T.C.

ALTINBAŞ UNIVERSITY

Electrical and Computer Engineering

AN INDOOR POSITIONING SYSTEM USING ULTRASONIC WAVES

Doaa Ali Jumaah ZIRJAWI

Master Thesis

Supervisor

Prof. Dr. Osman N. UÇAN

Istanbul (2019)

AN INDOOR POSITIONING SYSTEM USING ULTRASONIC WAVES

by

Doaa Ali Jumaah ZIRJAWI

Electrical and Computer Engineering

Submitted to the Graduate School of Science and Engineering

in partial fulfillment of the requirements for the degree of

Master of Science

ALTINBAŞ UNIVERSITY

2019

This is to certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Prof. Dr. Osman N. UÇAN

Supervisor

Examining Committee Members

Academic Title Name SURNAME	Faculty, University	____________________
Academic Title Name SURNAME	Faculty, University	____________________
Academic Title Name SURNAME	Faculty, University	____________________

I certify that this thesis satisfies all the requirements as a thesis for the degree of ....

Academic Title Name SURNAME

Head of Department

Academic Title Name SURNAME

Director

Approval Date of Graduate School of

Science and Engineering: ____/____/____

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Doaa Ali Jumaah ZIRJAWI

DEDICATION

I would like to dedicate this work to my lovely family, especially my father and mother, for their invaluable effort when I felt hopeless and weak in solving problems.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my advisor Prof. Dr. Osman N. UÇAN for his full support, experience, understanding and encouragement throughout my study and research. Without his unending patience, timely wisdom and counsel, this thesis work would not have been possible.

Finally, I would like to thank my family their continued love and support in every aspect of my life.

ABSTRACT

AN INDOOR POSITIONING SYSTEM USING ULTRASONIC WAVES

Doaa Ali Jumaah ZIRJAWI,

M.Sc., Electrical and Computer Engineering, Altınbaş University

Supervisor: Prof. Dr. Osman N. UÇAN

Date: April/2019

Pages: 54

With the rapid development of automation and robotics, more emphasis is being applied to indoor positioning, according to the importance of such information in these fields. For outdoor positioning, the Global Positioning System (GPS) has been widely used in different applications. However, according to the limited power of the signals transmitted by the satellites of the GPS, these signals cannot be used for indoor positioning, as they cannot be reliably received. Additionally, the positioning accuracy of three meters for the GPS is considered very low for indoor applications, according to the need for more precise coordinates to accomplish the tasks required from these applications. Different approaches have been proposed for indoor positioning, using different types of waves and distance measurement approaches. In this study, a new indoor positioning method is proposed, which employs ultrasonic waves and Time Difference of Arrival (TDOA) approach. A set of transceivers is deployed in reference points in the environment. These transceivers are connected to the same controller and commands are sent to all the transceivers simultaneously. However, only the designated transceiver transmits an ultrasonic wave, while the remaining transceivers listen to such signals when the command does not target them. As the position of each reference point is known to the other and each transceiver transmits a wave with a unique frequency, the time required by the wave to travel from the transmitter to the other transceivers is used to calculate the actual speed of ultrasound in the current ambient conditions. The object transmits an ultrasonic wave when a signal is received from any of the reference points, which is also received by the remaining nodes. The calculated speed of the wave is then used with the time deviation between the arrival of the electrical and the object signals to calculate the distance between the receiver and the transmitter through the object. These distances are then used to compute the distance between the object and each of the reference points, which are then used to calculate the coordinates of the object. The performance of the proposed method is evaluated using two different approaches to calculate the coordinates of the object based on the computed distances. The first approach interacts with every computed distance as a separate reference point to conclude a set of candidate coordinates, where the coordinates of the object are selected from that list using the average or median function. The other approach summarizes the distances between the object and each of the reference points into a single distance before being used in the computations of the candidate coordinates. The same average or median function are used to summarize these distances into a single distance. The evaluation results show that the use of a single distance per a reference point and the average function to select that distance and the coordinates of the object has the best performance with a mean positioning Root Mean Squared Error (RMSE) of 0.23, 0.20 and 0.15 when 4, 5 and 6 reference points are used for the positioning, respectively. The results also show that the proposed method has been able to outperform the state-of-the-art methods existing the earlier studies.

Keywords: *Indoor Positioning; Time Difference of Arrival; Ultrasound.*

ÖZET

ULTRASONIK DALGALARI KULLANAN İÇ MEKAN KONUMLANDIRMA SISTEMI

Doaa Ali Jumaah ZIRJAWI,

Yüksek Lisans, Elektrik ve Bilgisayar Mühendisliği, Altınbaş Üniversitesi

Danışman: Prof. Dr. Osman N. UÇAN

Tarih: Nisan / 2019

Sayfalar: 54

Otomasyon ve robotiğin hızlı gelişmesiyle, bu alanlardaki bilgilerin önemliliğine bakılırsa iç mekan konumlandırmaya daha fazla vurgu yapılmaktadır. Dış konumlandırma için, Global Konumlandırma Sistemi (GPS) farklı uygulamalarda yaygın olarak kullanılmaktadır. Bununla birlikte, GPS uyduları tarafından iletilen sinyallerin sınırlı güce sahip olmasından dolayı, güvenilir şekilde alınamayacağı için iç mekan konumlandırmada kullanılamaz. Ek olarak, GPS'in üç metrelik konumlandırma doğruluğu, bu uygulamalardan istenen görevleri yerine getirmek için daha kesin koordinatlara ihtiyaç duyulduğundan dolayı, iç mekan uygulamaları için çok düşük olarak kabul edilir. İç mekan konumlandırması için farklı dalga tipleri ve mesafe ölçüm yaklaşımları kullanılarak farklı yöntemler önerilmiştir. Bu çalışmada, ultrasonik dalgalar ve Varış Zamanı Farkı (TDOA) yaklaşımını kullanan yeni bir iç mekan konumlandırma yöntemi önerilmiştir. Ortamdaki referans noktalarına bir dizi alıcı-verici yerleştirilmiştir. Bu alıcı vericiler aynı denetleyiciye bağlanır ve tüm alıcı vericilere aynı anda komutlar gönderilir. Bununla birlikte, yalnızca belirlenmiş alıcı-verici ultrasonik bir dalga iletirken, kalan alıcı-vericiler komut onları hedeflemediğinde bu sinyalleri dinlerler. Her referans noktasının konumu diğer tarafından bilindiğinden ve her alıcı-verici benzersiz bir frekansa sahip bir dalga ilettiğinden, bu dalganın vericiden diğer alıcı vericilere gitmesi için gereken süre mevcut ortam koşullarında ultrasonun gerçek hızını hesaplamak için kullanılır. Nesne, kalan düğümler tarafından veya referans noktalarından herhangi bir sinyal alındığında ultrasonik bir dalga iletir. Dalganın ölçülen hızı, nesneden geçen alıcı ve verici arasındaki mesafeyi hesaplamak için elektriksel ve nesne sinyallerinin gelişi arasındaki zaman sapması ile birlikte kullanılır. Bu mesafeler daha sonra nesne ile referans noktalarının her biri arasındaki mesafeyi ve nesnenin koordinatlarını hesaplamak için kullanılır. Önerilen yöntemin performansı, hesaplanan mesafelere bağlı olarak nesnenin koordinatlarını hesaplamak için iki farklı yaklaşım kullanılarak değerlendirilir. İlk yaklaşım, nesnenin koordinatlarının ortalama veya ortanca işlevini kullanarak bu listeden seçildiği bir dizi aday koordinatını sonuçlandırmak için ayrı bir referans noktası olarak her hesaplanan mesafeyle etkileşime girer. Diğer yaklaşım, aday koordinatların hesaplanmasında kullanılmadan önce nesne ile referans noktalarının her biri arasındaki mesafeyi tek bir mesafede özetler. Aynı ortalama veya ortanca işlevi bu mesafeleri tek bir mesafede özetlemek için kullanılır. Değerlendirme sonuçları, bir referans noktası başına tek bir mesafenin ve bu mesafeyi ve nesnenin koordinatlarını seçmek için kullanılan ortalama fonksiyonun kullanılmasının, konumlandırma için sırasıyla 4, 5 ve 6 referans noktaları kullanıldığı zaman 0.23, 0.20 ve 0.15 olan Ortalama Karesel Hatanın Karekökünün (RMSE) ortalama konumlandırması ile en iyi performansa sahip olduğunu göstermektedir. Sonuçlar ayrıca önerilen yöntemin önceki çalışmalarda mevcut olan en gelişmiş yöntemlerden daha iyi performans sergilediğini göstermiştir.

Anahtar Kelimeler: *İç Mekan Konumlandırma; Varış Zaman Farkı; Ultrason.*

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

GPS	: Global Positioning System.
UAV	: Unmanned Arial Vehicle.
AOA	: Angle of Arrival.
RSS	: Received Signal Strength.
TOA	: Time of Arrival.
TDOA	: Time Difference of Arrival.
VLC	: Visible Light Communication.
LOS	: Line-of-Sight.
NLOS	: No Line-of-Sight.
LED	: Light Emitting Diode.
TDM	: Time Division Multiplexing.
RMSE	: Root Mean Squared Error.

LIST OF TABLES

Pages

LIST OF FIGURES

Pages

1. INTRODUCTION

The rapid development of artificial intelligence and robotics relies on collecting and processing data from the environment that the application is interacting with. One of the most important information to be collected in the position of the object in that environment, especially with moving objects such as robots and autonomous vehicles [1, 2]. The position of the object can be defined by its coordinates with respect to the environment it is interacting with. These coordinates define the distance between the object and a reference point in the environment, which can be described using two or three axes. Thus, positioning techniques rely on calculating the distance between the object and reference points with known coordinates in that environment [3, 4].

The Global Positioning System (GPS) is being widely used in different devices, such as smartphones and Unmanned Arial Vehicles (UAV), and applications, such as navigation and search and rescue operations [5]. The coordinates of the object in the GPS are calculated with respect to the center of the earth, based on the distance between the object and satellites, with known coordinates, orbiting the earth. Each of these satellites is equipped with an atomic clock that its value is periodically transmitted from the satellite. Upon the arrival of multiple clocks values from different satellites to the object being positioned, the object calculates the distance to each of the satellites based on the deviation among the times received from these satellites. These clock values are sent over electromagnetic signals, which can travel in both the space and the atmosphere of the earth [6, 7].

As the power of the signals received from these satellites is relatively low, these signals are highly affected by obstacles in the earth, which limits the use of GPS in indoor applications. Additionally, according to the high speed of the electromagnetic waves, about 3e8 m/s, the positioning accuracy of GPS is 3 meters, i.e. the minimum time deviation detected by the object is 10^{-8} Seconds [8]. These characteristics limit the use of GPS for indoor positioning applications. In addition to the difficulty of receiving the satellite signals indoors, according to their low power when received, indoor positioning requires more accurate coordinates than the three meters the GPS provide. These limitations have encouraged many researchers to investigate alternative techniques for indoor positioning [9, 10].

Positioning techniques can be categorized into four main categories, the Angle of Arrival (AOA), Received Signal Strength (RSS), Time of Arrival (TOA) and Time Difference of Arrival (TDOA) [11, 12]. Normally, the receiver in an AOA technique has multiple receivers in order to predict the direction of the source of the received signal to improve the accuracy of the positioning, as the angle between the source and the object is available in addition to the coordinates of the source. In RSS techniques, a single receiver is required, which is only responsible for computing the power of the received signals. As signals lose power during travel, knowing the power of the signal upon transmission can be used with the received power in order to calculate the distance between the object and the source of the signal, which has known coordinates [13-15].

Moreover, both of these methods are highly affected by the obstacles in the environment, as they can significantly affect the power of the received signals and create reflections of the signals. Thus, TOA and TDOA techniques have shown better resistance to such situations, as they rely on the time required by the wave to travel from the source to the destination instead of the power of the signal. In order to calculate the distance between the object and the source of the signal in TOA methods, the object requires the exact time that the signal has been transmitted in, so that, the time taken by the wave to reach the object is used to calculate the distance between them. TDOA techniques do not require such information, as the difference between the arrival of multiple signals is used to calculate the distance between the object and each of the sources [16, 17].

