A weighted least squares consideration for IR-UWB radar based device-free object positioning estimation for indoor environment

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ABSTRACT

Impulse Radio Ultra-Wideband (IR-UWB) radar is a type of radar functioning based on UWB transmission technology that uses an exceedingly wide bandwidth low power impulse signal to continuously transmitting and receiving the impulse signal for object detection within a range. To date, most of the proposed Ultra-Wideband (UWB) transmission technology based object positioning estimation systems for indoor environment depends on objects to be attached with an active UWB devices. In certain circumstances, it is ideal to track objects in passive manner without the requirement of any attached tracking devices or device-free object positioning estimation. IR-UWB radar has shown promising utilization in realizing device-free object positioning estimation for indoor environment. With this motivation, in this paper a work on weighted least squares consideration for IR-UWB radar based device-free object positioning estimation for indoor environment is presented.

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1. INTRODUCTION

Object positioning estimation can be defined as a process of locating an object or multiple objects and estimate its position on a known area. Subject on the environment in general there are two types of classification for object positioning estimation namely indoor and outdoor environment object positioning estimation. For outdoor environment, one common example is Global Positioning System (GPS), which has been used in various tracking scenarios. A GPS receiver establishes its distance from satellites by calculating signal arrival time from satellites. By performing complex positioning method, its location on earth's surface can be calculated. GPS based systems are used by military, government agencies and commercial institutions to locate object, people, vehicles and etc. [1-6]. However, since GPS is a system which line of sight between GPS receiver and satellites is required to function effectively, it is tough to provide object positioning estimation in the complicated indoor environment such as inside a building. Thus, object positioning estimation for indoor environment is needed where GPS or other outdoor based object positioning estimation systems are not available.

At present, there are numerous studies currently focusing on the usage of existing wireless technologies such as wireless local area network (WLAN), Bluetooth, ZigBee and Radio Frequency Identification (RFID) to enable object positioning estimation in indoor environment. This is especially true with the rapid adoption of Internet-of-Things (IoT) technology, which has become an important feature in several applications [7-11]. Ultra-Wideband (UWB) transmission technology is one of the emerging and promising wireless technologies for object positioning estimation in an indoor environment. However to date, most of the proposed UWB transmission technology based object positioning estimation systems for indoor environment depends on objects to be attached with active UWB devices. In certain circumstances, it is ideal to track objects in passive manner without the requirement of any attached tracking devices or device-free object positioning estimation [12-20]. Such capability has emerge as an area of interest with wide range of applications [21].

Among the applications that can be implemented by leveraging such circumstances are such as security monitoring, emergency rescue and intelligent monitoring. In security monitoring such as within a building, any motion of intrusion in evening or night time can be effectively monitored since device-free object positioning estimation system can cover a significant larger area compare to other systems such as vision based system and works well in smoky and dark conditions. In emergency rescue such as during hostage or fire rescue situation where military or law enforcement officers can employ device-free object positioning estimation system to facilitate in accessing possible threats inside a building or room prior launching counter measurement action or rescue operation. Consequently minimizing the risk of loss of life and increase operation success rate. In intelligent monitoring, senior citizens in home health care or patients in a hospital can be monitored without violating their privacy and interfering in their daily life. A state-of-the-art device-free object positioning estimation system can not only estimate position and activity information, but also estimate the respiratory rate and detect the occurrence of falls, both, which are equally important for elderly and patients monitoring.

Impulse Radio Ultra-Wide Band (IR-UWB) radar is one of the recent radar technology that leverage on UWB transmission technology. It uses an exceedingly wide bandwidth low power impulse signal to continuously transmitting and receiving the impulse signal for object detection within a range [22-23]. IR-UWB radar has shown promising utilization in realizing device-free object positioning estimation method for indoor environment [24-29]. The exceedingly wide bandwidth and short pulses waveforms can facilitate in minimizing the effect of multipath interference, good signal penetration through obstacles such as walls and objects as UWB pulses are operating in low power and simple hardware configuration, which can be easily used as an embedded type sensor [30].

With his motivation, a work on IR-UWB radar based device-free object positioning estimation for indoor environment has been carried out whereby in this particular work, the weighted least squares method has been considered and employed. The reason for using weighted least squares method in this work is to attempt to tackle the occurrence of ranging errors associated with IR-UWB radar which in this case might affect the performance of the device-free object positioning estimation system model.

