Active-Passive Two-Way Ranging Using UWB

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***Abstract*—This paper proposes a generalized approach combining two-way ranging (TWR) and passive ranging methods, called active-passive two-way ranging (AP-TWR). The proposed approach offers a generalized solution for a wide range of anchor configurations in positioning systems. The possibility to define active-passive and passive-only anchor roles allows scaling the system to improve the root-mean-square-error (RMSE) of the ranging estimations and the air time occupancy. Practical experiments show that with the proposed method consisting of 5 active-passive anchors and a single passive anchor, the RMSE is improved by 7.4% and the air time occupancy by 12.5% as compared to the single-sided TWR method with a 6 anchor configuration. Moreover, simulation results show that a maximum theoretical RMSE improvement of 31.7% can be achieved with the proposed setup.**

***Index Terms*—UWB, two-way ranging, passive ranging**

I. Introduction

The market for a wide range of location-based services (asset tracking, object locating, navigation, etc.) has been growing over the last years. The demand for ubiquitous access to these services has pushed for the development of indoor positioning systems, as opposed to classical Global Navigation Satellite Systems (GNSS) which typically operates outdoors. Indoor propagation conditions have raised new challenges for positioning systems: requirement for high accuracy, low interference towards other systems, robustness to multi-path effects, etc [1].

Ultra-Wideband (UWB) technology-based indoor positioning systems are becoming more popular over the last years. This is primarily due to their achievable accuracy of positioning as well as their robustness to multipath effects and presence of obstructions [2]. The most widely used range-based methods for UWB positioning are ToA (Time of Arrival) and TDoA (Time Difference of Arrival). The former is used to calculate distance by measuring the round-trip time of a ranging packet, and the latter employs synchronized anchors to calculate the distance differences of a tag to several anchors. Since ToA does not need clock synchronization between anchors, the complexity of these systems is generally lower [3].

Since employing ToA requires more air-time occupancy due to a larger amount of packets transmitted per ranging session and also depending on the ranging rate, the number of tags operating in a positioning system becomes limited [4]. To push the limitation, state of the art passive ranging schemes should be implemented, where the system consists of a single active anchor which is transmitting, and a number of passive anchors which are in dedicated receive mode. These passive methods allow decreasing the number of transmitted packets, effectively decreasing the air time and allowing more tags to operate in a system.

This paper proposes a generalized method which combines active and passive ranging to provide a flexible positioning system configuration. Depending on the requirements, the final configuration could be oriented towards better ranging precision, shorter protocol, or a balanced configuration offering slight improvements to both. The main principle is providing the active anchors with the functionality of passive ranging, making them so-called active-passive anchors. This ranging scheme allows each active-passive anchor to provide several range estimates during a single ranging sequence, compared to a single range estimate provided by conventional active ranging. Furthermore, the addition of passive-only anchors provides even more range estimates without increasing the number of transmitted packets, theoretically removing the limit to the maximum number of anchors participating in ranging. Depending on the number of active-passive anchors, the passive-only anchors also provide multiple measurements per ranging sequence, making them more precise.

The structure of this paper is as follows. Section II provides the state-of-the-art works on passive ranging; Section III describes the main idea of passive two-way ranging (TWR) and proposes the active-passive TWR (AP-TWR) method; Sections IV and V provide the numerical and experimental results of the proposed method, respectively. Finally, the conclusions are drawn in Section VI.

II. Related Works

This section gives an overview of the state of the art related to the usage of passive ranging schemes in UWB based systems.

Fujiwara, Mizugaki, Nakagawa, Maeda and Miyazaki [5] developed a seminal UWB ToA/TDoA hybrid positioning system, which reduces the needed number of anchors and packet exchanges in a positioning sequence. Sahinoglu and Gezici [6] give a theoretical analysis of the ToA/TDoA hybrid

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method provided in the previous paper. Although the usage of a hybrid system gives more accurate position estimations, the proposed system consisted of only 2 anchors. This would mean that only a 2-dimensional position estimation could be derived by setting geometric constraints for the tag location.

