Pure Play Ultrasonic 3D Positioning System with Unsynchronized Beacons and Receivers

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***Abstract* – This paper describes a work on 3D ultrasonic positioning system for mobile devices such as cellular phones and IoT devices with built-in microphones. The uniqueness of the described system is its ability to provide simultaneous and accurate positioning of multiple devices, based on ultrasonic signals transmitted by stationary beacons, while the devices are sampling the signals by their internal, unsynchronized clocks. Auxiliary information required for synchronization is collected and broadcasted by a monitor unit through an ultrasonic modem. The system is considered to be "pure play ultrasonic" since no wiring or radio transmission is used. The number of devices positioned simultaneously is practically unlimited since they do not emit any energy, and their position calculation is performed locally. In the demonstrated system the positioned devices were cellular phones, operating at a sampling rate of 44,100 samples per second. This sampling rate enables using ultrasonic signals beyond the human hearing range.**

Keywords – Acoustic, Cellular, IoT, Positioning, Pure Play, Ultrasonic.

I. INTRODUCTION

In recent years, as the usage of mobile smartphones, personal assistants and other IoT devices arise, there has been an increasing demand for positioning systems that provide a reliable and accurate location in areas where Global Positioning System (GPS) cannot work. Places such as office buildings, museums, underground parking lots, airports and shopping malls, all suffer from the limitation of satellite signals that do not pass through metal and concrete walls.

Some methods for positioning in such environments make use of electromagnetic waves such as Bluetooth or Wi-Fi, while others utilize a different approach where acoustic, often ultrasonic waves are used.

There are many advantages for using acoustic ultrasonic waves vs. electromagnetic waves. One advantage is the fact that acoustic waves propagate at a speed roughly a million times slower than electromagnetic waves, providing positioning systems with much slower sampling rate.

A tactical advantage of acoustic ultrasonic waves is their secrecy. Not only are they inaudible to the human ear, but they also lack an RF signature, and thus they benefit from the inability to be exposed in the same fashion as common communication and positioning systems that use electromagnetic waves.

One more tactical benefit of systems that use acoustics rather than electromagnetic waves is that they can work well in underwater environment.

Yet, ultrasonic waves have a few drawbacks compared with electromagnetic waves. One is that the smaller transmission bandwidth limits the data rate. Another drawback is the fact that in air ultrasonic waves decay faster than electromagnetic waves, and thus are usable in a limited range, typically up to 100 meters.

In [1], the authors have described and demonstrated a 2D ultrasonic positioning system which does not require an acoustic transmission by the mobile devices, nor timing synchronization of the system elements. The devices were positioned in an iterative process performed by a server, implying considerable processing requirements. The authors also demonstrated a method for position calibration of the unsynchronized beacons, which we use in our system as well.

In [2], a different 2D acoustic positioning system is proposed, having the mobile device transmit an acoustic signal to an asynchronous array of microphones located around the room. The authors have demonstrated a reliable and accurate positioning of ±10cm, yet the use of an iterative solution and a transmitting mobile device make it unscalable for multiple users simultaneously.

In [3], different methods of ultrasonic positioning using array of microphones are presented. The authors have also shown that the usage of one of the microphones as a reference to others simplified the positioning process, but at the cost of having a common clock between all microphones.

In [4], an ultrasonic 3D positioning system is proposed, consisting of five synchronized transmitters with each speaker playing a unique audio signal simultaneously. The system is capable of localizing 95% of the chosen test points to below 10cm accuracy.

The work described in this paper provides the design and performance analysis of an unsynchronized ultrasonic 3D positioning system with an analytic position calculation performed by the mobile device. In the described system, signal processing and devices positions calculations are performed independently by each positioned device, and thus the overall computation power in the system increases in direct relation to the number of positioned devices, forming a *distributed processing* system.

II. SYSTEM CONFIGURATION

Figure 1 shows the positioning system. The system includes four stationary beacons and a monitor at known positions, and a mobile device to be positioned. There is no common timing source in the system, thus the sampling timing of the beacons, the monitor and the mobile devices are independent and unsynchronized.