2. SYSTEM MODEL

Referring to Figure 1, an IR-UWB radar first generates an impulse signal $S(x)$ that has an exceedingly wide bandwidth and very low transmission power. Should the transmitted signal hit a target or object, a L delayed and scaled signals is reflected back to the IR-UWB radar [31-32] . By using an analog-to-digital converter, the reflected delayed and scaled received impulse signals are transformed into digital signals. These digital signals are then being fed into a bandpass filter to filter out unwanted signals prior being output for further processing. The digitized received signal can be expressed as follows:

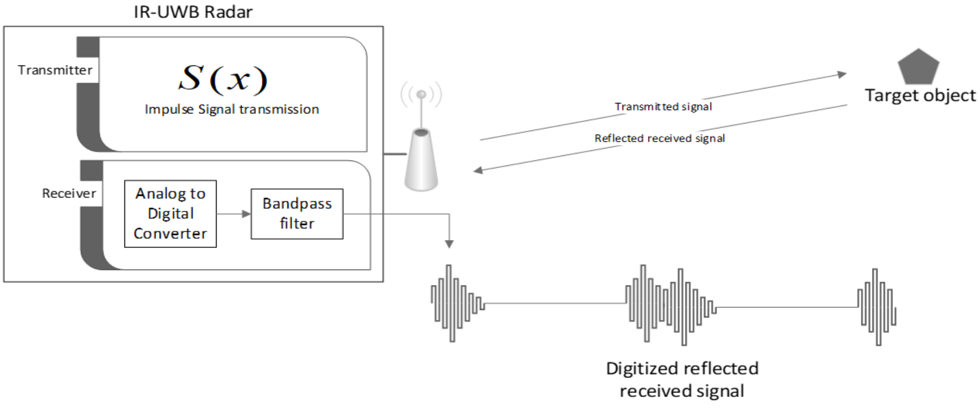

Figure 1. IR-UWB target object detection

$$r(x) = \sum_{n=1}^{L} \alpha_n S(x - \tau_n) + N(x) \quad (1)$$

Where τ_n is the delay and α_n is the amplitude of n-th received signal, x is the digitized sample index while L and $N(x)$ represent the number of impulse signals reflected back from the surroundings and associated noise respectively. The next step is to perform object positioning estimation by employing suitable object positioning estimation technique. Commonly UWB transmission technology based object positioning estimation can be achieved by using either Angle of Arrival (AOA), Received Signal Strength (RSS), Time Difference of Arrival (TDOA) or Time-On-Arrival (TOA) techniques. However in the case of IR-UWB radar, only TOA technique can be used [32].

Referring to Figure 2, the TOA technique fundamentally leverage on the target object's signal TOA when arriving at three different IR-UWB radars. Since the wireless signals travels at the speed of light $c = 3 \times 10^8$m/s, the target object distance r can be calculated using (2).

