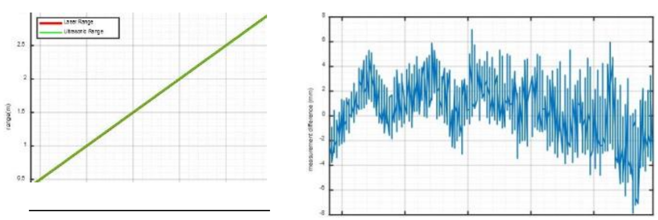

Fig. 4. Ultrasonic and laser range measurement comparison. On average the measurements differ by 2 mm which is within the accuracy of the laser ranger

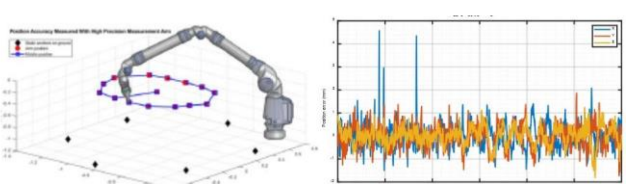

Fig. 5. Reported 3D positions for the measurement arm and the ultrasonic system (left), ultrasonic position error for each 3D axis (right)

The test results reported here are from experiments performed in a ZeroKey laboratory.

IV. DEPLOYMENT EXAMPLES

The industrial partners that ZeroKey is currently engaged with require accurate positioning and localization of employees, automated/autonomously guided vehicles, tools, and other movable assets. Since competing solutions fail to meet similar accuracy specifications, are often larger in form-factor, and require complex installation procedures, our partner participants have highlighted the attractiveness of our solution's performance, ease-of-use, flexibility, size, and portability. The patented technology [10][15][16] is available in multiple form factors as shown in Fig. 7 to suit the needs of a wide variety of deployment scenarios; from coin-cell powered mobiles and nodes to power-over-ethernet (POE) driven anchors.

Fig. 6. Form factors of ZeroKey's IPS solution, from left to right: coin-cell powered mobile/node, USB or battery powered anchor, USB or battery powered mobile, POE anchor

Current deployments demonstrate the flexibility of the solution from small-scale workbench applications to large building scale factories and warehouses. Fig. 7 shows an example of the system working on a small scale, with mobile devices worn on the wrists for tracking hand movements during employee training and workflow optimization applications. In this case the mobile devices are powered by batteries whereas the anchors are powered by USB connections.

Fig. 7. Assembly station deployment where anchors track hands using wrist mounted mobiles

Large scale deployments include factories and warehouses such as those shown in Fig. 8 and Fig. 9 where the anchors are deployed at heights in excess of 7 metres above the floor. In scenarios such as these, several of the Power-over-Ethernet (POE) anchor variant devices are daisy chained together for convenience and low cost of installation. Despite the large scale of these types of installations, accuracy is still on the order of millimeters which is an industry leading offering. This enhanced digitization of factory spaces has broad implications for improved worker safety, reduced downtime, and improved process efficiencies. Ongoing deployments span several industries, including supply chain management and logistics, advanced manufacturing, and health and safety. These deployments are demonstrating the viability of this technology, taking localized workflow monitoring to scales that include the entire line of a factory process.

Fig. 8. Ceiling deployment 7.2 m above ground using POE daisy chained anchors

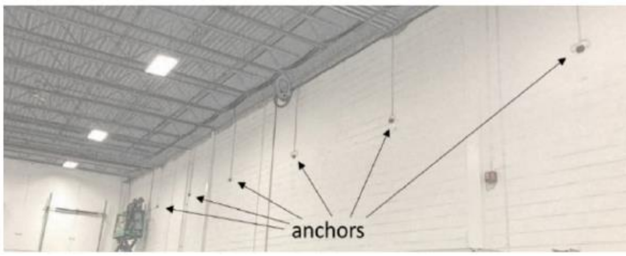

Fig. 9. Wall deployment daisy chaining from the ceiling

Application software for control and visualization by the end user has also been developed for a variety of platforms, including desktop PC's and Android devices. Fig. 10 shows some examples of interfaces created. On the left, a real-time quality assurance digital twinning application is displayed where technicians are guided through the assembly process of a part while having their hands, tools, and supplies monitored, verifying the correct procedure is followed precisely. On the right, a generic visualization of IPS data is shown on the Android platform.

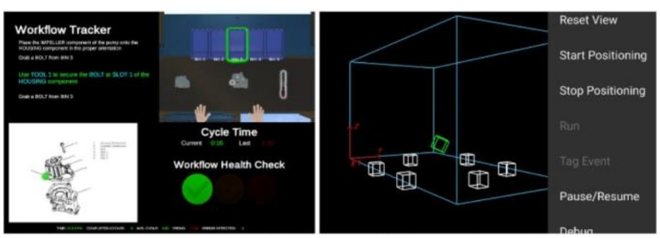

Fig. 10. Examples of user interface monitoring and control

ZeroKey's device software is agile and can be interfaced with standard third party platforms including several virtual reality platforms, such as SteamVR, Unity, Google Glass, and Microsoft Hololens for an immersive interactive experience as depicted in Fig. 11.

V. SUMMARY

Laboratory testing and pilot deployments have continued to verify the commercial readiness of ZeroKey's state-of-the-art IPS solution. At the core of the implementation is a robust analytical description of the positioning problem, followed by a rigorous mathematical and innovative solution that has undergone stringent testing to produce results besting industry incumbents in its class.

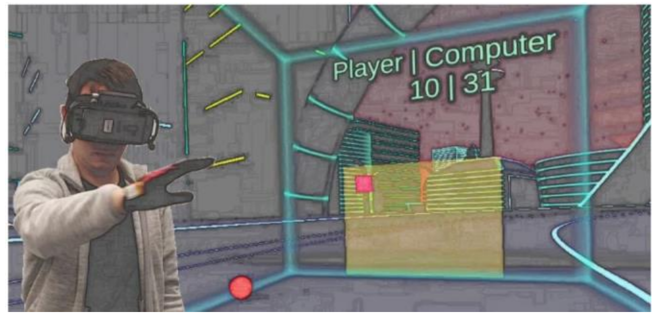

Fig. 11. ZeroKey positioning integration has been tested with industry standard VR platforms including SteamVR, Unity, Samsung SXR, Google Glass, and Microsoft Hololens

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