Several methods have been proposed from these categories for indoor positioning. Most of these methods rely on light and electromagnetic waves, which imposes significant limitations on the positioning accuracy of the method. The high speed that light and electromagnetic waves travel with is extremely high, which makes the effect of variations in the waves more dramatic on the positioning accuracy. Such variations can be imposed by the obstacles in the environment, which may affect the power of these waves or produce echoes or reflections that confuses the computations in these systems. Thus, in this study, a new indoor positioning method is proposed, which relies on ultrasonic waves instead of the light or electromagnetic. According to the low speed of these waves, compared to light and electromagnetic waves, the effect of the noise can be significantly reduced [18-20].

1.1 PROBLEM STATEMENT

Despite the popularity of the GPS, which is implemented in many devices and employed to achieve a variety of applications, the positioning accuracy of this system and the low power of the signals received from the satellites limit the use of this system in indoor positioning applications. According to the growing importance of indoor positioning, with the rapidly growing fields of automation and robotics, several attempts have been conducted to improve the positioning accuracy in indoor environments. These techniques are of different available positioning categories but mainly rely on light and electromagnetic waves. The reliance on these waves imposes limitations to the accuracy of the positioning method, according to the high speed these waves travel in the environment. Additionally, the use of the power of the received signal is very sensitive to the effects imposed by the obstacles in the environment, which can affect the power of the signal and generate echoes and reflection. Moreover, the use of light waves for the positioning is subjected to the need for direct line-of-sight, where shadows can completely disconnect the communications or produce wrong computations.

1.2 AIM OF THE STUDY

This study aims to propose a new indoor positioning method that uses ultrasonic waves instead of light or electromagnetic waves. The lower speed of these waves can significantly improve the positioning accuracy, as the effect of noise can have less significance over the computations. Additionally, as ultrasonic waves do not require direct line-of-sight in order to travel from the source to the destination, these signals are less affected by the obstacles in the environment. The proposed method relies on the time difference on arrival, which eliminates the effect of echoes generated by any obstacles or walls in the indoor environment.

1.3 THESIS LAYOUT

The chapters of this thesis following this introduction are organized as follows:

- Positioning approaches and related indoor positioning methods are discussed in Chapter Two.
- The proposed indoor positioning method is illustrated in Chapter Three.

- The experiments conducted to evaluate the performance of the proposed method and their results are illustrated in Chapter Four.
- The evaluation results are summarized, discussed and compared to the state-of-the-art methods from earlier studies in Chapter Five.
- The conclusions from this study and suggestions for future work are illustrated in Chapter Six.

2. LITERATURE REVIEW

In order to position an object in an environment, indoor or outdoor, the distance between the object and a set of reference points, which known coordinates, are required. The number of reference points required to calculate the coordinates of an object is equal to the number of dimensions, i.e. the number of axes in the coordinates, plus one [21]. However, when only this number of reference points are available, it is important that the object does not fall in a hyperplane that joins two or more of these points. In such case, the computations of the position in one or more axes fail, as no variation in that axis exists to calculate it for the object. As the computations of the positioning procedure rely on finding the intersections among the distances between the object and each reference points, the absence of the variation in one of the axes has no benefit toward such intersection [22, 23].

In a three-dimensional space, an object *O* can have any coordinates (x, y, z) that satisfy the equation of a sphere's surface *S* that has a center located at the coordinates of the reference point (x_r, y_r, z_r) and a radius r, which is equal to the distance between the object and the reference point, as shown in Equation 2.1.

$$(x - x_r)^2 + (y - y_r)^2 + (z - z_r)^2 = r^2 \tag{2.1}$$

As the results of the intersection between two spheres is a circle, by finding the distance to two reference points reduces the possible coordinates of the object to that circle produced by the intersection. Consequently, a circle interacts with a sphere in two points, which are the possible coordinates of the object when the distance to a third reference point is recognized. To select the actual position of the object from these two candidates, a fourth sphere is required, which required measuring the distance between the object and a fourth reference point [24]. Additionally, if this sphere is in the same hyperplane that the object and any of the other reference points belong to, the surface of this sphere passes through both points, which makes it impossible to recognize the actual coordinates of the object [25]. Mathematically, the distances measured between the object and each of the reference points are used to define Equations 2.2 through 2.5.

$$x^2 - 2xx_1 + x_1^2 + y^2 - 2yy_1 + y_1^2 + z^2 - 2zz_1 + z_1^2 = r_1^2 \quad (2.2)$$

$$x^2 - 2xx_2 + x_2^2 + y^2 - 2yy_2 + y_2^2 + z^2 - 2zz_2 + z_2^2 = r_2^2 \quad (2.3)$$

$$x^2 - 2xx_3 + x_3^2 + y^2 - 2yy_3 + y_3^2 + z^2 - 2zz_3 + z_3^2 = r_3^2 \quad (2.4)$$

$$x^2 - 2xx_4 + x_4^2 + y^2 - 2yy_4 + y_4^2 + z^2 - 2zz_1 + z_4^2 = r_4^2 \quad (2.5)$$

As shown in these equations, only three variables have unknown values, which are the *x*, *y* and *z*. However, the existence of the squared values of these variables imposes the need of the fourth equation, as three variables can be normally solved using only three equations when linear. As the square root of x^2 can be either *x* or -*x*, it important to get rid of any squared variables in order to produce three linear equations that can be solved for *x*, *y* and *z*. This elimination can be conducted by subtracting any of the four equations from the other. For instance, the subtraction of equation 2.5 from the other equations results in the formulas shown in Equations 2.6 through 2.8.

$$x(2x_1 - 2x_4) + y(2y_1 - 2y_4) + z(2z_1 - 2z_4) = r_4^2 - r_1^2 + x_1^2 - x_4^2 + y_1^2 - y_4^2 + z_1^2 - z_4^2 \quad (2.6)$$

$$x(2x_2 - 2x_4) + y(2y_2 - 2y_4) + z(2z_2 - 2z_4) = r_4^2 - r_2^2 + x_2^2 - x_4^2 + y_2^2 - y_4^2 + z_2^2 - z_4^2 \quad (2.7)$$

$$x(2x_3 - 2x_4) + y(2y_3 - 2y_4) + z(2z_3 - 2z_4) = r_4^2 - r_3^2 + x_3^2 - x_4^2 + y_3^2 - y_4^2 + z_3^2 - z_4^2 \quad (2.8)$$

As the values of all the variables in these equations are known, except the values of *x*, *y* and *z*, the values of these variables can be calculated using matrices operations, as shown in Equation 2.9. Additionally, the GPS can still compute the latitude and longitude of an object using only three satellites by selecting the position closest to the surface of the earth, i.e. uses the sphere of the globe as the fourth sphere for the computations, as shown in Figure 2.1. However, in such a scenario, the altitude cannot be calculated, which can be considered as two-dimensional positioning.

$$Inv\left(\begin{bmatrix} (2x_1 - 2x_4) & (2y_1 - 2y_4) & (2z_1 - 2z_4) \\ (2x_2 - 2x_4) & (2y_2 - 2y_4) & (2z_2 - 2z_4) \\ (2x_3 - 2x_4) & (2y_3 - 2y_4) & (2z_3 - 2z_4) \end{bmatrix}\right) \cdot \begin{bmatrix} (r_4^2 - r_1^2 + x_1^2 - x_4^2 + y_1^2 - y_4^2 + z_1^2 - z_4^2) \\ (r_4^2 - r_2^2 + x_2^2 - x_4^2 + y_2^2 - y_4^2 + z_2^2 - z_4^2) \\ (r_4^2 - r_3^2 + x_3^2 - x_4^2 + y_3^2 - y_4^2 + z_3^2 - z_4^2) \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (2.9)$$

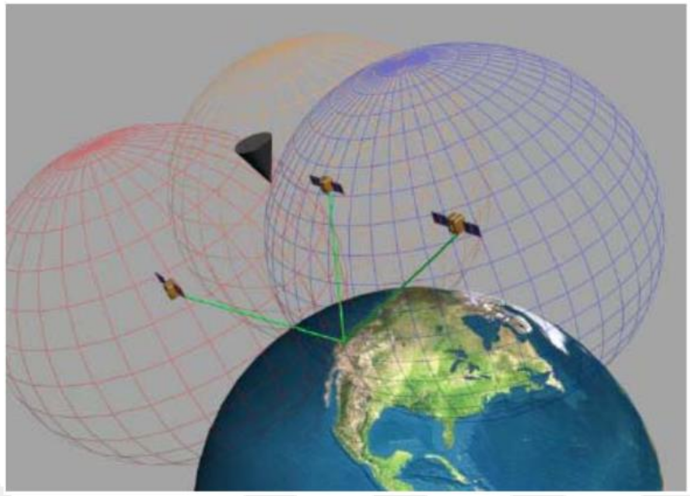

Figure 2.1: Positioning using three satellites in GPS.

In a two-dimensional space, according to the absence of the *z* axis, the coordinates of the object can be of any values that are defined by the circle located at the intersection between the hyperplane *z=constant* and the sphere centered at the reference point, and with radius equal to the distance from the point to the object. Two-dimensional positioning is widely used for indoor applications, as the objects in the environment are usually at a certain level. Hence, only three reference points can be used for such applications but increasing the number of reference points can increase the accuracy of the calculated position, compared to the actual location of the object [26, 27].

With the growing use of Wi-Fi access points to provide wireless internet services, these signals are being employed for indoor positioning using RSS approach. The power of the signal received from each access point is measured and compared to a set of predefined reference points, where the power of each access point in the environment is measured at each reference point in advance, as shown in Figure 2.2. Then, one of two approaches is used to calculate the coordinates of the object, by selecting the coordinates of the nearest reference point as the coordinates of the object or by using the coordinates of multiple points, nearest to the object, to calculate its position using regression [14, 28] or machine learning [29, 30] techniques.

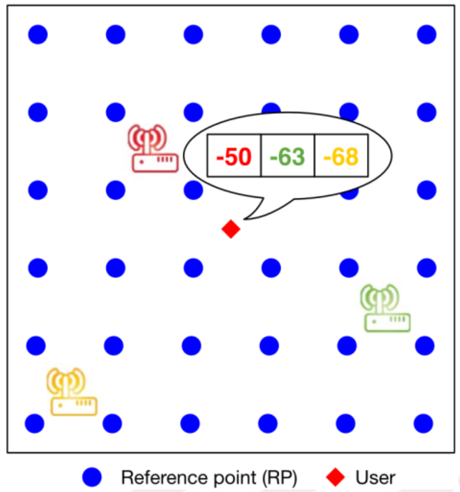

Figure 2.2: Indoor positioning using Wi-Fi signals and RSS approach [31].

Unlike outdoor environments, the existence of different types of obstacles and conditions in an indoor environment can significantly affect the positioning accuracy, especially when electromagnetic waves are used, such as Wi-Fi. A power measured from a certain access point at a certain position may vary depending on the obstacles between the object and the access point. For an access point positioned in a different room in the environment, the power of the received signal at the exact same position is different when the door is opened or closed, so that, the measured distance may vary despite the fact that neither the object and reference point are in the same position, i.e. the actual distance is the same [32, 33].

Moreover, as the attenuation of the wave in a medium is affected by the density of that medium, the temperature and humidity can impose changes to the measured distance. Thus, RSS methods that use Wi-Fi signals are highly affected by the atmosphere of the environment implemented in. Another important challenge that these methods face is the existence of moving objects in the environment, which can impose changes to the power of the received signal and unexpected reflections. As shown in Figure 2.3, the problem of humans gathering at a certain position can significantly affect the positioning accuracy at the point [34].