In the positioning process, the beacons transmit positioning signals consecutively and asynchronously, i.e. the time between transmissions is random. A monitor captures the signals transmitted by the beacons and broadcasts their TDoA (Time Difference of Arrival) to the mobile device through an ultrasonic modem. The mobile device receives the beacons transmissions and the monitor data broadcast and calculates its own position. In the demo system we use cellular phones as a monitor and as a positioned device.

Since each mobile device calculates its own position, the available processing power in the system is proportional to the number of positioned devices, creating a distributed computing system free of processing power constraint. Moreover, since the mobile devices are passive, i.e., do not emit any signals, no time frame or spectrum needs to be allocated for them, and the system can support a practically unlimited number of mobile devices.

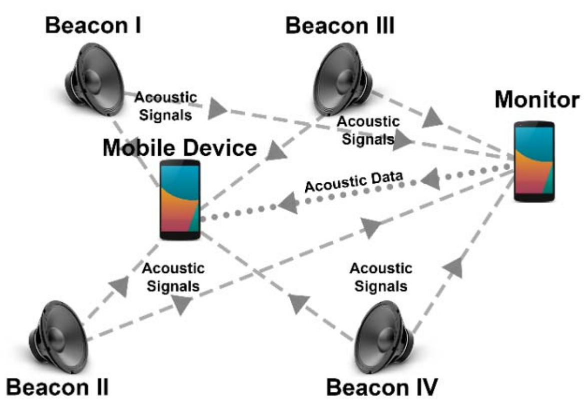

Figure 1: System configuration.

The sampling rate of all the system elements is 44,100 samples per second, a sampling rate available in any modern smartphone. This allows the use of ultrasonic signals beyond the human hearing range from around 18 kHz to 22.05 kHz.

III. ACOUSTIC SIGNALS

A. Positioning Signals

In systems where precise timing and synchronization are required, a unique signal is typically transmitted at one end, received and correlated at the other end in order to provide the reference timing. This signal must have an autocorrelation that characteristically has one strong peak and is close to zero for all other time delays, as well as close to zero cross-correlation with other signals at all times. In the described system the case is similar, since the difference between the times at which the signals arrive to the mobile devices is the crucial data. These time intervals can be extracted in the same manner by correlating the received signal with the known waveforms of the positioning signals transmitted by the beacons, in order to find the exact times at which they were received.

A bandwidth constraint to consider is that the ultrasonic frequency band starts from about 17 kHz, and as a result of 44.1 kHz sampling rate of the system elements, the upper bound limit is 22.05kHz. Anti-Aliasing filtering reduces this limit to about 20KHz. A margin is required since while working close to the upper bound, leakage of energy has an adverse effect on correlation

In [1], the authors chose a band-limited white Gaussian noise (WGN) signal, shaped with a Blackman window envelope in the time domain. This signal meets the system constraints by the qualities of Gaussian noise, and one can easily control the side-lobe amplitude of the window by choosing the window length.

In [4][5], a chirp signal is proposed as an option that exploits the full bandwidth and has low interference. The proposed chirp signals are sinusoid signals with linearly increasing/decreasing frequencies in time. These signals provide robust correlations and are a popular choice in communication systems. However, when transmitting long chirps the change in frequency is relatively slow and thus the autocorrelation peak is widened by the same factor, which is undesirable.

Another signal family proposed by Guan *et al.* [6] is a Gold sequence modulated by binary phase-shift keying (BPSK). Gold sequences have a correlation characteristic satisfying the orthogonality constraint and one can choose the effective bandwidth of such signal by the relation between the symbol transmission duration and the main lobe bandwidth. One more advantage of using these signals is robustness to multipath interruptions; since the coded information is stored in the signal's phase, a reflection from a wall that changes the phase of the signal will correlate badly and not interrupt the system. The main problem with using these signals is that they have a large amount of out-of-band energy leakage, due to the many bits that need to be modulated, each with a relatively small-duration window, which results in a larger main-lobe bandwidth and thus larger effective bandwidth.