$$r = c \times TOA \quad (2)$$

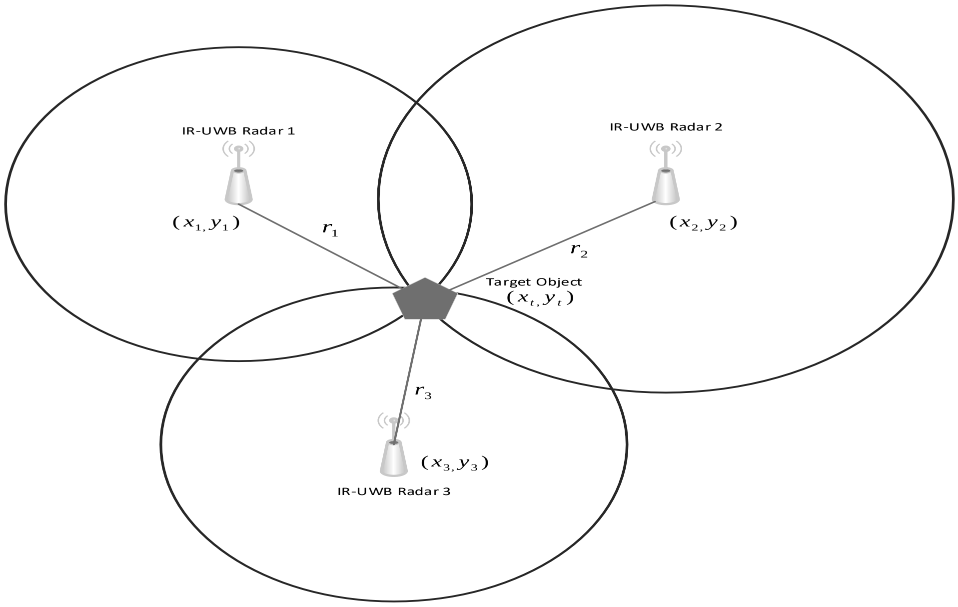

Figure 2. TOA technique using three IR-UWB radars for 2-D space

Object positioning estimation is achieved when the target object lies at the intersection of circles at center (x_t, y_t) and measured distance r_n. For object positioning estimation perform in two-dimensional (2-D) space, a minimum of three IR-UWB radars are required while three-dimensional (3-D) space requires a minimum of four IR-UWB radars [33]. This study will focus on operating in 3-D space. Assuming there are n-th IR-UWB radars being employed to perform object positioning estimation, the coordinates of the n-th IR-UWB radar and target object are expressed by (x_n, y_n, z_n) and (x_t, y_t, z_t) respectively. Once there is one target object entered within a defined space in this system model, the measured distance r_n from the n-th IR-UWB radar to the target object is represented by (3).

$$\begin{aligned} r_1^2 &= (x_1 - x_t)^2 + (y_1 - y_t)^2 + (z_1 - z_t)^2 \\ r_2^2 &= (x_2 - x_t)^2 + (y_2 - y_t)^2 + (z_2 - z_t)^2 \\ r_3^2 &= (x_3 - x_t)^2 + (y_3 - y_t)^2 + (z_3 - z_t)^2 \\ &\vdots \\ r_n^2 &= (x_n - x_t)^2 + (y_n - y_t)^2 + (z_n - z_t)^2 \end{aligned} \quad (3)$$

Then, based on (2), the corresponding weights are then assigned to each calculated r_n by using (4) and then sorted in an ascending order.

$$w = \frac{1}{r^2} \tag{4}$$

Where in principle, the shorter the distance r_n, the greater the weight is being assigned. The sorted weight, $W = \{w_{r_1,} w_{r_2} \dots w_{r_n}\}$ can also be represented in matrix form as in (5)

$$W = \begin{bmatrix} w_{r_1,} & 0 & 0 & 0 \\ 0 & w_{r_2,} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & w_{r_n,} \end{bmatrix} \tag{5}$$

Then, with $\{2 \dots n\}$ equations subtract equation $n = 1$ as found in (3), this resulted in the formulation of (6),

$$\begin{aligned}
2x_t(x_1 - x_2) + 2y_t(y_1 - y_2) + 2z_t(z_1 - z_2) &= r_2^2 - {r_1}^2 - (x_2^2 + y_2^2 + z_2^2) + ({x_1}^2 + {y_1}^2 + {z_1}^2) \\
2x_t(x_1 - x_3) + 2y_t(y_1 - y_3) + 2z_t(z_1 - z_3) &= r_3^2 - {r_1}^2 - (x_3^2 + y_3^2 + z_3^2) + ({x_1}^2 + {y_1}^2 + {z_1}^2) \\
2x_t(x_1 - x_4) + 2y_t(y_1 - y_4) + 2z_t(z_1 - z_4) &= r_4^2 - {r_1}^2 - (x_4^2 + y_4^2 + z_4^2) + ({x_1}^2 + {y_1}^2 + {z_1}^2) \\
&\vdots \\
2x_t(x_1 - x_n) + 2y_t(y_1 - y_n) + 2z_t(z_1 - z_n) &= r_n^2 - {r_1}^2 - (x_n^2 + y_n^2 + z_n^2) + ({x_1}^2 + {y_1}^2 + {z_1}^2)
\end{aligned} \tag{6}$$