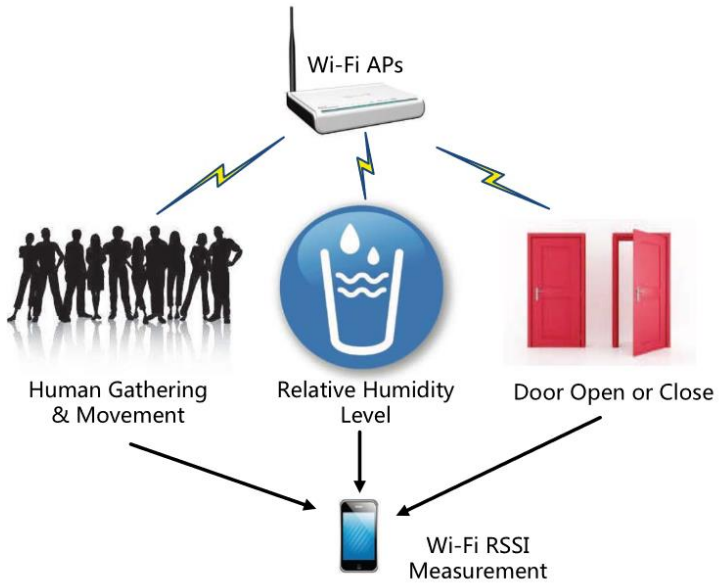

Figure 2.3: Environmental conditions that affect the positioning accuracy based on Wi-Fi signals [34].

According to the limited accuracy of RSS methods, objects in the environment can collaborate to improve the accuracy of their positions. Liu et al. [35] propose a method that uses the pairwise distances between each object and the others in the environment to improve the positioning accuracy. Per each object, the distance to other objects is also measured, in addition to the distances to the access points. The coordinates computed for the other objects are then used as reference points, with the pairwise distances as the distances to those reference points. The distances to the access points in the environment are measured based on the power of the received signal, while the pairwise distances are measured using sound waves, transmitted by the handheld smartphones of the objects, as shown in Figure 2.4. Despite the improvement in the positioning accuracy and the ability of this approach to overcome the human gathering problem, the dependency on other objects in the environment limits the application of such method, where the accuracy is highly affected by the density of the objects in the environment and is reduced to the standard accuracy when a single object is in the environment [35].

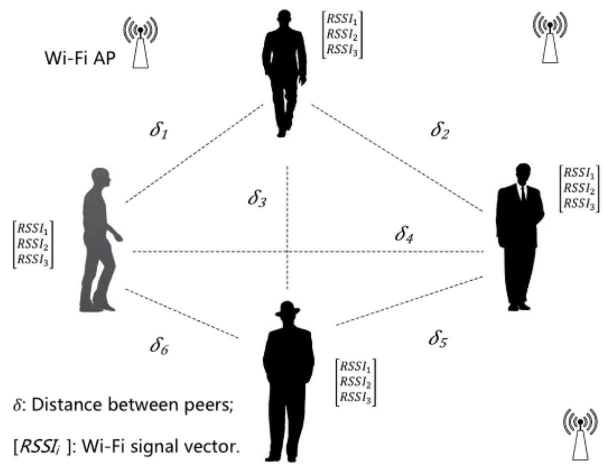

Figure 2.4: Improving Wi-Fi based positioning using pairwise distances [35].

To overcome the variable conditions of the environment, some methods rely on updating the power measures at the reference points in real-time, so that, any measurements collected by the object in the environment are compared to more similar measurements. However, updating the powers at the reference points, in such approach, requires sniffing the access points' signals at each of those reference points, which can be a difficult task to be achieved in real-time [36]. This approach also adds additional cost to the system, as a sniffer is required per each reference points, while using the positions of the objects in the environment to update the heatmap of the signals imposes additional challenges toward improving the system's accuracy [31].

Another collaborative method based on Visible Light Communications (VLC) is proposed in [37], which uses the spring model to improve the positioning accuracy. The spring model implements virtual springs among the objects being positioned in the environment. These virtual springs attempt to bring calculated position to more stable coordinates to reduce the effect of noise [38]. The VLC method uses virtual points with known positions to collaborate with the objects in order to improve their positioning accuracy, as shown in Figure 2.5. The intensity of the light received by the sensors is used to estimate the distance between that sensor and the source of the light. By computing the distances to multiple light sources and using the coordinates of these lights, the position of the object can be estimated and improved using the spring model. Unlike the power sniffing methods, the use of the spring model eliminates the need of additional sensors in the environment but the accuracy of the positioning is still dependent on the number of objects in the environment [16].

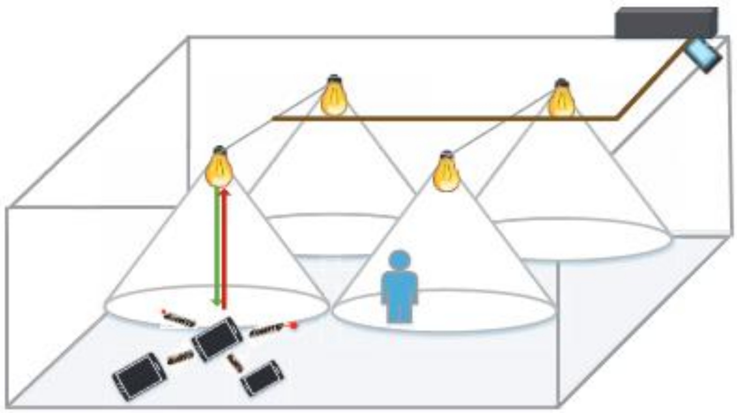

Figure 2.5: VLC-based RSS positioning method using the spring model [37].

The main disadvantage of RSS methods is the need for a direct Line-of-Sight (LOS), which is difficult to be guaranteed in an indoor environment according to the obstacles in such an environment. These obstacles can also reflect the signals, so that, they reach to the object being positioned but using a longer path when No Line-of-Sight (NLOS) exist, as shown in Figure 2.6. During the traveling of the longer path, the signal loses some of its power, or intensity in case of using light waves, so that, the distance from the reference points measured by the object is longer than the actual distance between them. Such disadvantage does not exist in the AOA, TOA and TDOA methods [39].

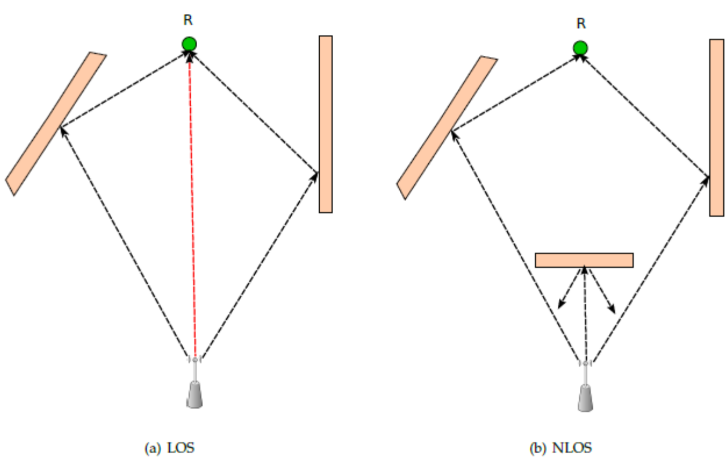

Figure 2.6: RSS positioning with LOS and NLOS [40].

To improve the positioning accuracy without the need of additional sensors in the environment to collaborate with the object being positions, a VLC-based method is proposed in [41], which takes the NLOS condition into consideration. Light Emitting Diodes (LEDs) are placed in the ceiling of the environment as the reference points of the positioning approach. Time Division Multiplexing (TDM) is used to distinguish the source of the wave received by the object, which its intensity is used with the coordinates of the source to position the object. As the transmitting LEDs are located in the ceiling facing down to the sensors of the objects being positioned and according to the known diameter of these LEDs, the shape of the light projected over the sensors is used to recognize NLOS. Measurements that match this criterion are neglected from the positioning computations.

The position of the object using AOA approaches is computed by calculating the intersection point of the line that passes through the position of the object with an angle equal to the measured angle value, to the position of the source point [17, 42]. AOA approaches suffer from high positioning errors, especially with the lack of high-resolution angle calculation schemes. Moreover, TDOA methods have shown higher positioning accuracy, as the distance is calculated using the coordinates of two reference points instead of one, similar to TOA approaches, as shown in Figure 2.7. Thus, the TDOA approach is the most suitable for indoor positioning [40, 43].

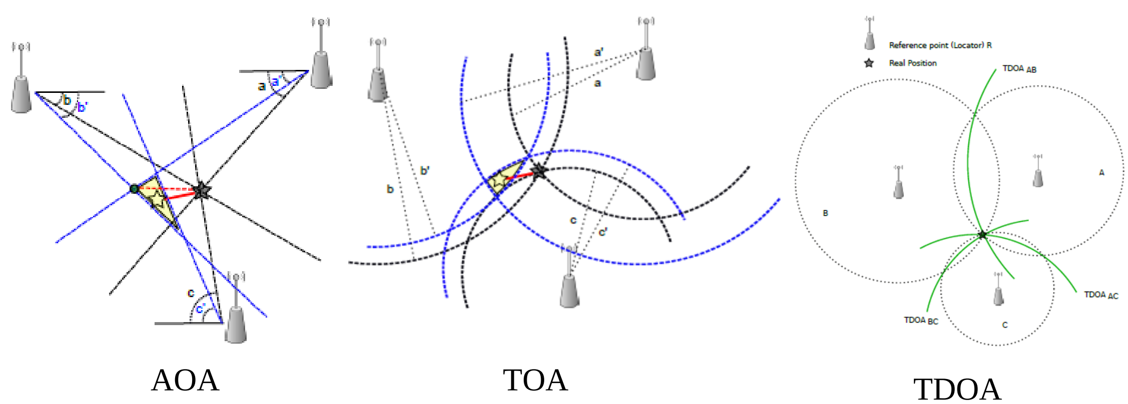

Figure 2.7: Positioning approaches for indoor positioning methods [40].

3. METHODOLOGY

The indoor positioning method proposed in this study employs ultrasonic waves instead of the electromagnetic or light waves. As these waves are mechanical waves and travel in a significantly lower speed than the electromagnetic and light waves, higher positioning accuracy can be achieved according to the higher resistance to noise. However, the according to the dependency of the traveling speed of mechanical waves on the characteristics of the medium that the waves travel through, different conditions of the atmosphere, such as the temperature and humidity, in the environment can cause variation in the speed of the ultrasonic waves. Thus, the proposed method also uses an approach similar to the sniffing model implemented in earlier studies but without the need for any additional sensors. The proposed method also adopts the TDOA approach, according to its better positioning accuracy.

Each reference point in the environment contains an ultrasonic transceiver, which can send and receive ultrasonic signals. These transceivers are electrically connected to a controller that controls the transmission of the signals from these reference points. Each reference point transmits ultrasonic waves using a different frequency, as the speed of the waves is irrelative to their frequency. This difference in frequencies allows the receivers in the environment to distinguish the transmitter. As shown in Figure 3.1, when a signal is transmitted by one of the reference points, upon a command from the controller, all the transceivers in the other reference points receive both the command from the controller and the ultrasonic wave from the transmitter. By measuring the time difference between the arrival of the command and the ultrasonic wave, the speed of the waves in the current environment can be calculated using Equation 3.1.