In this paper, the signal proposed is a 'parabolic chirp', the spectrogram of which can be seen in Figure 2. This signal was chosen since as in a linear chirp, it utilizes the full bandwidth, has low interference and a continuous phase; but it is superior in that it is essentially two orthogonal signals transmitted one after the other, both of which span the full allocated bandwidth, allowing for a faster sweep of frequencies without decreasing the transmission duration.

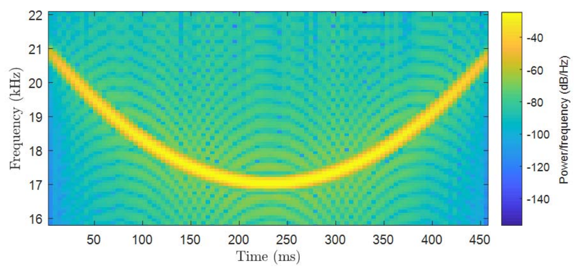

Figure 2 - Spectrogram of a parabolic chirp

In Figure 3, one can observe the difference in autocorrelation peak width and amplitude between the different signals.

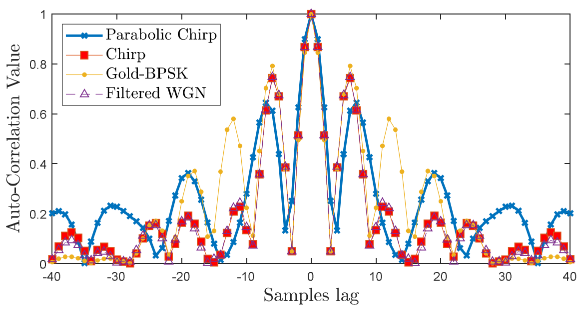

Figure 3 - Autocorrelation waveforms of the evaluated positioning signals

It is evident that the parabolic chirp shows less dominant side lobes that occur at further lags, which makes it more suited for combatting the multipath effect.

B. Preamble Signal

To initialize each run of the positioning process, the Monitor device sends a signal called the Preamble that is then recognized by all other devices. The signal chosen in this project is a sine wave with a constant frequency of 16.5 kHz and a duration of 372 milliseconds, equal to four times the microphone buffers duration at the sampling rate of 44.1 kHz.

In order to detect the Preamble, each one of the beacons and all of the mobile devices which are being positioned calculate the received signal SNR measure on every microphone buffer (4096 samples) by calculating the buffer's DFT and comparing the 16.5 kHz bin value to the value of a few of its adjacent bins. Since this measurement is prone to false-alarms, or misdetections, depending on the chosen threshold, a majority-decision process is used, as described in Figure 4. This essentially means that out of three selected buffers, at least two must surpass the threshold. This method allows for very reliable and robust detection of the preamble.

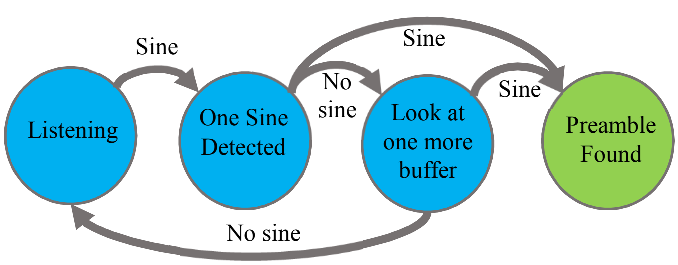

Figure 4 - Majority decision flowchart

C. Ultrasonic Modem

In order to broadcast the TDoA measurements result from the monitor to the mobile devices, we used an acoustic modem provided by Sonarax Technologies. This modem transmits in an ultrasonic frequency band and is robust to echo and ambient noise.