Gholami, Gezici, Rydström and Ström [7] develop a maximum likelihood estimator (MLE) in conjunction with the hybrid ToA/TDoA for position estimation. Due to the simultaneous usage of ToF and TDoA, the proposed system needs complicated post-processing, combining range and time difference based positioning methods. In [8], [9] the previous idea is expanded, so not only the anchors, but also the tags provide the TDoA values by acting as passive listeners. Although, this method provides improved performance in terms of position estimation root-mean-square-error (RMSE), the implementation raises some practical limitations. Firstly, in order for the tags to provide the TDoA values, they should be in receive mode at all times, which drains the batteries quicker than being in sleep mode in between data transmissions. Furthermore, the tags would need *a priori* knowledge of the location of anchors, or in the case of a centralized positioning system, the TDoA values need to be communicated to a positioning server, requiring more time spent transmitting.

A mixture of symmetric double-sided two-way ranging (SDS-TWR) and passive ranging, called Passive Extended (PE) ranging, is presented by Horvath, Ill and Milankovich [10]. The PE ranging increases the accuracy of ranging at the cost of adding a single packet to a positioning sequence, when compared to standard passive ranging. The same authors further improved on PE ranging by introducing an alternative calculation to the method in [11], providing more robustness against time measurement errors in nodes. In addition to the added packet, the practical implementation of said method is again bounded by the battery life of tags, as the ranging is initiated by the anchor, meaning the tag has to be in constant receive mode, rather than sleeping in between rangings.

The three Multiple Simultaneous Ranging (MSR) methods presented by Shah and Demeechai [12] employ a single active and multiple passive anchors to estimate the distances to a tag during a single positioning sequence. The main idea is to provide the estimated anchor-to-tag distances with the lowest possible airtime occupancy. While reducing the number of needed packets in a positioning sequence, MSR method 1 also tackles the previously mentioned practical limitations by setting the tag as the ranging session initiator. Results show that the airtime occupancy is reduced at the cost of range estimation RMSE. Although, the protocol length is reduced by using this method, the authors only focus on the case of a single active anchor and k number of passive anchors,

This paper proposes a ranging scheme which combines active and passive ranging to provide a system configuration with m active-passive anchors and k passive anchors. Depending on the requirements of the system, a network could be constructed to optimize the range estimate RMSE, the length of protocol or providing a balancing point in between.

III. Ranging Methods

This section describes the main idea of passive ranging and the proposed AP-TWR method.

A. Passive Two-Way Ranging

Passive ranging is based on the assumption of having anchors at a fixed, known location, so the distances between each anchor can be calculated beforehand. In the scope of this paper, a tag-initiated single-sided two-way-ranging (SS-TWR) method is used for the active transmission, the clock offsets are not considered as they can be compensated for SS-TWR [13]. This method allows the tag to remain in sleep mode to conserve its battery charge when not ranging.

Figure 1 describes the TWR method using passive anchors that do not participate in active packet exchange, the notation is as follows:

- $t_{\triangleleft}^{\diamond}$ is $\diamond$-th time interval measured by node $\triangleleft$
- $t_{\bullet\leftrightarrow\circ}$ is time of flight (ToF) from node $\bullet$ to node $\circ$

Tag T initiates the ranging sequence with a ranging request. Upon receiving it, anchor A responds with a ranging reply after processing time t_A^I. The tag in turn sends out a ranging report after its own processing time t_T^{II}, while the passive listening anchor L receives all the packets and records the corresponding timestamps.

Note that the value of $t_{A\leftrightarrow L}$ can be calculated with (1) via speed of light c since the physical distance $d_{A\leftrightarrow L}$ between A and L is known.

$$t_\star = \frac{d_\star}{c} \Leftrightarrow d_\star = ct_\star \tag{1}$$

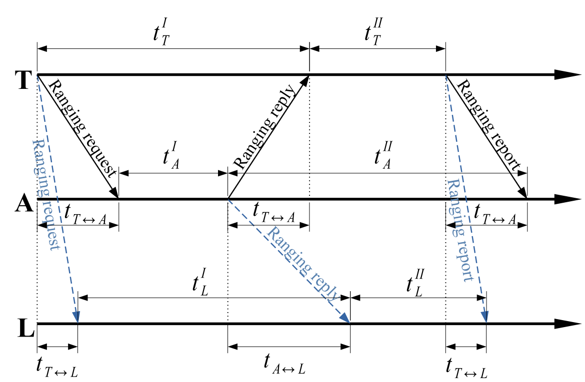

Fig. 1. Passive ranging packet exchange

The ToF value from T to L, $t_{T\leftrightarrow L}$ can be calculated in two ways: by using the 1^{st} and 2^{nd}, or 2^{nd} and 3^{rd} packet exchange, respectively, as can be seen from Fig. 1:

$$t_{T\leftrightarrow L} = t_{T\leftrightarrow A} + t_A^I + t_{A\leftrightarrow L} - t_L^I \tag{2a}$$
$$t_{T\leftrightarrow L} = t_L^{II} + t_{A\leftrightarrow L} - t_{T\leftrightarrow A} - t_T^{II} \tag{2b}$$