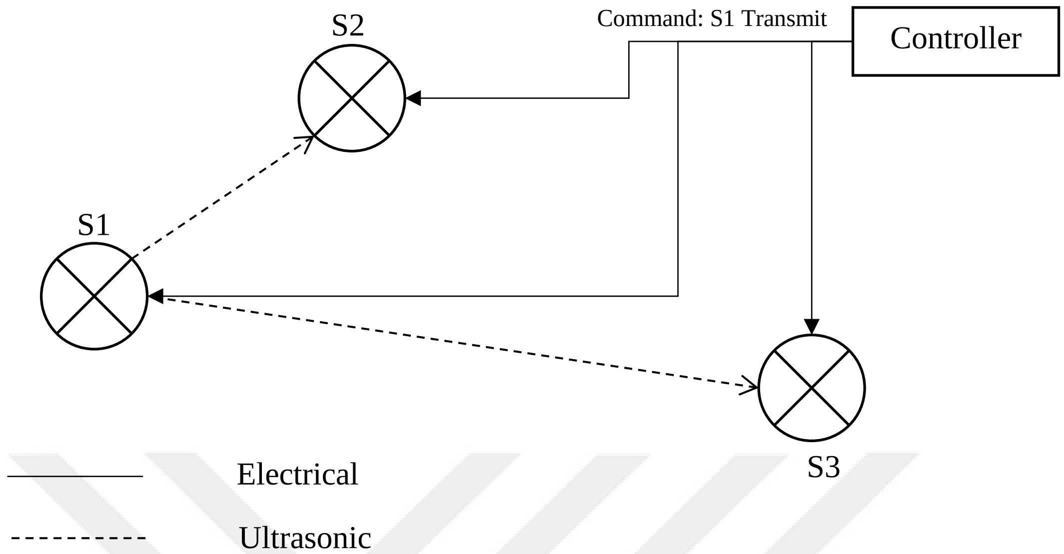

Figure 3.1: Electrical and ultrasonic signals among the reference points of the proposed method.

$$S = \frac{D}{T} \tag{3.1}$$

where S is the speed of the ultrasonic waves in the environment, D is the distance between the transmitting and the receiving points and T is the time difference between the arrival of the electrical and ultrasonic signals.

Each object being positioned in the environment is instructed to transmit an ultrasonic wave using its own frequency when an ultrasonic wave is received from one of the reference points. When this signal is received by the other reference points, the time difference between the arrival of the electrical signal and the object's ultrasonic wave is also measured and converted to distance, based on the speed of the waves calculated earlier, as shown in Figure 3.2.

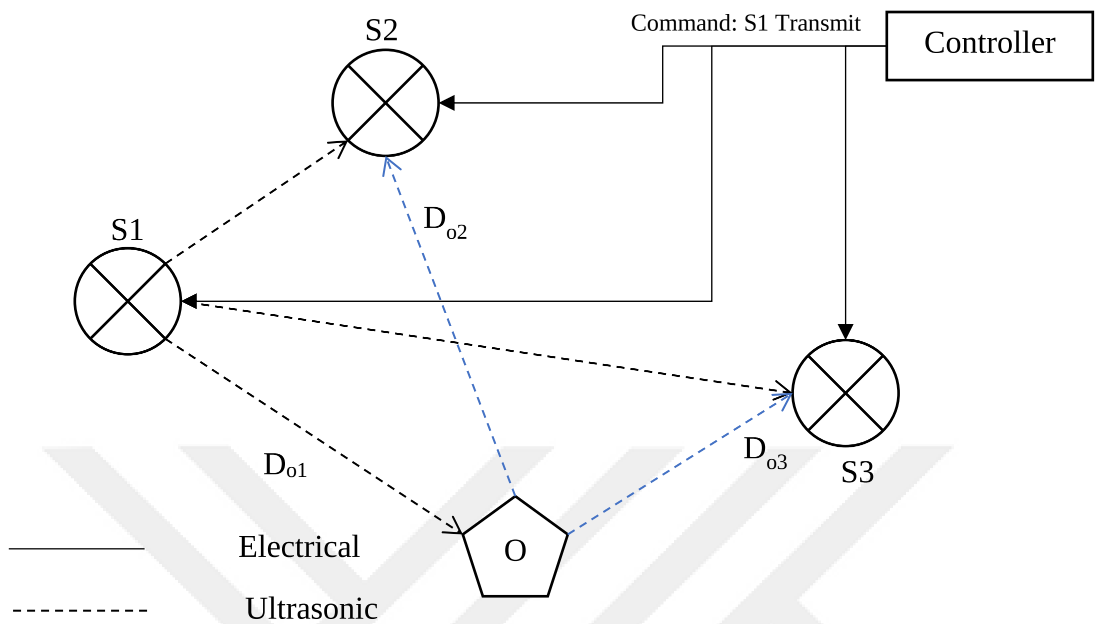

Figure 3.2: Ultrasonic signals among the reference points and the object.

For example, the distance D_{o12} from the reference point *S1* to the reference point *S2* through the object *O* is calculated based on the speed of the wave from the previous step using Equation 3.2. Similarly, the distances D_{o13} can also be measured in addition to other distances when the remaining reference points transmit their signals. Moreover, to avoid the lower accuracy of TOA approach, compared to the TDOA, the reference point that is the source of the wave neglects the signal received from the object based on the transmission of its signal.

$$D_{o12} = T_{o12} \times S \tag{3.2}$$

Knowing that

$$D_{o12} = D_{o1} + D_{o2} \tag{3.3}$$

$$D_{o13} = D_{o1} + D_{o3} \tag{3.4}$$

$$D_{o23} = D_{o2} + D_{o3} \tag{3.5}$$

The distance D_{o1} between the object and the reference point *S1* can be calculated based on the TDOA using Equation 3.9, which is derived from Equations 3.6 through 3.8.

$$D_{o2} = D_{o12} - D_{o1} \quad (3.6)$$

$$D_{o3} = D_{o13} - D_{o1} \quad (3.7)$$

$$D_{o23} = D_{o12} - D_{o1} + D_{o13} - D_{o1} \quad (3.8)$$

$$D_{o1} = \frac{D_{o12} + D_{o13} - D_{o23}}{2} \quad (3.9)$$

Using the same equation, the distances D_{o2} and D_{o3} can be calculated and used as the radius r of the sphere that the object is positioned on its surface, which is defined by Equation 3.10. However, as indoor positioning mainly requires two-dimensional positioning, the value of z axis is considered constant, which eliminates the $(z-z_1)$ part of Equation 3.10.

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = r_1^2 \quad (3.10)$$

Using Equation 3.10 with the three reference points and considering the value of z axis as constant, the equation 3.11 to 3.13 can be concluded.

$$x^2 - 2xx_1 + x_1^2 + y^2 - 2yy_1 + y_1^2 = r_1^2 \quad (3.11)$$

$$x^2 - 2xx_2 + x_2^2 + y^2 - 2yy_2 + y_2^2 = r_2^2 \quad (3.12)$$

$$x^2 - 2xx_3 + x_3^2 + y^2 - 2yy_3 + y_3^2 = r_3^2 \quad (3.13)$$

To eliminate the squared values of x and y and produce two linear equation with only two unknown variables, any of the equations is subtracted from the remaining two equations. For example, subtracting Equation 3.13 from Equation 3.11 and 3.12 results in Equations 3.14 and 3.15 respectively.

$$x(2x_3 - 2x_1) + y(2y_3 - 2y_1) = r_1^2 - r_3^2 + x_3^2 - x_1^2 + y_3^2 - y_1^2 \quad (3.14)$$

$$x(2x_3 - 2x_2) + y(2y_3 - 2y_2) = r_2^2 - r_3^2 + x_3^2 - x_2^2 + y_3^2 - y_2^2 \quad (3.15)$$

Then, using matrices operations, Equations 3.14 and 3.15 can be solved for x and y as shown in Equation 3.16.

$$Inv\left(\begin{bmatrix} (2x_3 - 2x_1) & (2y_3 - 2y_1) \\ (2x_3 - 2x_2) & (2y_3 - 2y_2) \end{bmatrix}\right) \cdot \begin{bmatrix} r_1^2 - r_3^2 + x_3^2 - x_1^2 + y_3^2 - y_1^2 \\ r_2^2 - r_3^2 + x_3^2 - x_2^2 + y_3^2 - y_2^2 \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} \quad (3.16)$$

Although these equations show that the use of three reference points is enough to calculate the x and y coordinates of the object, for indoor positioning, larger numbers of reference points are used in real-life applications to increase the coverage area of the positioning system. This allows the existence of more than three reference points within the range of the object, which can be employed to increase the positioning accuracy. Since increasing the number of reference points to more than three produces multiple values for the distance between the object and each reference point, two approaches can be used to calculate the coordinates of the object based on these values using the proposed method. The first approach uses each value as a separate reference point then searches for the solution of every possible combination of three in the resulting equations. This approach results in a set of possible coordinates for the object, where the actual position is selected using one of two methods, the average or median of these coordinates. The second approach summarized each distance using the values calculated for that distance, also using the average or median functions, before creating the equations per each reference point. Then, all possible combinations of threes are collected from the resulting equations and the same function is used to produce the position of the object from the candidate coordinates.

4. EXPERIMENTAL RESULTS

The performance of the proposed method using the different approaches is evaluated by implementing an indoor environment, shown in Figure 4.1, for simulation. The dimensions of the environment are set to 8 × 8 meters in length and width with 3.5m height. The ultrasonic transceivers are positioned in the ceiling of the space, while the object is considered a handheld device at height of 1.2m. This model is implemented and simulated using Matlab programming environment using a Windows operating system on a computer with 2.81GHz CPU and 8 GB of random-access memory. Per each experiment, the object is located in 300 random positions in the space, 100 positions per the inner, outer and the entire space. Random noise is also added to the signals communicated between the reference points and the object being positioned and the Root Mean Squared Error (RMSE) is calculated. Per each model, the use of both approaches using the median and average functions is evaluated, resulting in a total of 12 experiments distributed into four sets depending on the approach and the summarization function used in that experiment in addition to an experiment to evaluate the effect of echoes on the positioning error.

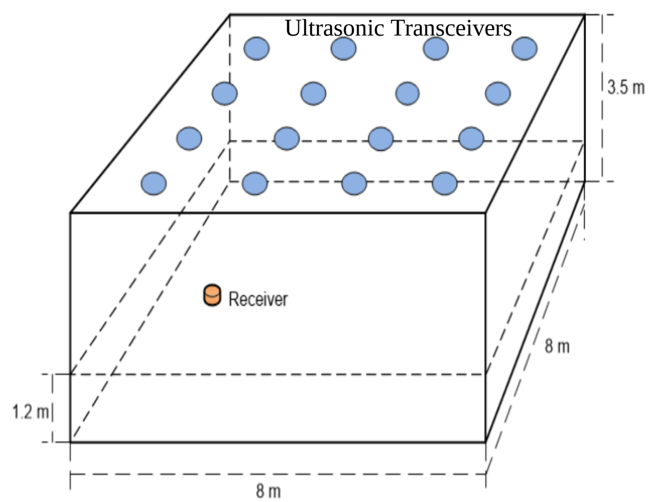

Figure 4.1: Illustration of the implemented environment and the distribution of the ultrasonic transceivers and object.

4.1 EXPERIMENT A – MULTIPLE SPHERES AND AVERAGE FUNCTION

In this experiment, the values calculated for the distances between the object and each of the reference points are used to create the spheres that the object is located on their surfaces. These equations are then used to calculate multiple candidate positions and the final position of the object is calculated by calculating the average of each axis in the coordinates. Four to six reference points are used in the experiment, wherein each number of reference points random errors are added to the calculated distances, in order to simulate any errors that may occur in the real-world applications. The error is added to none up to all the reference points and the positioning error is calculated. The maximum error in the calculated distance is set to 10% and each positioning is repeated for 100 different object positions per each region, to produce an accurate evaluation. The results of this experiment are shown in Table 4.1.

Table 4.1: Positioning error when using multiple spheres per reference point and average function.

	RMSE			
Number of Reference Points	**Outer**	**Inner**	**Entire**	**Mean**
4	0.19	0.24	0.23	**0.22**
5	0.17	0.23	0.21	**0.20**
6	0.19	0.25	0.23	**0.22**

As shown in Figure 4.2, despite the reduction in the positioning error when the number of reference points within the range of the object is increased from four to five, this error increases when the sixth point is introduced to the computations. Such behavior is a result of using the average function, where extreme values are still considered in the computations for the output value. Moreover, the results also show that the positioning error at the outer region is lower than those in the inner and entire region, which illustrates the lower effect of echoes produced by the walls of the simulated space.