IV. Mobile Device Positioning in 2D Space

For the sake of simplicity, we first derive the analytic equations for 2D positioning which requires only three beacons. As depicted in Figure 5, A, B, C are the beacons positions and P is the unknown mobile device position.

For each beacon transmission, we define t_P^i as the ToA (Time of Arrival) measured by the mobile device and t_M^i the ToA measured by a monitor which, without loss of generality, can be located at the same position as one of the Beacons. The transmission time of beacon (i) is: $T_{tr}^i = t_M^i - \frac{d^i}{c}$, where c is the speed of sound, and d^i is the distance between beacon (i) and the monitor. In order to simplify the derivation, we assume without loss of generality that the signal transmitted from beacon A propagates to beacon B which then immediately transmits its own signal.

To emulate immediate transmission, we compensate for the effective time delay, which could be negative, by computing and subtracting it. For beacon (j) the time delay is

$$T_{pr}^j = T_{tr}^j - T_{tr}^A - \left(\frac{d_{1,j}}{c}\right) \tag{1}$$

where c is the speed of sound and $d_{A,j}$ is the distance between beacon A and beacon (j).

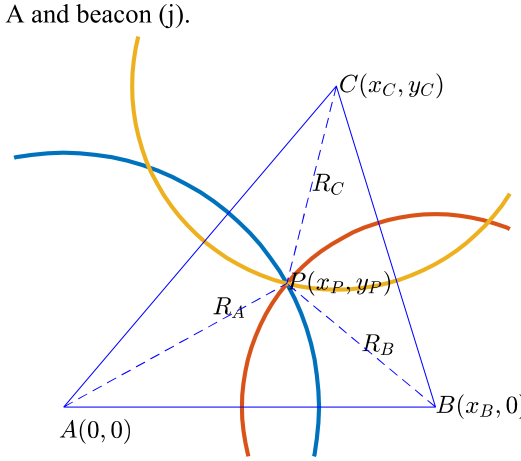

Figure 5 – Geometric layout of the system elements - beacons A, B, C and a mobile device P at the intersection point of the three circles.

Define:

$$u_1 = AB + R_B - R_A \tag{2}$$
$$u_2 = AC + R_C - R_A \tag{3}$$

We can show that the following equation holds:

$$u_1 = \left(t_p^{\mathrm{B}} - t_p^{\mathrm{A}} - T_{pr}^{\mathrm{B}}\right) \cdot c \quad (4)$$
$$u_2 = \left(t_p^{\mathrm{C}} - t_p^{\mathrm{B}} - T_{pr}^{\mathrm{C}}\right) \cdot c \quad (5)$$

Let the beacons positions be $A(0,0)$, $B(x_B, 0)$, $C(x_C, y_C)$, and the mobile device position $P(x_P. y_P)$. Since P can be represented as the intersection point of three circles with origins at A, B, C and radii R_A, R_B, R_C:

$$x_P^2 + y_P^2 = R_A^2 \quad (6)$$
$$(x_P - x_B)^2 + y_P^2 = R_B^2 \quad (7)$$
$$(x_P - x_C)^2 + (y_P - y_C)^2 = R_C^2 \quad (8)$$

These equations, together with constants defined in Appendix A – 2D Positioning, provide the quadratic equation for the unknown R_A:

$$(\alpha^2 + \gamma^2 - 1)R_A^2 + 2(\alpha\beta + \gamma\lambda)R_A + \beta^2 + \lambda^2 = 0 \quad (9)$$

Eqn. (9) has two possible solutions for R_A, from which R_B and R_C can be derived by substitution in equations (2) and (3). One of the solutions for R_A can be ruled out by not meeting the measurements results. Once R_A is found the position of the mobile device P is found by

$$x_p = \alpha R_A + \beta \quad (10)$$
$$y_p = \gamma R_A + \lambda \quad (11)$$