Rearranging terms, (6) can be expressed in matrix form as can be found in (7)

$$AX = b \tag{7}$$

Where

$$A = \begin{pmatrix} 2(x_2 - x_1) & 2(y_2 - y_1) & 2(z_2 - z_1) \\ \vdots & \vdots & \vdots \\ 2(x_n - x_1) & 2(y_n - y_1) & 2(z_n - z_1) \end{pmatrix}$$

$$b = \begin{pmatrix} x_2^2 - x_1^2 + y_2^2 - y_1^2 + z_2^2 - z_1^2 + r_1^2 - r_2^2 \\ \vdots \\ x_n^2 - x_1^2 + y_n^2 - y_1^2 + z_n^2 - z_1^2 + r_1^2 - r_n^2 \end{pmatrix}$$

$$X = \begin{pmatrix} x_t \\ y_t \\ z_t \end{pmatrix}$$

From (5) and (7), target object coordinate X can be obtained by solving (8)

$$X = \hat{X} = (A^T W A)^{-1} A^T W b \tag{8}$$

3. TEST SETUP

In order to test the system model described in previous section, a three-dimensional cube space measuring 10m x 10m x 20m (m3) and an array of randomly positioned IR-UWB radars are defined for object positioning estimation to be executed. An example where 16 IR-UWB radars are positioned in randomly order within the defined cube space is shown in Figure 3. Two type of tests with simulated data and one target object within the defined cube space have been conducted in this work.

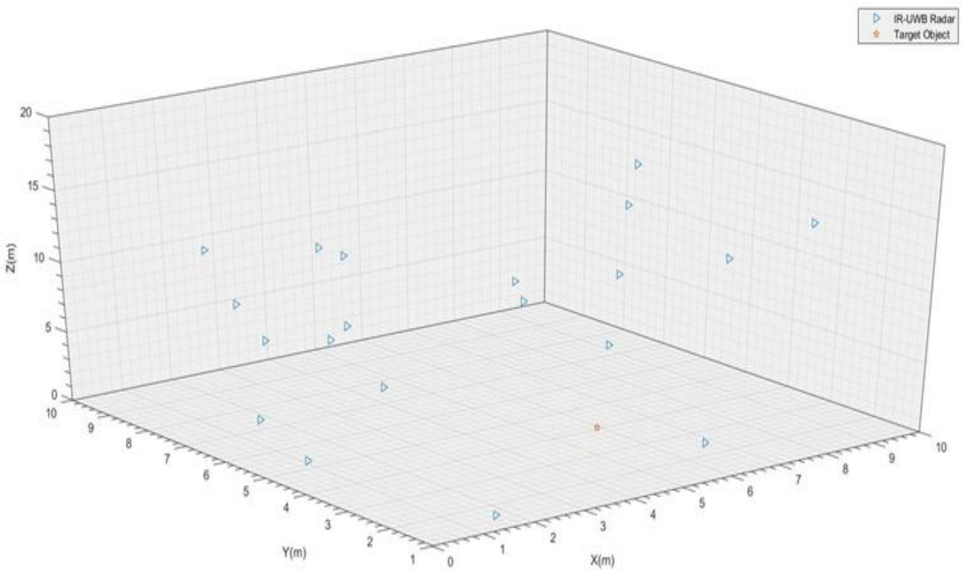

Figure 3. Example generated map with n=16 randomly distributed IR-UWB radar

The first test is to evaluate the system model positioning accuracy with respect to a range of randomly positioned IR-UWB radars starting from a minimum number of $n = 4$ til $n = 16$ IR-UWB radars. For each IR-UWB radar, its randomly generated position are then distorted by an unbiased Gaussian noise N with mean $\mu_N = 0$ and a fixed standard deviation $\sigma_N = 0.1m$. The second test is to evaluate the system model positioning accuracy with respect to varying magnitudes of noise added to a fixed $n = 4$ randomly generated IR-UWB radar position. The position are then distorted by an unbiased Gaussian noise N with mean $\mu_N = 0$ with varying standard deviation $\sigma_N = \{0.1m \cdots 1m\}$.

4. RESULT AND DISCUSSION

Referring to the first test result as depicted in Figure 4, as can be observed the object positioning estimation error is in a descending order from 0.56m until 0.08m as the number of IR-UWB radars used increased from $n = 4$ to $n = 16$. As for the result for second test as depicted in Figure 5, the object positioning estimation error is in an ascending trend from 0.49m to 5.50m as the magnitude of noise is increased from 0.1m to 1.0m.