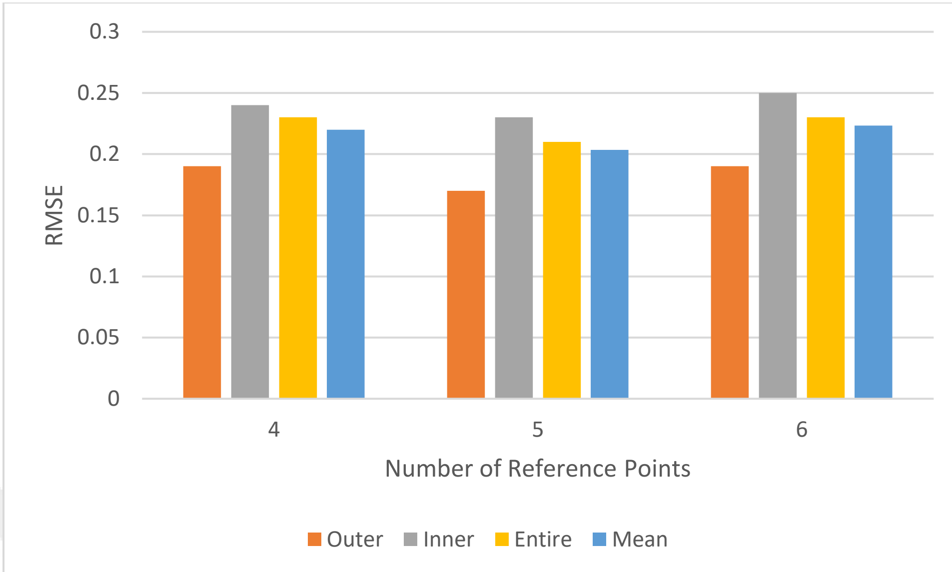

Figure 4.2: Illustration of the proposed method's performance using multiple spheres per reference point and average function.

4.2 EXPERIMENT B - MULTIPLE SPHERES AND MEDIAN FUNCTION

The median function is used in this experiment to select the coordinates of the object from the list of candidates generated by the proposed positioning method. The positioning RMSE measured in this experiment are shown in Table 4.2 and illustrated in Figure 4.3. These results show that despite the use of the median function, which excludes the effect of extreme values, the position error using six reference points has also increased. Such error indicates that the positioning approach is more dependent on the accuracy of the measured distances than the number of reference points, which emphasizes the importance of using the ultrasonic waves with TDOA.

Table 4.2: Positioning error when using multiple spheres per reference point and median function.

	RMSE			
Number of Reference Points	**Outer**	**Inner**	**Entire**	**Mean**
4	0.19	0.25	0.23	**0.22**
5	0.19	0.24	0.23	**0.22**
6	0.18	0.23	0.23	**0.21**

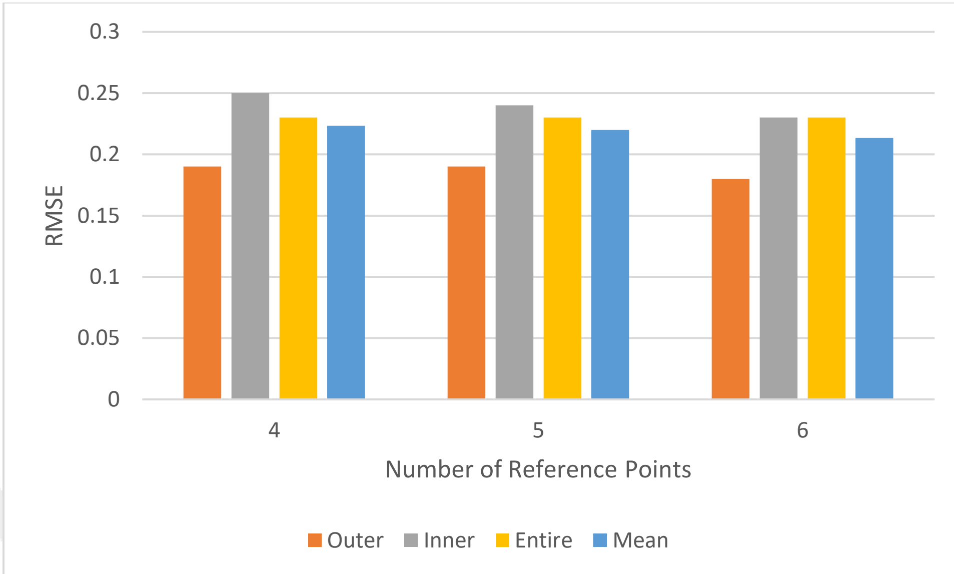

Figure 4.3: Illustration of the proposed method's performance using multiple spheres per reference point and median function.

4.3 EXPERIMENT C - SINGLE SPHERE AND AVERAGE FUNCTION

The distances measured between the object and each of the reference points are summarized into a single distance using the average function before generating the equation required to compute the coordinates of the object. Then, the actual coordinates are generated based on the list of candidates using the average function as well. The results shown in Table 4.3 and Figure 4.4 summarize the positioning RMSE of the object in this experiment.

Table 4.3: Positioning error when using single sphere per reference point and average function.

	RMSE			
Number of Reference Points	**Outer**	**Inner**	**Entire**	**Mean**
4	0.20	0.25	0.23	**0.23**
5	0.18	0.22	0.21	**0.20**
6	0.13	0.16	0.15	**0.15**

The results show that increasing the number of reference points with this approach has been able to significantly improve the positioning accuracy as the error is handled per each reference point instead of the entire computations. Such handling allows more flexibility and less effect of the error in further computations, after the distance between each of the reference points and the object is calculated.

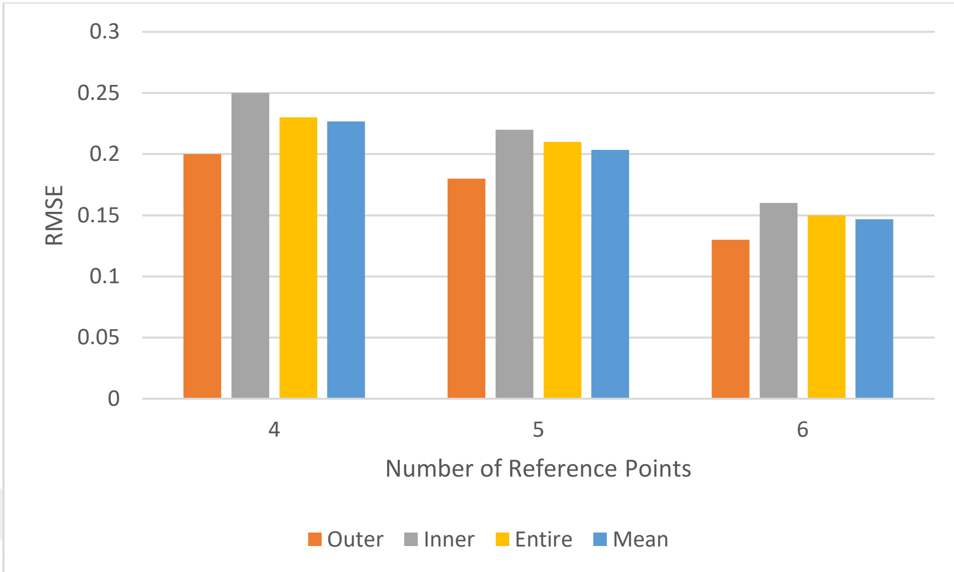

Figure 4.4: Illustration of the proposed method's performance using a single sphere per reference point and average function.

4.4 EXPERIMENT D - SINGLE SPHERE AND MEDIAN FUNCTION

The median function is used in this experiment to select the distance between each reference point and the object from the distances calculated based on multiple other reference points. Then, the median function is also used to calculate the coordinates of the object based on the candidates list produced by the reference points and the computed distances. Table 4.4 summarized the positioning error of the proposed method in this experiment, which are illustrated in Figure 4.5.

Table 4.4: Positioning error when using single sphere per reference point and median function.

	RMSE			
Number of Reference Points	**Outer**	**Inner**	**Entire**	**Mean**
4	0.20	0.25	0.23	**0.23**
5	0.19	0.23	0.23	**0.22**
6	0.13	0.16	0.15	**0.15**

These results also show that the use of a single sphere per reference point, based on the distance calculated between the object and that reference points, has better performance than the use of multiple spheres. Increasing the number of reference points has also been able to reduce the positioning error, hence, improving the accuracy.

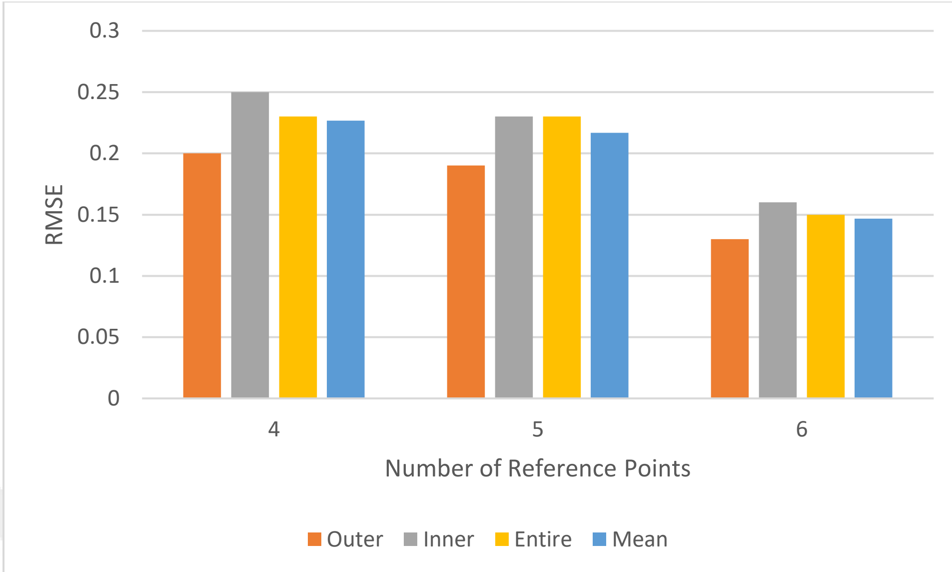

Figure 4.5: Illustration of the proposed method's performance using a single sphere per reference point and median function.

4.5 EXPERIMENT E – ECHO'S EFFECT ON THE POSITIONING ACCURACY

As ultrasonic waves are used for the positioning process, and as these waves can be reflected by walls creating echoes of the same frequency, the time required for the echoes to reach the object is investigated. Three positions of the object are used for this investigation, which are A(0,0,1.2), B(4,0,1.2) and C(4,4,1.2). Per each position, the transmitters with the positions shown in Table 4.5 are used for the evaluation, where the time required by the wave to travel from each transmitter and the first three echoes arrive at the object are illustrated in Figure 4.6 to 4.8.

Table 4.5: Coordinates of the transmitter used for the echo times investigation.

Transmitter No.	**Coordinates**
1	(1,1,3.3)
2	(3,1,3.3)
3	(1,3,3.3)
4	(3,3,3.3)
5	(5,1,3.3)
6	(1,5,3.3)

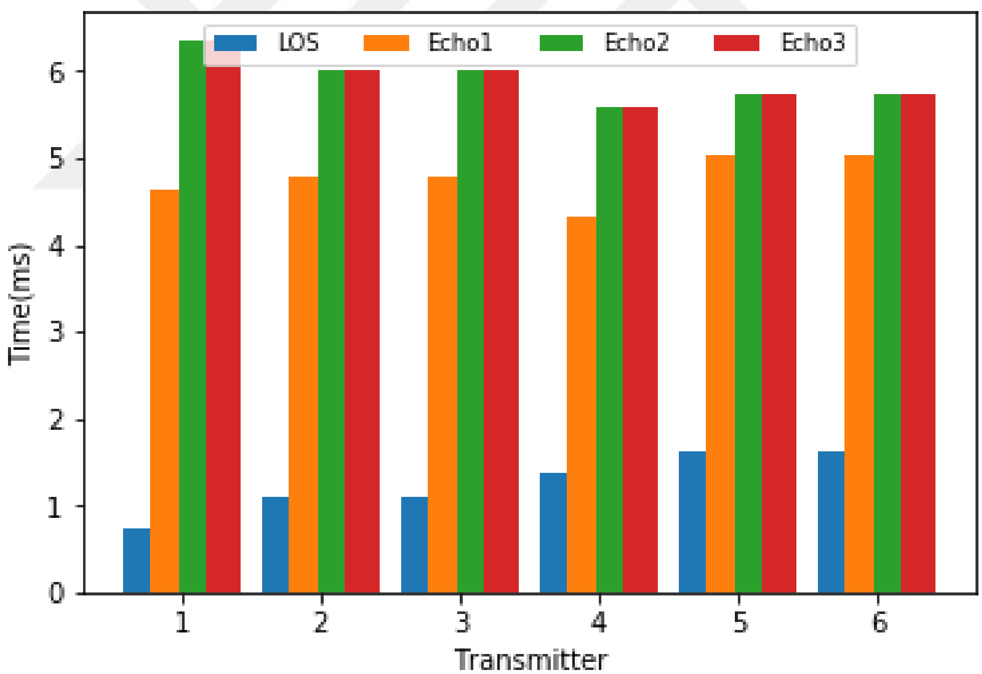

Figure 4.6: Waves travel time for the Line-Of-Sight and first three echoes to the object in position A.