V. Mobile Devices Positioning in 3D Space

In this section we show that with four unsynchronized beacons, it is possible to position a mobile device in 3D space. As depicted in Figure 6, A, B, C, D are the beacons positions and P is the unknown mobile device position. The analytic solution addresses the case where all beacons are on the same plane. Without loss of generality, the derivation assumes the same height coordinate for all beacons, while a simple transformation can be made for other planar configurations. Using similar definitions as in the 2D case:

$$u_1 = AB + R_B - R_A \quad (12)$$
$$u_2 = AC + R_C - R_A \quad (13)$$
$$u_3 = AD + R_D - R_A \quad (14)$$

where the beacons' positions are at $A(x_A, y_A, z_0)$, $B(x_B, y_B, z_0)$, $C(x_C, y_C, z_0)$, $D(x_D, y_D, z_0)$ and the mobile device position is at $P(x_P. y_P, z_P)$. Since P can be represented as the intersection point of four spheres with origins at A, B, C, D and radii R_A, R_B, R_C, R_D:

$$(x_A - x_P)^2 + \left(y_A - y_p\right)^2 + (z_0 - z_P)^2 = R_A^2 \quad (15)$$
$$(x_B - x_P)^2 + \left(y_B - y_p\right)^2 + (z_0 - z_P)^2 = R_B^2 \quad (16)$$
$$(x_C - x_P)^2 + \left(y_C - y_p\right)^2 + (z_0 - z_P)^2 = R_C^2 \quad (17)$$
$$(x_D - x_P)^2 + \left(y_D - y_p\right)^2 + (z_0 - z_P)^2 = R_D^2 \quad (18)$$

Solving equations (12)-(18) provides R_A:

$$R_A = \frac{\frac{1}{2}\gamma + \Delta x_3 \cdot n + \Delta y_3 \cdot \lambda}{(b_3 - \Delta x_3 \cdot m - \Delta y_3 \cdot v)} \quad (19)$$

where all the constants appearing in (19) are defined in appendix B.

Once R_A is known, the coordinates of P can be calculated:

$$y_P = vR_A + \lambda \quad (20)$$
$$x_P = mR_A + n \quad (21)$$

And a quadratic equation w.r.t z_P is obtained:

$$(x_A - x_P)^2 + \left(y_A - y_p\right)^2 + (z_0 - z_P)^2 = R_A^2 \quad (22)$$

Resulting in:

$$z_P = z_0 \pm \sqrt{R_A^2 - (x_A - x_P)^2 - \left(y_A - y_p\right)^2} \quad (23)$$

There are two possible solutions to (23), and one of the solutions can be ruled out by assuming the relative position of the device and the z_0-plane - above or below the plane.

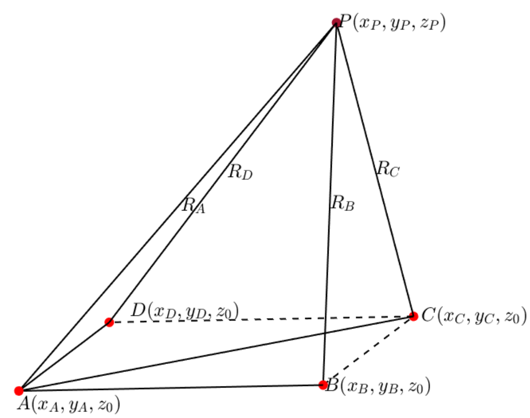

Figure 6 – Geometric layout of the system elements - beacons A, B, C, D and a mobile device P.

VI. System Implementation

As seen in Figure 7, in our implementation of the system, the four Beacons are loudspeakers connected to the stereo outputs of two smartphones. In addition to driving the Beacons, one of the smartphones is used as the Monitor, while its microphone captures the signals transmitted by the Beacons. The other smartphone, referred to as Player is merely driving the other pair of speakers.