Based on the two tests conducted, in principle by using the system model described in this work, the more IR-UWB radars being deployed the more accurate the system model calculate the estimated position of the target object. However, for the case when noise is being intentionally injected to the system model the capability of the system model to cope while performing object positioning estimation is gradually tarnished as the magnitude of noise is increased. Although generally the system model described in this work performs reasonably well, improvement from various aspect has to be introduced in future works. Among the improvements that will be considered are to employ suitable noise suppression and reduction techniques, which can be incorporated within the algorithm in the system model in this work.

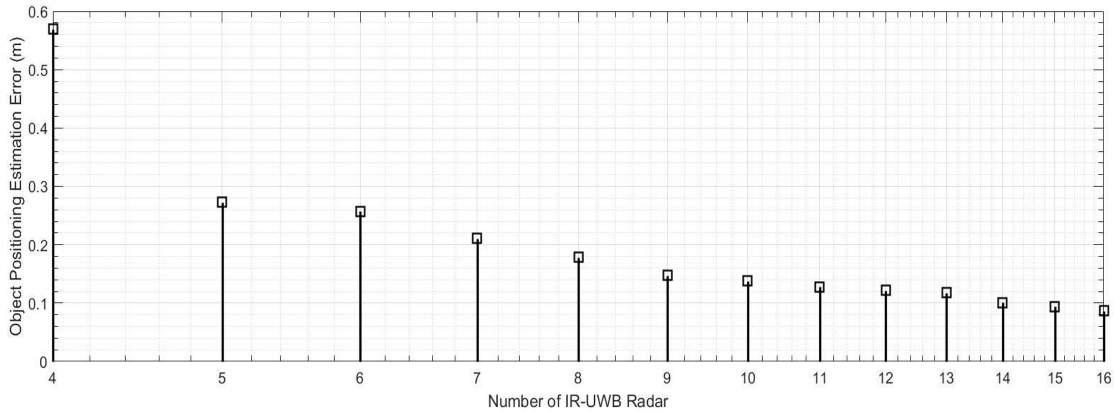

Figure 4. Object positioning estimation error vs number of IR-UWB Radars plot, $n = \{1 \cdots 16\}$, $\sigma_N = 0.1m$

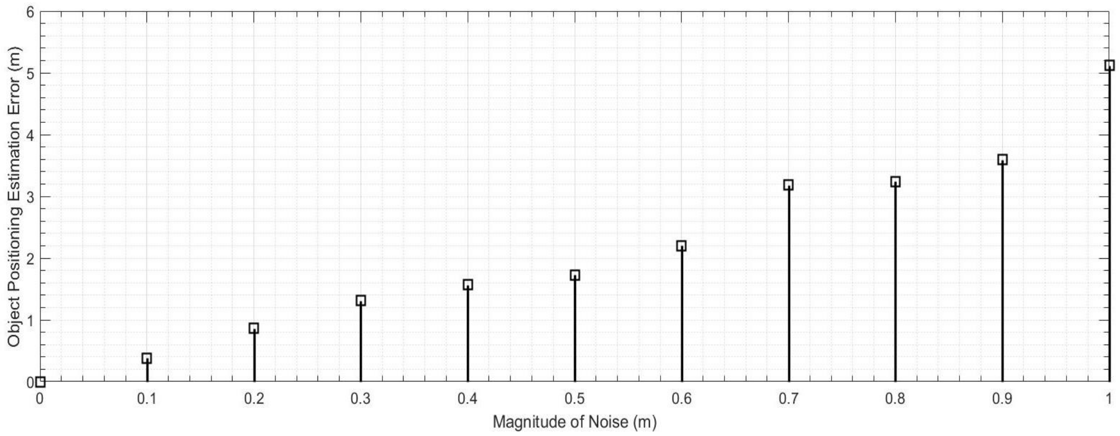

Figure 5. Object positioning estimation error vs magnitude of noise plot, $n = 4$, $\sigma_N = \{0.1m \cdots 1m\}$

5. CONCLUSION

In this paper, a work on weighted least squares consideration for IR-UWB radar based device-free object positioning estimation for indoor environment is presented. Generally, the system model performed well if the magnitude of noises are kept low. However, such case is not viable when operating in real indoor environment as noises will always present in varying magnitude. Therefore, further improvement and other consideration to suppress and reduce noises will be implemented on the system model in future works.