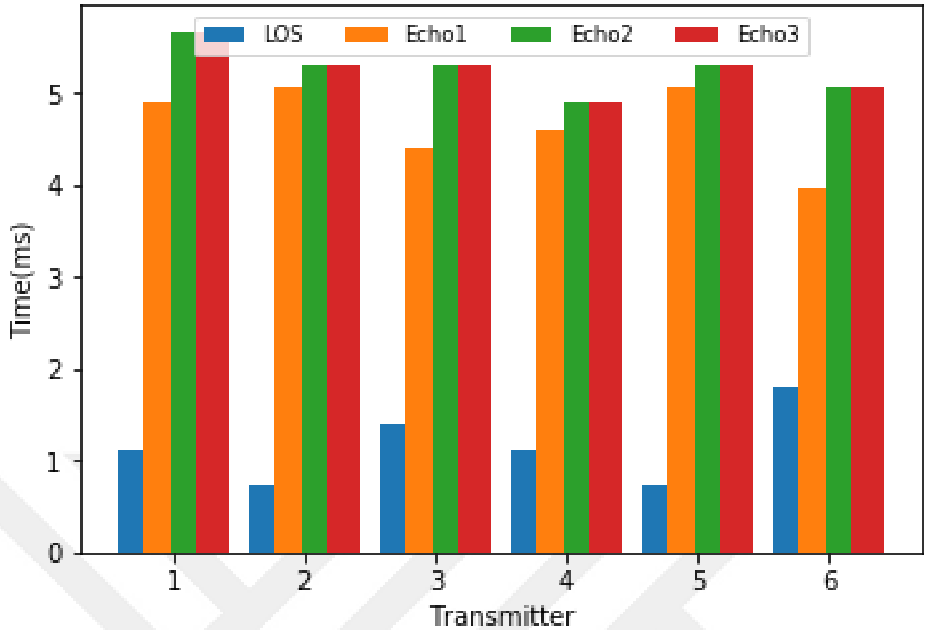

Figure 4.7: Waves travel time for the Line-Of-Sight and first three echoes to the object in position B.

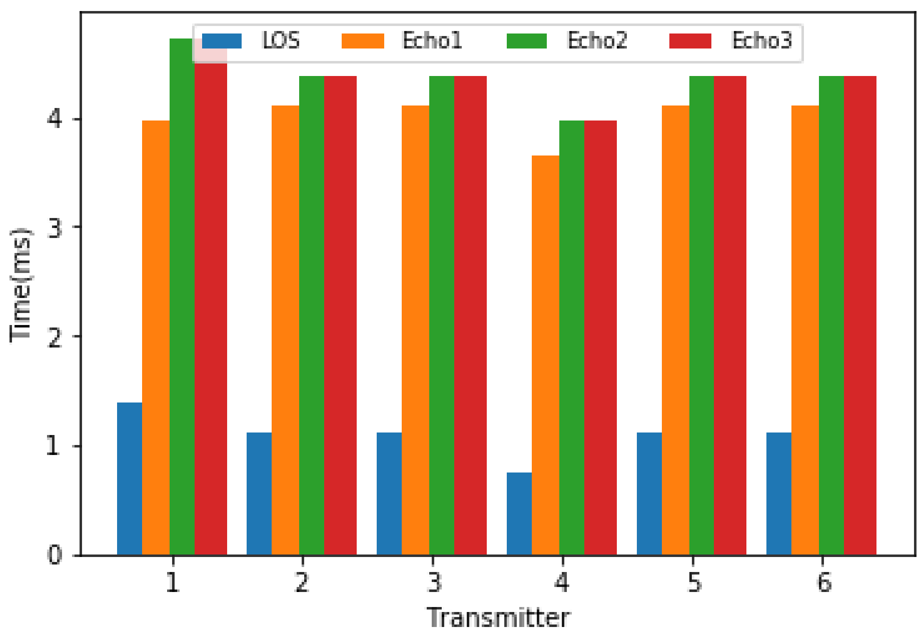

Figure 4.8: Waves travel time for the Line-Of-Sight and first three echoes to the object in position C.

The figures show that the difference in the time between the Line-Of-Sight signal and the echoes is significantly large and can be distinguished easily. However, as the proposed method relies on the arrival of the first signal that uses the required frequency, and as the obstacles in the environment cannot block the ultrasonic waves, these echoes have less effect on the positioning accuracy, which is the main reason behind the improved positioning accuracy. Figure 4.9 shows the histogram of the errors occurred using the proposed method with a single sphere per reference point and the average function for coordinates computations, which shows that most of the positioning operations have very low positioning errors.

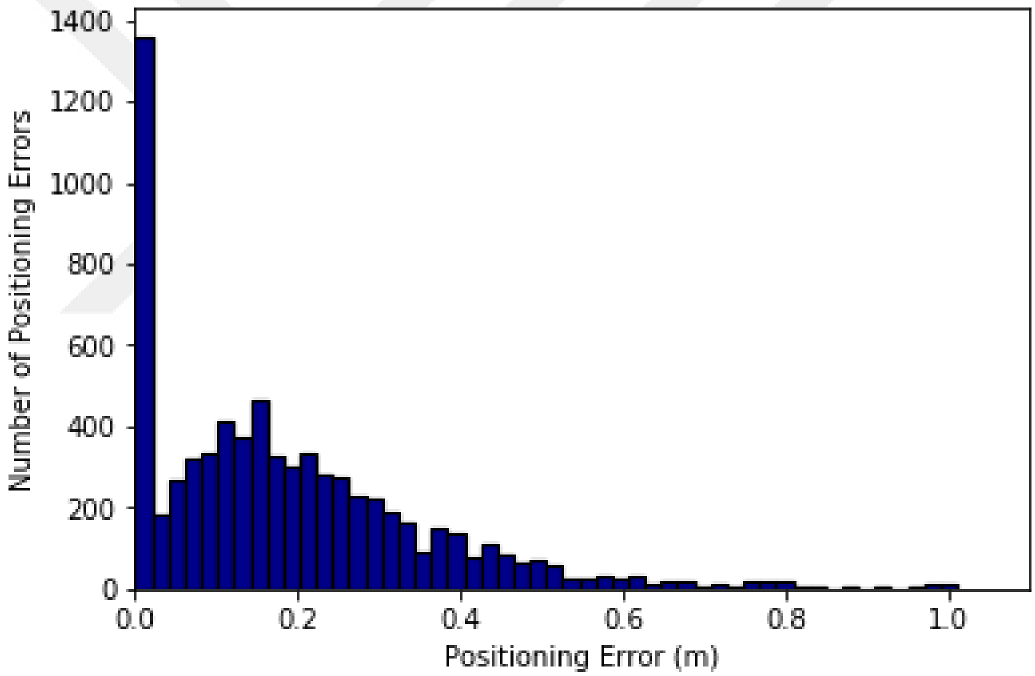

Figure 4.9: Histogram of the positioning errors without considering the echo.

Moreover, Figure 4.10 shows the error histogram for the same experiments, using the exact coordinates and error values, considering the echo of the ultrasonic signals. The identical results illustrate that the echo does not have any effect on the positioning accuracy. This immunity to the effect of the echo is according to the use of time, instead of power, in the positioning process, so that, the distance is calculated between the object and the reference point as soon as the ultrasonic signal is received. Thus, when the echo arrives, with the same frequency, it is neglected as the distance with that source reference point is already calculated. Moreover, the distribution of the positioning error in the environment, shown in Figure 4.11, show that no certain areas suffer from lower positioning accuracy, such as the corners of the environment. Moreover, all the positioning operations in the experiments have been able to maintain positioning accuracy within one meter, i.e., the object is still positioned within one meter from its actual position, in worst cases.

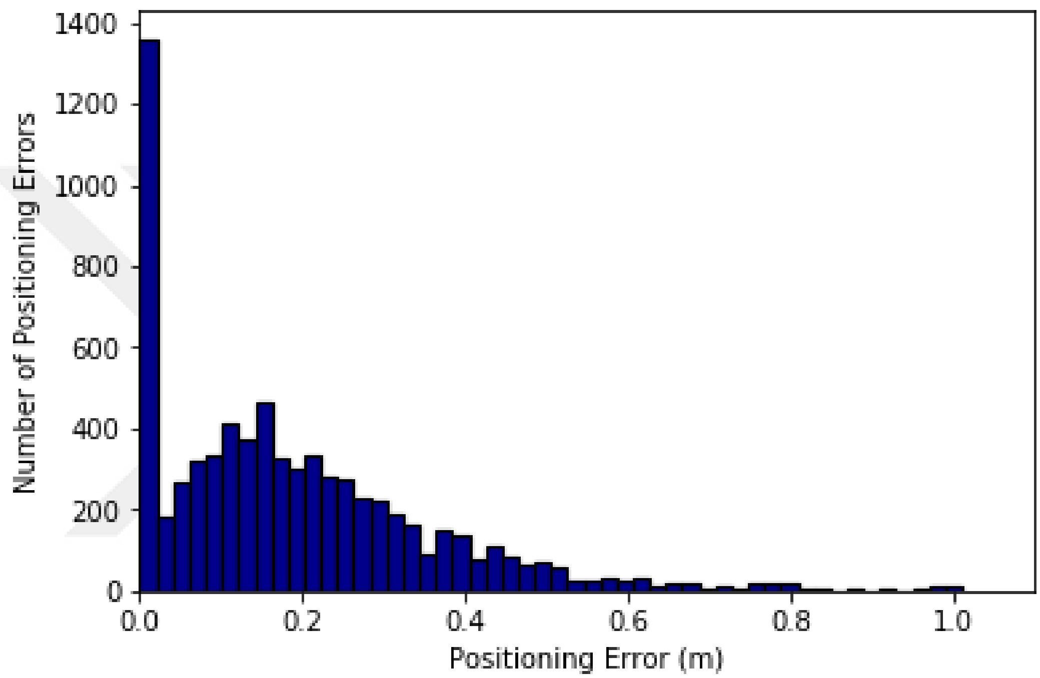

Figure 4.10: Histogram of the positioning errors considering echoes.