The method by which our system works is as follows: The Monitor starts recording, and then sends a Preamble signal, which is recognized by the Mobile device(s) and the Player. Once the preamble is recognized, the Mobile device(s) start recording and the Player starts a time out counter for its transmissions. The Monitor, after transmitting the preamble, transmits two positioning signals from the Beacons connected to it. Then the Player transmits two positioning signals from the Beacons connected to it. Once all Beacons transmissions are done, each Mobile device to be positioned stops recording and analyses its recording to calculate the TDoA of the Beacons signals. The Monitor also stops recording and calculates the TDoA of the signals received. Then, by using Sonarax Ultrasonic Modem, the Monitor transmits the TDoA values of the received Beacons signals to the Mobile devices. Each Mobile device uses the formulas provided above to calculate its own position and displays it on its screen.

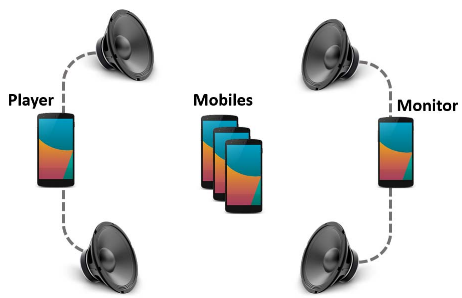

Figure 7 – System implementation

The following flowcharts (Figure 8 to Figure 10) describe the implementation in each of the system elements:

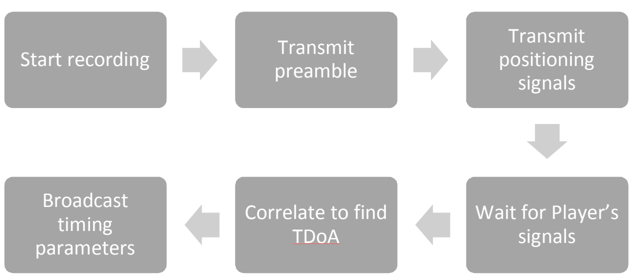

Figure 8 – Monitor flowchart

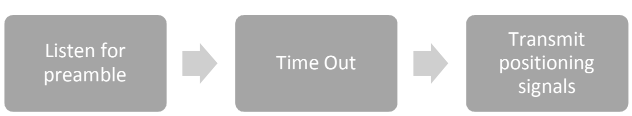

Figure 9 - Player flowchart

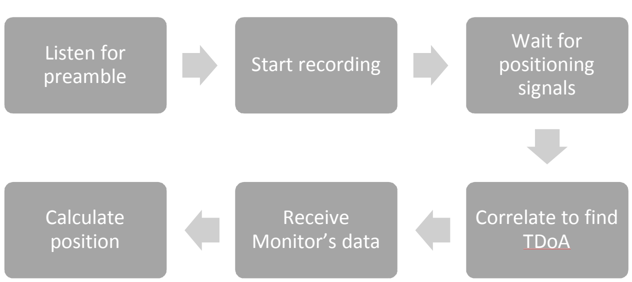

Figure 10 – Mobile device flowchart

VII. Performance Evaluation

The system was simulated in Matlab for various beacons, monitor and mobile device positions. Accurate results were received for noise free simulation, proving the correctness of the equations provided in sections IV and V.

Robustness to ToA estimation was assessed using a Gaussian error distribution with a standard deviation in the range 0.5 – 5 samples. For sampling rate of 44.1 kHz, one sample error is equivalent to $2.27 \cdot 10^{-5}$ seconds.

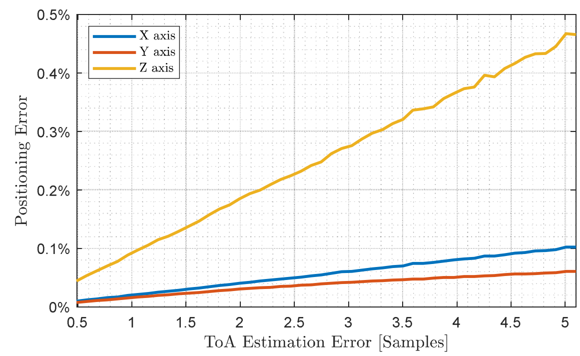

Figure 11 – Positioning error percentage per each axis as a function of ToA estimation error.