Then the sum of (2a) and (2b) becomes

$$2t_{T\leftrightarrow L} = 2t_{A\leftrightarrow L} + t_A^I - t_L^I + t_L^{II} - t_T^{II} \tag{3}$$

Since $t_T^I + t_T^{II} = t_L^I + t_L^{II}$, rearranging it so that $t_T^{II} = t_L^I + t_L^{II} - t_T^I$ and substituting it into (3), then by simplifying it becomes

$$t_{T\leftrightarrow L} = \frac{t_A^I + t_T^I}{2} + t_{A\leftrightarrow L} - t_L^I \tag{4}$$

Equation (4) serves the basis for passive ToF measurement, employing dedicated active and passive anchors. It is also a simplified form of Multiple Simultaneous Ranging (MSR) Equation (16) published in [12].

B. Proposed Method

The proposed method takes the concept described in Section III-A and generalizes it, so a total of m active anchors and n passive anchors take part in the ranging process, noting that the active anchors simultaneously take part in passive ranging as well. In order to develop the generalized equation for the proposed method, some changes to the notation of equations presented in Section III-A had to be made:

- t_{Ti} - i^{th} time interval measured by tag T
- t_{Ai} - processing time of active anchor i
- t_{Li} - passive anchor time interval of i^{th} active anchor
- $t_{Ai\leftrightarrow Aj}$ - ToF from anchor i to anchor j
- $t_{i,j}$ - ToF from tag to passive anchor j while listening on anchor i's transmission

This also is illustrated in Figure 2. Note that the report packet which contains the information from ranging is omitted from the figure.

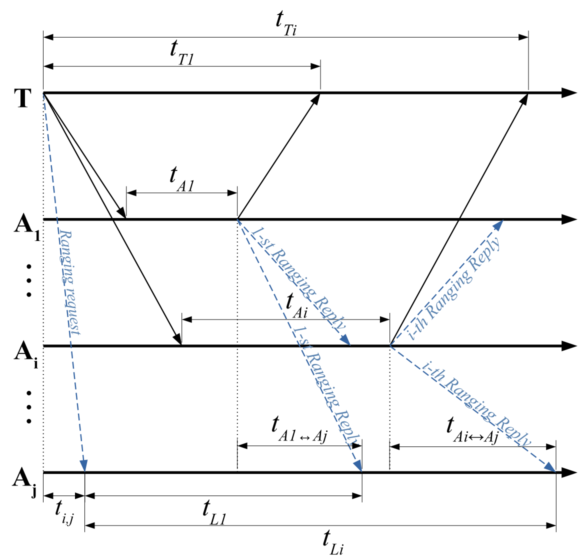

Fig. 2. Proposed generalized active-passive ranging. T initiates sequence, A_1 and A_i respond, A_j listens.

Similar to previous Section, the tag T starts the ranging sequence by transmitting a ranging request packet to active anchor A_i, which responds after its reply processing time t_{Ai}. The tag records the round-trip time corresponding to anchor i as t_{Ti}, while the passive anchor A_j measures the time intervals corresponding to anchor i as t_{Li}. $t_{Ai\leftrightarrow Aj}$ denotes the ToF value from anchor i to anchor j. Finally, the estimated ToF from tag T to listener anchor A_j while listening to anchor A_i's transmissions is denoted as $t_{i,j}$.

The first part of (5) corresponds to active ranging employing the SS-TWR method [13]. The second part illustrates passive ranging, which is the product of generalizing (4). The resulting equation covers active-passive ranging for a total of n anchors from which m are active-passive anchors, making the number of passive-only anchors as $k = n - m$.

$$t_{i,j} = \begin{cases} \dfrac{t_{Ti} - t_{Ai}}{2}, & \text{for } i = j \\ \\ \dfrac{t_{Ti} + t_{Ai}}{2} + t_{Ai\leftrightarrow Aj} - t_{Li}, & \text{for } i \neq j \end{cases} \tag{5}$$

where $i \in \{1, 2, \ldots, m\}$, $j \in \{1, 2, \ldots, n\}$ and $n \geqslant m$. The constraint of $n \geqslant m$ is introduced to eliminate sub-optimal cases. Assuming the anchors are not power constrained, there is no added cost for anchors to listen to other transmissions. So it is sensible to receive every active ranging packet.