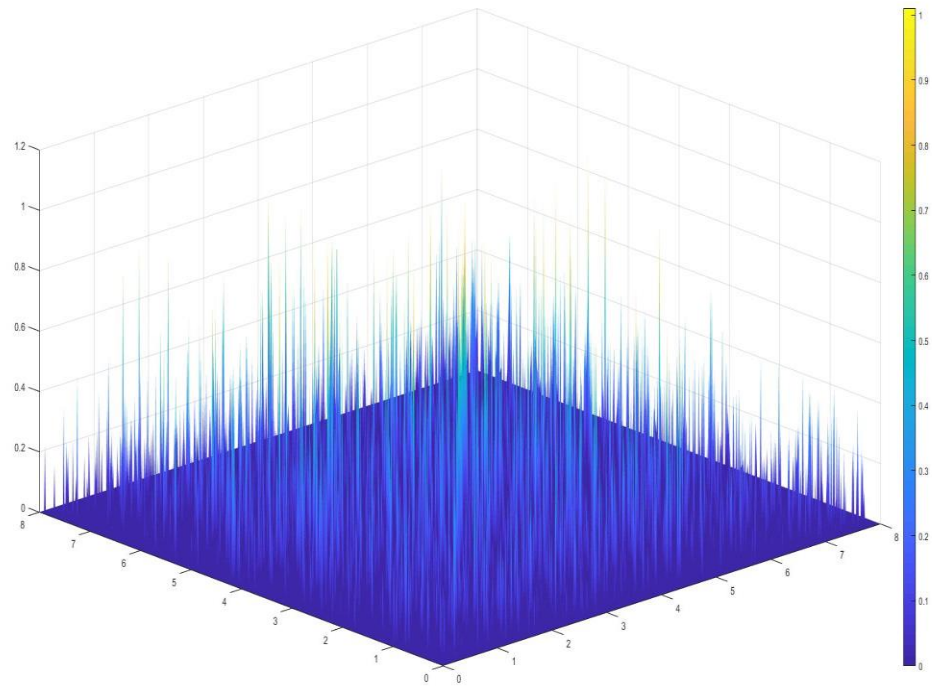

Figure 4.11: Distribution of the positioning error in the environment.

5. DISCUSSION

The positioning errors in the different scenarios evaluated in the experiments conducted in this study are summarized in Table 5.1 and Figure 5.1. the summary shows that the RMSE when multiple spheres per each reference point are used does not decrease as the number of reference points is increased. The summary also shows that, surprisingly, the average function has achieved better positioning results, which is an unexpected result as the median function has better resistance to extreme noise. Moreover, in general, the use of a single sphere per each reference point has better performance when both the average and median functions are used.

Table 5.1: Summary of the positioning RMSE for the simulated scenarios.

	RMSE			
	Multiple Spheres		Single Sphere	
Number of Reference Points	**Average Function**	**Median Function**	**Average Function**	**Median Function**
4	**0.22**	**0.22**	**0.23**	**0.23**
5	**0.20**	**0.22**	**0.20**	**0.22**
6	**0.22**	**0.21**	**0.15**	**0.15**
Mean	**0.213**	**0.217**	**0.193**	**0.200**

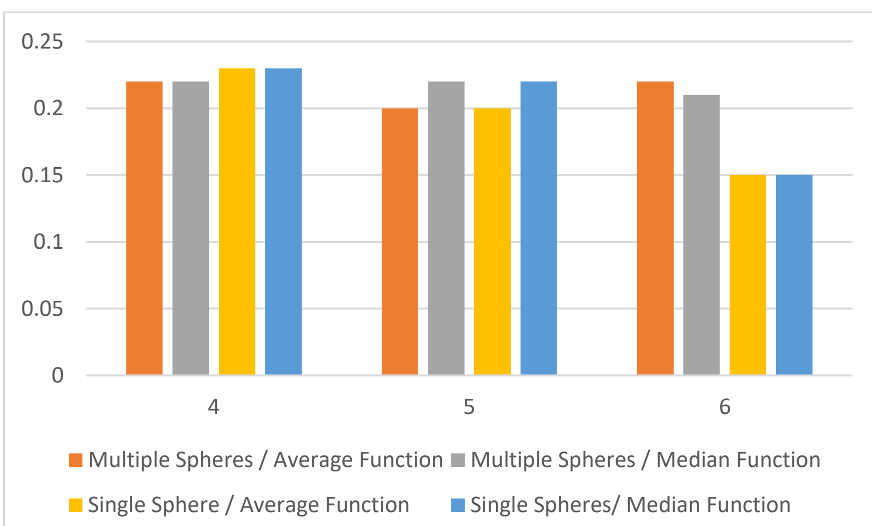

Figure 5.1: Illustration of the positioning RMSE for the simulated scenarios.

As the use of the single sphere per reference point has achieved the lowest positioning error, the results of the corresponding experiments are compared to those from the experiments conducted by Gu et al. [41], which uses VLC for the positioning of the object, in Table 5.2. The mean positioning RMSE values from this table are illustrated in Figure 5.2, which shows that the proposed method has been able to outperform Gu et al.'s in both the outer and the entire regions, while Gu et al.'s method has better performance in the inner region of the simulated space. Moreover, the figure shows that the method proposed in this study has very similar positioning error rates in the regions, while the method proposed by Gu et al. has significant differences between the error in the outer and inner regions.

Table 5.2: Comparison between the use of the single sphere per reference point and the method proposed by Gu et al. [41].

	Single Sphere / Reference Point						**Gu et al. [41]**					
	Average			**Median**			**Linear Estimation**			**Non-linear Estimation**		
Number of Reference Points	**Outer**	**Inner**	**Entire**	**Outer**	**Inner**	**Entire**	**Outer**	**Inner**	**Entire**	**Outer**	**Inner**	**Entire**
4	0.20	0.25	0.23	0.20	0.25	0.23	0.48	0.09	0.33	0.43	0.07	0.29
5	0.18	0.22	0.21	0.19	0.23	0.23	0.55	0.13	0.37	0.53	0.09	0.35
6	0.13	0.16	0.15	0.13	0.16	0.15	0.68	0.16	0.46	0.60	0.11	0.40
Mean	**0.17**	**0.21**	**0.20**	**0.18**	**0.21**	**0.20**	**0.57**	**0.13**	**0.39**	**0.52**	**0.09**	**0.35**

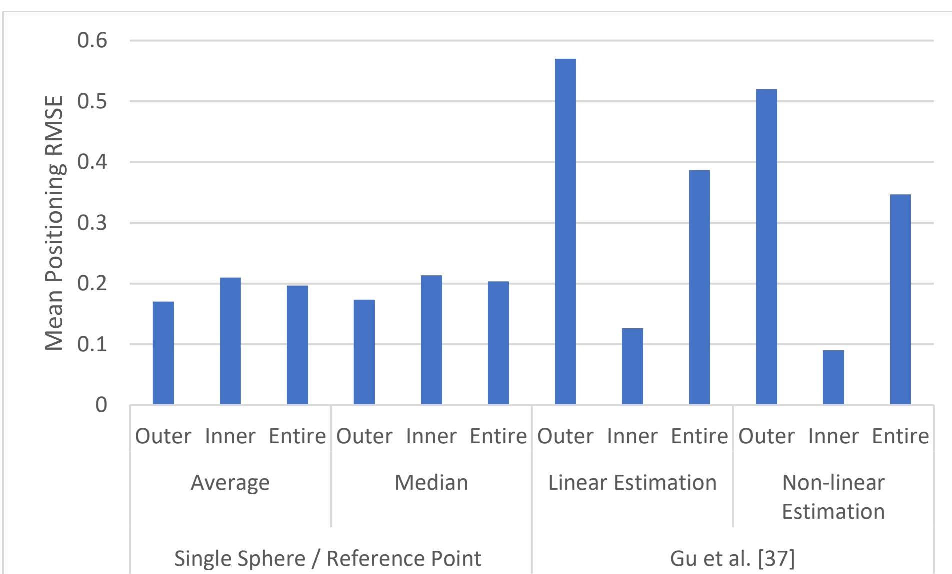

Figure 5.2: Illustration of the mean positioning RMSE of the single sphere per reference point and the method proposed by Gu et al. [41].

Moreover, Figure 5.3 provides a better illustration for the distribution of the positioning error in the method proposed by Gu et al. [41], which illustrates the significant increase in the positioning error in the outer region. Such increment in the positioning error is caused by the difficulty of recognizing NLOS signals reflected by the walls in the environment as the projection angle become very similar to that from a perpendicular source, which makes the detection of these signals difficult using the proposed method. Comparing this figure to Figure 4.11 shows that the method proposed in this study is more resistant to echoes from these walls. Such resistance is a result of using the TDOA approach. The first signal received by the sensor is considered in the distance computations, where any further signals have no value in these computations. Moreover, as the ultrasonic wave does not require LOS to travel to the destination sensor, the effect of obstacles in the environment is significantly lower.

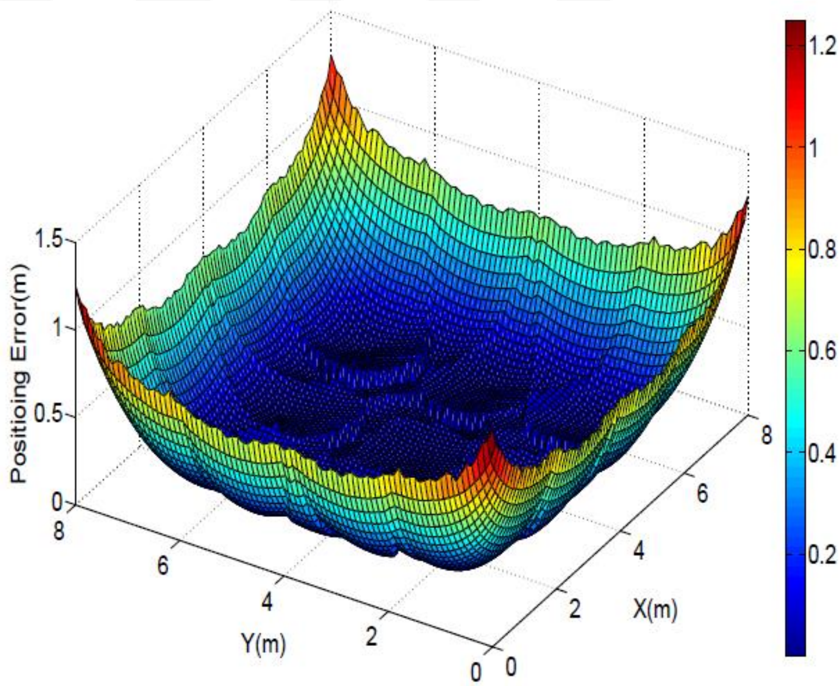

Figure 5.3: Distribution of the positioning error in the space [41].

The proposed method has also been able to achieve higher positioning accuracy than the method proposed by Jae and Kim [44], which uses Wi-Fi signals in order to measure the distances between the object and access point in the space. In addition to the ability of 3-dimensional positioning in the proposed method, which is not applicable in Jae and Kim’s method, the use of ultrasonic signals instead of electromagnetic has been able to reduce the positioning error to less than one meter, according to the lower speed of these signals. Moreover, obstacles in the space can have a significant effect over the received WiFi signals, which is unlike ultrasonic signal it cannot be detected. In an ultrasonic wave, obstacles can produce echoes, which can be easily neglected as the proposed method relies on computing the time difference between the arrival of the electrical signal and the first arrival of the ultrasonic. Additionally, the amplitude of the received signal does not affect the positioning computation, which imposes less effect of noise and obstacles in the space [45].

6. CONCLUSION

Indoor positioning is gaining growing attention according to the different applications it is being used for and the difficulty of using GPS for that purpose. Several techniques have been proposed for indoor positioning, which can be categorized into three main categories, the Angle of Arrival, Received Signal Strength, Time of Arrival and Difference in Time of Arrival. In addition to the high cost of AOA techniques, the accuracy of the coordinates calculated for the object is low compared to other techniques, especially according to the limited resolution of the angles measurements. The positioning accuracy in RSS methods is limited by the effect of the obstacles in the environment, which may cause undesired attenuation to the traveling signal and reflections that can confuse the receiver during the computation of the distance. TDOA methods have also shown better positioning accuracy, compared to TOA, according to the more accurate computations using the TDOA approach.

In this study, a new indoor positioning method is proposed using ultrasonic waves and TDOA approach. As mechanical waves, ultrasound travels in a significantly lower speed than the electromagnetic and light waves. This lower speed allows more resistance to noise imposed by the obstacles in the environment, hence, provide more accurate positioning. With the existence of more than three reference points, several candidate coordinates can be produced, one per each possible combination of three reference points. Such variation is employed to improve the accuracy of the calculated coordinates, using two approaches. The first approach considers each distance with its reference point as a separate reference point in the computations to generate a list of candidate coordinates. Then, the average or median function is used to select the coordinates of the object from the list. The second approach calculates a single distance between the object and the reference point using the measured distances, also using the average or median function, before calculating the coordinates using the same procedure.