The simulation shows a linear relationship between the ToA estimation error and the positioning error, where the positioning error for the z-axis is larger than for the x and y axes. We assume that this because the beacons are on the $z = z_0$ plane. Hence, the accuracy could be improved by adding beacons that are not on this plane. Moreover, for better positioning accuracy one can interpolate the correlation samples and achieve sub-sample ToA accuracy.

VIII. Conclusions

The motivation for this work was to design and validate the performance of an ultrasonic positioning system. A key requirement was independence of synchronization (sampling timing) of the system elements. We have derived an analytic solution for both 2D and 3D positioning in a distributed system configuration. The system is pure play ultrasonic, since no radio transmission is required. High positioning accuracy was achieved.

Future work may attempt to survey other positioning signals waveforms, such as orthogonal signals for overlapped Beacons transmissions. It would be possible to work in higher frequencies at higher sampling rates, and possibly to find other robust preamble signals. Another improvement can be the utilization of a Kalman filter to improve error variance. Further effort can be done to overcome Doppler Effect in the positioning signals received by mobile devices in motion.

IX. Appendix A – 2D Positioning

This appendix provides the formulas for calculating the variables values for the 2D solution. These values are to be substituted in Eqn. (9):

$$\alpha \triangleq -\frac{(u_1 - x_B)}{x_B} \tag{24}$$

$$\beta \triangleq -\frac{1}{2x_B}(u_1 - x_B)^2 + \frac{1}{2}x_B \tag{25}$$

$$\gamma \triangleq \frac{1}{y_C} \cdot \left(\delta + \alpha(x_B - x_C)\right) \tag{26}$$

$$\delta \triangleq u_1 - u_2 + AC - AB \tag{27}$$

$$\lambda \triangleq \frac{1}{2y_C} \cdot \begin{bmatrix} 2\delta(u_2 - AC) + \delta^2 + \\ AC^2 - x_B^2 + 2(x_B - x_C)\beta \end{bmatrix} \tag{28}$$

X. APPENDIX B – 3D POSITIONING

This appendix provides the formulas for calculating the variables values for the 3D solution. These values are to be substituted in Eqn. (32):

$$\alpha \triangleq x_B^2 + y_B^2 - x_A^2 - y_A^2 - (u_1 - AB)^2 \tag{29}$$

$$\beta \triangleq x_C^2 + y_C^2 - x_A^2 - y_A^2 - (u_2 - AC)^2 \tag{30}$$

$$\nu \triangleq \frac{\Delta x_2 \cdot b_1 - b_2 \cdot \Delta x_1}{\Delta x_2 \cdot \Delta y_1 - \Delta x_1 \cdot \Delta y_2} \tag{31}$$

$$\lambda \triangleq -0.5 \frac{\Delta x_2 \alpha - \beta \Delta x_1}{\Delta x_2 \cdot \Delta y_1 - \Delta x_1 \cdot \Delta y_2} \tag{32}$$

$$m \triangleq \frac{b_2 - \Delta y_2 \cdot \nu}{\Delta x_2} \tag{33}$$

$$n \triangleq \frac{-0.5\beta - \Delta y_2 \cdot \lambda}{\Delta x_2} \tag{34}$$

$$b_1 \triangleq (u_1 - AB) \quad b_2 \triangleq (u_2 - AC) \quad b_3 \triangleq (u_3 - AD) \tag{35}$$

$$\begin{aligned} \Delta x_1 &\triangleq x_A - x_B & \Delta y_1 &\triangleq y_A - y_B \\ \Delta x_2 &\triangleq x_A - x_C & \Delta y_2 &\triangleq y_A - y_C \\ \Delta x_3 &\triangleq x_A - x_D & \Delta y_3 &\triangleq y_A - y_D \end{aligned} \tag{36}$$

XI. ACKNOWLEDGMENTS

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