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REFERENCES

[1] A. C. Mayong, V. U. Wanniarachchi, O. N. N. Fernando and M. O. Lwin, "*GPS Trail Visualizer for Online Communities*," 2018 International Conference on Cyberworlds (CW), Singapore, 2018, pp. 164-167.

[2] I. Akbar and A. F. Misman, "*Research on Semantics Used in GPS Based Mobile Phone Applications for Blind Pedestrian Navigation in an Outdoor Environment*," 2018 International Conference on Information and Communication Technology for the Muslim World (ICT4M), Kuala Lumpur, 2018, pp. 196-201.

[3] K. Chen, G. Tan, and M. Lu, "Improving the Energy Performance of GPS Receivers for Location Tracking Applications," pp. 85-90, 2017.

[4] L. Kamelia, E. A. D. Hamidi, W. Darmalaksana and A. Nugraha, "*Real-Time Online Attendance System Based on Fingerprint and GPS in the Smartphone*," 2018 4th International Conference on Wireless and Telematics (ICWT), Nusa Dua, 2018, pp. 1-4.

[5] S. Saha, "GPS Based Smart Spy Surveillance Robotic System Using Raspberry Pi for Security Application and Remote Sensing," pp. 705-709, 2017.

[6] K. Wan and V. Alagar, "*Integrating context-awareness and trustworthiness in IoT descriptions*," Proc. - 2013 IEEE Int. Conf. Green Comput. Commun. IEEE Internet Things IEEE Cyber, Phys. Soc. Comput. GreenCom-iThings-CPSCom 2013, pp. 1168-1174, 2013.

[7] S. Gaur, "*Bringing context awareness to IoT-based wireless sensor networks*," 2015 IEEE Int. Conf. Pervasive Comput. Commun. Work. PerCom Work. 2015, pp. 228–229, 2015.

[8] R. Souza, J. Lopes, C. Geyer, C. Garcia, P. Davet, and A. Yamin, "*Context awareness in UbiComp: An IoT oriented distributed architecture*," Proc. IEEE Int. Conf. Electron. Circuits, Syst., vol. 2016–March, pp. 535-538, 2016.

[9] A. Pir, M. U. Akram, and M. A. Khan, "Internet of things based context awareness architectural framework for HMIS," *E-health Networking, Appl. Serv. (HealthCom)*, 2015 17th Int. Conf., no. ReHIS, pp. 55–60, 2016.

[10] A. Patel and T. A. Champaneria, "*Fuzzy logic based algorithm for Context Awareness in IoT for Smart home environment*," 2016 IEEE Reg. 10 Conf., pp. 1057-1060, 2016.

[11] J. Wilson and N. Patwari, "A Fade-level skew-laplace signal strength model for device-free localization with wireless networks," *IEEE Trans. Mob. Comput*. vol. 11, no. 6, pp. 947-958, 2012.

[12] A. Pantelopoulos and N. G. Bourbakis, "A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis," *IEEE Trans. Syst. Man, Cybern. Part C (Applications Rev*., vol. 40, no. 1, pp. 1-12, 2010.

[13] M. Cimdins, M. Pelka and H. Hellbrück, "*Sundew: Design and Evaluation of a Model-Based Device-Free Localization System*," 2018 International Conference on Indoor Positioning and Indoor Navigation (IPIN), Nantes, 2018, pp. 1-8.

[14] C. Jing, Y. Cui, F. Guo and B. Zhou, "*An Area estimation Scheme For Indoor Device-Free Tracking Systems*," 2018 1st IEEE International Conference on Knowledge Innovation and Invention (ICKII), Jeju, 2018, pp. 343-345.

[15] Y. Noh, H. Yamaguchi and U. Lee, "Infrastructure-Free Collaborative Indoor Positioning Scheme for Time-Critical Team Operations," in *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 48, no. 3, pp. 418-432, March 2018.

[16] O. Kaltiokallio, R. Hostettler, N. Patwari and R. Jäntti, "*Recursive Bayesian Filters for RSS-Based Device-Free Localization and Tracking*," 2018 International Conference on Indoor Positioning and Indoor Navigation (IPIN), Nantes, 2018, pp. 1-8.

[17] B. Zhou, D. Ahn, J. Lee, C. Sun, S. Ahmed and Y. Kim, "*An Energy Conservation Tracking System for the Device-free Target in Wireless Sensor Networks*," 2018 1st IEEE International Conference on Knowledge Innovation and Invention (ICKII), Jeju, 2018, pp. 305-308.