As the time of transmission of the signal is known to the object but is known for the other reference points, as they receive the same electrical signal sent to the transmitting device, the object only transmits a signal with its own unique frequency when a signal is received from one of the reference points. The remaining reference points receive the signals from both the transmitting reference point and the object to measure the time difference between the arrival of both signals and then calculate the distance between the object and each reference point. Moreover, as the speed of the ultrasonic waves depends on the characteristics of the atmosphere of the environment, the actual speed of the ultrasound is measured per each positioning process. This speed is calculated by measuring the time required to travel from one reference point to another.

The performance of the proposed method is evaluated using all the coordinates selection approaches. The results show that the use of a single distance from each reference point to the object has produced more accurate positioning than the use of each distance as a separate reference point. The results also show that using the average function has slightly better performance than the use of the median. Moreover, the results show that the proposed method has better resistance to the noise imposed by the obstacles in the environment, which produce undesired attenuation and reflections, i.e. echoes, to the signals traveling the environment. The results also show that the method has similar positioning accuracy in different regions of the space, inner, outer and the entire space. The results also show the positioning using the proposed method is more accurate the state-of-the-art methods proposed in earlier studies.

In future work, the use of electromagnetic waves alongside with ultrasound is going to be investigated. According to the significant difference in the speed between these waves, the time difference of the arrival of these signals is going to be used to calculate the distance between the reference point and the object. These distances are then used to calculate the coordinates of the object directly by the object. However, such method requires updating the object with the speed of the ultrasonic signal in order to be able to conduct the required computations.

REFERENCES

[1] A. M. Ladd, K. E. Bekris, A. P. Rudys, D. S. Wallach, and L. E. Kavraki, "On the feasibility of using wireless ethernet for indoor localization," *IEEE Transactions on Robotics and Automation*, vol. 20, pp. 555-559, 2004.

[2] W. Winterhalter, F. Fleckenstein, B. Steder, L. Spinello, and W. Burgard, "Accurate indoor localization for RGB-D smartphones and tablets given 2D floor plans," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2015, pp. 3138-3143.

[3] R. S. Campos, "Evolution of positioning techniques in cellular networks, from 2G to 4G," *Wireless Communications and Mobile Computing,* vol. 2017, 2017.

[4] W. Xu, J. Wang, H. Shen, H. Zhang, and X. You, "Indoor positioning for multiphotodiode device using visible-light communications," *IEEE Photonics Journal,* vol. 8, pp. 1-11, 2016.

[5] B. Zhao, O. Hellwich, T. Hu, D. Zhou, Y. Niu, and L. Shen, "Employing smartphone as on-board navigator in unmanned aerial vehicles: implementation and experiments," *Industrial Robot: An International Journal,* vol. 42, pp. 306-313, 2015.

[6] C. Dailey, B. Roberts, V. Dumont, I. Khan, G. Panelli, G. Blewitt, *et al.*, "Progress in dark matter search with the global positioning system," *Bulletin of the American Physical Society,* 2019.

[7] L. B. Oliveira, M. Zapella, and R. Hunt, "Global Positioning System and GLObal NAvigation Satellite System constellations for better time synchronising reliability," *The Journal of Engineering,* vol. 2018, pp. 935-937, 2018.

[8] B. Suwandi, T. Kitasuka, and M. Aritsugi, "Low-cost IMU and GPS fusion strategy for apron vehicle positioning," in *TENCON 2017-2017 IEEE Region 10 Conference*, 2017, pp. 449-454.

[9] Z. B. Tariq, D. M. Cheema, M. Z. Kamran, and I. H. Naqvi, "Non-GPS positioning systems: A survey," *ACM Computing Surveys (CSUR),* vol. 50, p. 57, 2017.

[10] J. A. Jayakody, S. Lokuliyana, D. Chathurangi, and D. Vithana, "Indoor positioning: Novel approach for Bluetooth networks using RSSI smoothing," *International Journal of Computer Applications,* vol. 137, pp. 26-32, 2016.

[11] M. A. Landolsi and R. Shubair, "TOAI/AOA/RSS Maximum Likelihood Data Fusion for Efficient Localization in Wireless Networks," in *2018 15th International Multi-Conference on Systems, Signals & Devices (SSD)*, 2018, pp. 458-462.

[12] T. Sanchez, R. C. Hincapie, and C. Gomez, "Performance study of localization techniques: hybrid vs. non hybrid TDOA/DOA," in *2018 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, 2018, pp. 957-960.

[13] A. Malik, T. Zulfiqar, M. A. Javed, and N. S. Nafi, "Performance Evaluation of Wi-Fi Finger Printing based Indoor Positioning System," in *2018 IEEE Conference on Wireless Sensors (ICWiSe)*, 2018, pp. 56-61.

[14] A. M. Bernardos, J. R. Casar, and P. Tarrío, "Real time calibration for rss indoor positioning systems," in *2010 International Conference on Indoor Positioning and Indoor Navigation*, 2010, pp. 1-7.

[15] C. Yang and H.-R. Shao, "WiFi-based indoor positioning," *IEEE Communications Magazine,* vol. 53, pp. 150-157, 2015.

[16] J. Luo, L. Fan, and H. Li, "Indoor positioning systems based on visible light communication: State of the art," *IEEE Communications Surveys & Tutorials,* vol. 19, pp. 2871-2893, 2017.

[17] H. Liu, H. Darabi, P. Banerjee, and J. Liu, "Survey of wireless indoor positioning techniques and systems," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews),* vol. 37, pp. 1067-1080, 2007.

[18] D. Namiot, "On indoor positioning," *International Journal of Open Information Technologies,* vol. 3, pp. 23-26, 2015.

[19] H. Eldeeb, M. Arafa, and M. T. F. Saidahmed, "Optimal placement of access points for indoor positioning using a genetic algorithm," in *2017 12th International Conference on Computer Engineering and Systems (ICCES)*, 2017, pp. 306-313.

[20] A. De Angelis, A. Moschitta, P. Carbone, M. Calderini, S. Neri, R. Borgna, *et al.*, "Design and characterization of a portable ultrasonic indoor 3-D positioning system," *IEEE Transactions on Instrumentation and Measurement,* vol. 64, pp. 2616-2625, 2015.

[21] L. Ma and Y. Xu, "Received signal strength recovery in green WLAN indoor positioning system using singular value thresholding," *Sensors,* vol. 15, pp. 1292-1311, 2015.

[22] J. B. Lundberg, "Alternative algorithms for the GPS static positioning solution," *Applied mathematics and computation,* vol. 119, pp. 21-34, 2001.

[23] P. Wang and Q. Xu, "Design of a flexure-based constant-force XY precision positioning stage," *Mechanism and Machine Theory,* vol. 108, pp. 1-13, 2017.

[24] M. Chen, "Formation and flight control of affordable quad-rotor unmanned air vehicles," University of British Columbia, 2003.

[25] Y. Yan, M. Bohn, S. Peters, and U. Heisel, "Complementing and enhancing definitions of position tolerance for a real point based on ISO Geometrical Product Specifications (GPS)," *CIRP Journal of manufacturing Science and Technology*, 2018.

[26] M. E. Rida, F. Liu, Y. Jadi, A. A. A. Algawhari, and A. Askourih, "Indoor location position based on bluetooth signal strength," in *2015 2nd International Conference on Information Science and Control Engineering*, 2015, pp. 769-773.

[27] K. Yan, H. Zhou, H. Xiao, and X. Zhang, "Current status of indoor positioning system based on visible light," in *2015 15th International Conference on Control, Automation and Systems (ICCAS)*, 2015, pp. 565-569.

[28] M. M. Atia, A. Noureldin, and M. J. Korenberg, "Dynamic online-calibrated radio maps for indoor positioning in wireless local area networks," *IEEE Transactions on Mobile Computing*, vol. 12, pp. 1774-1787, 2013.

[29] J. Yin, Q. Yang, and L. Ni, "Adaptive temporal radio maps for indoor location estimation," in *Third IEEE international conference on pervasive computing and communications*, 2005, pp. 85-94.

[30] J. Yin, Q. Yang, and L. M. Ni, "Learning adaptive temporal radio maps for signal-strength-based location estimation," *IEEE transactions on mobile computing*, vol. 7, pp. 869-883, 2008.

[31] S. He and S.-H. G. Chan, "Wi-Fi fingerprint-based indoor positioning: Recent advances and comparisons," *IEEE Communications Surveys & Tutorials*, vol. 18, pp. 466-490, 2016.

[32] S. Suherman, "WiFi-Friendly Building to Enable WiFi Signal Indoor," *Bulletin of Electrical Engineering and Informatics*, vol. 7, pp. 264-271, 2018.

[33] A. Lindemann, B. Schnor, J. Sohre, and P. Vogel, "Indoor Positioning: A Comparison of WiFi and Bluetooth Low Energy for Region Monitoring," in *HEALTHINF*, 2016, pp. 314-321.

[34] Y.-C. Chen, J.-R. Chiang, H.-h. Chu, P. Huang, and A. W. Tsui, "Sensor-assisted wi-fi indoor location system for adapting to environmental dynamics," in *Proceedings of the 8th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*, 2005, pp. 118-125.

[35] H. Liu, Y. Gan, J. Yang, S. Sidhom, Y. Wang, Y. Chen, *et al.*, "Push the limit of WiFi based localization for smartphones," in *Proceedings of the 18th annual international conference on Mobile computing and networking*, 2012, pp. 305-316.

[36] C.-C. Lo, L.-Y. Hsu, and Y.-C. Tseng, "Adaptive radio maps for pattern-matching localization via inter-beacon co-calibration," *Pervasive and Mobile Computing,* vol. 8, pp. 282-291, 2012.

[37] Z. Luo, W. Zhang, and G. Zhou, "Improved spring model-based collaborative indoor visible light positioning," *Optical Review*, vol. 23, pp. 479-486, 2016.

[38] W. Chen, T. Mei, M. Meng, H. Liang, Y. Liu, Y. Li, *et al.*, "Localization algorithm based on a spring model (LASM) for large scale wireless sensor networks," *Sensors,* vol. 8, pp. 1797-1818, 2008.

[39] R. Derrico, A. Conti, D. Dardari, and A. Sibille, "Localization method and system using non-regenerative UWB relays," ed: Google Patents, 2016.

[40] A. Alarifi, A. Al-Salman, M. Alsaleh, A. Alnafessah, S. Al-Hadhrami, M. Al-Ammar, *et al.*, "Ultra wideband indoor positioning technologies: Analysis and recent advances," *Sensors,* vol. 16, p. 707, 2016.

[41] W. Gu, M. Aminikashani, P. Deng, and M. Kavehrad, "Impact of multipath reflections on the performance of indoor visible light positioning systems," *Journal of Lightwave Technology,* vol. 34, pp. 2578-2587, 2016.

[42] Á. De-La-Llana-Calvo, J.-L. Lázaro-Galilea, A. Gardel-Vicente, D. Rodríguez-Navarro, I. Bravo-Muñoz, and F. Espinosa-Zapata, "Characterization of Multipath Effects in Indoor Positioning Systems by AoA and PoA Based on Optical Signals," *Sensors,* vol. 19, p. 917, 2019.

[43] T.-N. Lin and P.-C. Lin, "Performance comparison of indoor positioning techniques based on location fingerprinting in wireless networks," in *2005 international conference on wireless networks, communications and mobile computing*, 2005, pp. 1569-1574.

[44] E. Jae and C. Kim, "An indoor positioning method using a combination of the triangulation and fingerprinting techniques," in *Proceedings of the 2015 Conference on research in adaptive and convergent systems,* 2015, pp. 260-261.

[45] D. A. J. U. ZIRJAWI, Osman N. ; BAYAT Oguz "A Novel Approach For Indoor Positioning Using Ultrasound Waves," *AURUM Journal of Engineering Systems and Architecture,* vol. Submitted, 2019.