Equation (5) allows to construct a m by n matrix each ranging sequence, where the ToF estimates from active ranging lay on the main diagonal, and passive rangings off the main diagonal:

$$M = \begin{bmatrix} t_{1,1} & \dots & t_{1,m} \\ \vdots & \ddots & \\ t_{n,1} & & t_{n,m} \end{bmatrix} \tag{6}$$

Equation (6) enables row-wise averaging to reduce the effect of range estimation noise. The resulting values correspond to averaged anchor-to-tag ToF values, which can be used as inputs for position estimation.

IV. Numerical Simulation Results

This section provides an overview of the numerical simulation results for the proposed active-passive ranging scheme. The performance of the range estimation, as well as the impact on air-time occupancy are considered.

A. Ranging Performance

The ranging performance was assessed by conducting Monte Carlo simulations over 1000 iterations, each consisting of 1000 separate ranging sequences. During each iteration, the anchors and tag were placed at random positions in a simulated 600 by 400 by 250 cm room. Each ranging sequence, the measurement matrix was constructed with (6) and the active and passive range estimations were averaged row-wise to reduce the effect of measurement noise. Finally, the RMSE values were calculated.

In order to evaluate the performance of AP-TWR, the following assumptions were made to the numerical simulations: propagation condition is line-of-sight (LoS), range estimation noise follows a Gaussian distribution, clock errors are omitted, calibration errors are omitted, distances between anchors are known and exact, ToF values in (6) are converted to distances via (1), baseline active and passive anchor performance values taken from [12].

TABLE I
ACTIVE-PASSIVE RANGING ESTIMATED RANGE RMSE (CM), NUMERICAL SIMULATION RESULTS

m \ k	0	1	2	3	4	5	6	7	8	9
1	3.159	4.236	4.539	4.682	4.768	4.822	4.860	4.891	4.913	4.931
2	2.997	3.211	3.313	3.370	3.410	3.437	3.459	3.474	3.487	3.496
3	2.620	2.704	2.752	2.783	2.807	2.825	2.836	2.846	2.856	2.861
4	2.342	2.384	2.411	2.431	2.446	2.456	2.466	2.473	2.479	2.483
5	2.132	2.157	2.174	2.187	2.196	2.206	2.212	2.218	2.223	2.226
6	1.968	1.984	1.996	2.006	2.013	2.019	2.023	2.028	2.032	2.035
7	1.838	1.848	1.857	1.864	1.869	1.874	1.878	1.881	1.884	1.886
8	1.728	1.737	1.744	1.748	1.753	1.757	1.759	1.762	1.764	1.766
9	1.638	1.643	1.649	1.652	1.656	1.659	1.662	1.664	1.666	1.667
10	1.559	1.564	1.568	1.571	1.574	1.576	1.578	1.581	1.582	1.583

TABLE II
ESTIMATED RANGE RMSE (CM) EXPERIMENTAL RESULTS FOR THE PROPOSED ACTIVE-PASSIVE RANGING.

m \ k	0	1	2	3	4	5
1	3.286	4.608	5.334	5.337	5.466	5.533
2	3.259	3.764	3.838	3.958	4.076	
3	3.251	3.384	3.544	3.670		
4	2.946	3.144	3.268			
5	2.901	3.043				
6	2.892					

Table I presents the results of numerical simulations. The results show the final RMSE values (cm) depending on the number of active-passive anchors m and the number of additional passive-only anchors k. The case of $m = 1$ and $k = 0$ represents the performance of an active anchor utilizing only SS-TWR.

Each additional active-passive anchor decreases the resulting RMSE. This can be seen in case $k = 0$ where increasing the number of active-passive anchors m in the range of 1...10 the RMSE decreases from 3.159 cm to 1.559 cm as well as each case up to the maximum of $k = 10$ where the RMSE values decrease from 4.931 cm to 1.583 cm, respectively. Furthermore, additional passive-only anchors increase the RMSE, which can be seen for each case where $m =$ const, increasing the number of passive-only anchors k from 1 to 10. Although passive anchors have less precision than active anchors with TWR, employing 3 active-passive anchors provides a situation where all added passive anchors perform better than an active anchor with TWR.