[18] S. Shi, S. Sigg, L. Chen and Y. Ji, "Accurate Location Tracking From CSI-Based Passive Device-Free Probabilistic Fingerprinting," in *IEEE Transactions on Vehicular Technology*, vol. 67, no. 6, pp. 5217-5230, June 2018.

[19] H. Liu, N. Xia, D. Guo and P. Qing, "CSI-based Indoor Tracking with Positioning-Assisted," *2018 Ubiquitous Positioning, Indoor Navigation and Location-Based Services (UPINLBS)*, Wuhan, 2018, pp. 1-8.

[20] T. F. Sanam and H. Godrich, "*An Improved CSI Based Device Free Indoor Localization Using Machine Learning Based Classification Approach*," 2018 26th European Signal Processing Conference (EUSIPCO), Rome, 2018, pp. 2390-2394.

[21] L. Lampe and K. Witrisal, "Challenges and recent advances in IR-UWB system design," *ISCAS 2010 - 2010 IEEE Int. Symp. Circuits Syst. Nano-Bio Circuit Fabr. Syst.*, pp. 3288-3291, 2010.

[22] J. R. Fernandes and D. Wentzloff, "Recent advances in IR-UWB transceivers: An overview," *ISCAS 2010 - 2010 IEEE Int. Symp. Circuits Syst. Nano-Bio Circuit Fabr. Syst.*, pp. 3284-3287, 2010.

[23] A. Alarifi et al., "Ultra-Wideband Indoor Positioning Technologies: Analysis and Recent Advances," *Sensors*, vol. 16, no. 5, p. 707, 2016.

[24] H. Li, R. Miura, T. Kagawa, F. Kojima and H. Nishikawa, "Improvement of receiver sensitivity for enhancing IR-UWB performance for indoor positioning," *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Montreal, QC, 2017, pp. 1-5.

[25] D. Yim and S. H. Cho, "Indoor Positioning and Body Direction Measurement System Using IR-UWB Radar," *2018 19th International Radar Symposium (IRS)*, Bonn, 2018, pp. 1-9.

[26] J. Liu, "An IR-UWB indoor positioning based on TOA and band-gap modulations," *2017 International Applied Computational Electromagnetics Society Symposium (ACES)*, Suzhou, 2017, pp. 1-2.

[27] Y. Lee, D. Kang, K. Moon and S. Cho, "*Enhancement of the real-time indoor ranging and positioning algorithm using an UWB system*," 2017 IEEE 17th International Conference on Ubiquitous Wireless Broadband (ICUWB), Salamanca, 2017, pp. 1-4.

[28] S. P. Rana, M. Dey, H. U. Siddiqui, G. Tiberi, M. Ghavami and S. Dudley, "*UWB localization employing supervised learning method*," 2017 IEEE 17th International Conference on Ubiquitous Wireless Broadband (ICUWB), Salamanca, 2017, pp. 1-5.

[29] R. Bharadwaj, S. Swaisaenyakorn, C. G. Parini, J. C. Batchelor and A. Alomainy, "Impulse Radio Ultra-Wideband Communications for Localization and Tracking of Human Body and Limbs Movement for Healthcare Applications," in *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 7298-7309, Dec. 2017.

[30] Z. Irahhauten, H. Nikookar, and G. J. M. Janssen, "An overview of ultra-wide band indoor channel measurements and modeling," *IEEE Microw. Wirel. Components Lett.* vol. 14, no. 8, pp. 386-388, 2004.
[31] G. Llano, J. Reig, L. Rubio, A. P. García, and U. P. De Valencia, "Ultra-wideband Frequency Analysis : State-of-the-art, Measurements and Modeling," pp. 147-154, 2009.
[32] V. H. Nguyen and J. Y. Pyun, "Location detection and tracking of moving targets by a 2D IR-UWB radar system," *Sensors (Switzerland)*, vol. 15, no. 3, pp. 6740-6762, 2015.
[33] Y. T. Chan, H. Y. C. Hang, and P. C. Ching, "Exact and approximate maximum likelihood localization algorithms," *IEEE Trans. Veh. Technol.*, vol. 55, no. 1, pp. 10-16, 2006.

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