B. Air Time Occupancy

The air time occupancy, or protocol length, is measured as the total number of packets transmitted per single ranging sequence in the scope of this paper.

The AP-TWR method proposed in this paper entails the tag initiating a ranging sequence with a ranging request packet and concluding it with a ranging report. From the standpoint of air time efficiency, it is not reasonable to transmit a separate ranging report packet to each of the active anchors, so the range estimation results are aggregated and broadcast as a single report packet. Thereby, SS-TWR systems consisting of N active anchors transmit a total of $N + 2$ packets in each ranging sequence: a ranging request, a ranging reply and N packets corresponding to each actively transmitting anchor.

The minimum number of range estimates needed for a 3-dimensional position estimation is 4. Therefore, a standard TWR application (with 4 active-only anchors) requires the transmission of at least 6 packets per ranging sequence. However, compared to AP-TWR case $m = 3$ and $k = 1$, the number of packets transmitted is 5, since there are 3 active-passive anchors. In this example, compared to standard TWR, the protocol length and measurement RMSE both decrease by 16.7% (number of transmitted packets decrease from 6 to 5) and 14.4%, respectively.

V. EXPERIMENTAL RESULTS

This section presents the outcome and analysis of experimental tests, which were conducted to validate the simulation results. The experiments were conducted with Decawave DW1000 UWB IC [14] based devices: 6 anchors and 1 tag, ensuring that LoS propagation conditions were met between all devices.

Table II presents the resulting RMSE values dependent on the number of active-passive anchors m and the number of additional passive anchors k. With the available 6 anchors it is possible to compose all combinations from 6 active-passive anchors to 1 active-passive + 5 passive anchors. Although the experimental system shows slightly inferior performance than in the simulations, it can be seen that starting from case $m = 4$, the RMSE starts to overtake the standard SS-TWR case $(m = 1, k = 0)$.

The simulation results showed that using 3 active-passive anchors, along with data averaging, the precision of ranging is improved for each additional passive anchor, when compared to regular TWR. The preliminary experimental results provide lower performance compared to simulations, showing that 5 active-passive anchors and 1 passive-only anchor provide a 7.4% decrease in RMSE and 12.5% decrease of air time compared to SS-TWR with 6 anchors (number of transmitted packets decreased from 6 to 5). Despite this, it is fair to say that experimental results support the results of the simulations.

VI. Conclusion and Future Works

This article proposed a method for combining active and passive ranging in an UWB network, providing a generalized equation for active-passive and passive-only anchors. The proposed AP-TWR concept allows each active anchor to simultaneously act as a passively ranging node, in addition to extra passive-only anchors. Furthermore, all anchors gain additional measurements based on the number of active-passive anchors. This information can be averaged to increase the precision of ranging, which is demonstrated in the simulation and experimental results. Moreover, the proposed method allows to reduce the air time by making use of passive-only anchors, with no impact on the number of range estimations per ranging sequence.

The numerical results show that for an example case of 4 anchors, compared to SS-TWR, the AP-TWR method (with 3 active-passive anchors and 1 passive-only anchor) provides a decrease of RMSE by 14.4% and the air time by 16.7% by decreasing the number of transmitted packets from 4 to 3. The RMSE or air time efficiency could be further improved by respectively increasing or decreasing the number of active-passive anchors in a system. The addition of passive-only anchors provides more range estimates while the air time efficiency is not hindered. The results also show that a configuration of 3 active-passive anchors along with any number of passive anchors provides more precise ranging estimates than an active SS-TWR method.

The simulation results were validated by experimental tests. The tests indicated that the active-passive ranging method performed as it should, with only a slight decrease in performance compared to simulations. Results showed that, for example utilizing 5 active-passive anchors and 1 passive-only anchor the RMSE and air time decreased 7.4% and 12.5% respectively, when compared to 6 anchor SS-TWR.

The experimental results show that for future works there is still room for improvement in the practical system. Alongside striving for better performance, the table presented in Section V could be expanded to match the 10-by-10 table of numerical results. The performance of active-passive ranging could be further improved by employing weighted averaging on range estimations. The proposed method should also be implemented into a positioning system to assess the impact on position estimates.

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