Indoor Inter-Robot Distance Measurement in Collaborative Systems

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***Abstract* — This paper focuses on the problem of autonomous distance calculation between multiple mobile robots in collaborative systems. We propose and discuss two distinct methods, specifically developed under important design and functional constraints, such as the speed of operation, accuracy, energy and cost efficiency. Moreover, the methods are designed to be applied to indoor robotic systems and are independent of fixed landmarks. The measurement results, performed on the CORE-TX case study, show that the proposed solutions meet the design requirements previously specified.**

***Index Terms* — collaborative system, distance measurement, indoor communication, mobile robots, Sonar**

I. INTRODUCTION

Distance measurement and location monitoring are key aspects of mobile robotic systems operation, with direct applicability in a large variety of fields, including: environment exploration and monitoring [1], smart environments and buildings, manipulation in dangerous or difficult areas [2], rescue operations, automatic industrial manipulators, robotic home appliances [3], traffic monitoring and routing, and space exploration and probing.

In this paper we consider the problem of collaborative distance measurement in mobile robotic systems, under the following set of design and functional constraints: a) indoor and outdoor operation, b) independence of fixed landmarks, c) good speed of execution, d) robustness and accuracy, e) energy efficiency, and f) low cost and complexity.

We propose and discuss two methods of distance measurement, MTDOA (Modified Time-Difference-of-Arrival) and CTOF (Combined Time-of-Flight), which bring significant improvements to the corresponding classical techniques, TDOA and TOF, and we will show how the new methods meet the above specified requirements, in collaborative environments of mobile robots. Both methods rely simultaneously on wireless communication for message and command exchange, and on active Sonar systems for sensing and measurement. In addition, a robot alignment algorithm is also introduced in this paper, as a prerequisite operation for the proposed distance estimation techniques.

This paper is organized as follows. In the next section, similar relevant approaches are discussed. Section III contains the presentation of the proposed robot alignment algorithm, and of the MTDOA and CTOF distance measurement techniques. In Section IV we describe the case study used to test and evaluate the proposed methods. Next, the experimental results are presented and discussed. The concluding remarks are contained in the last section.

II. RELATED WORK

Various aspects of inter-robot distance estimation and location monitoring are being extensively studied and discussed, and many techniques have been proposed and implemented.

Radio signal based systems are a frequent solution. One of the most common localization techniques currently used is the Global Positioning System (GPS) [4], [5]. It calculates the distance between a receiver and multiple transmitters (in this case, satellites), based on the difference in the time-of-flight (TOF) of the received radio signals. For relatively small-sized, indoor mobile robots though, the GPS system has at least two major drawbacks. First, its accuracy (for unauthorized users) is in the range of meters, which is, therefore, in the order of magnitude of 10 to 10^2 as compared to the size of robots. The second issue is the indoor reception problem of the GPS radio frequency.

Another radio-based technique uses the power of the received signal to calculate the distance to the transmitter. Usually, the accuracy of such systems is also in the range o meters ($2 \div 3$ m). In [6], the authors describe a system of nodes based on the Zigbee protocol (IEEE 802.15.4) [7] and use the mathematical model of the radio signal power to determine the distance between two nodes. Building Positioning System [8] estimates the position of a portable device using a principle similar to the GPS system, with 4 fixed transmission elements, but with radio signals at a much lower frequency. The accuracy of such a system is in the range of centimeters ($\approx$5 cm), but the solution is dependent of fixed landmarks.

Another common solution is the use of acoustic waves (at ultrasound frequencies, usually 40 KHz) and of Sonar

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systems. The Cricket Indoor Location System, described in [9] and [10], is an indoor location system based on multiple fixed transmitter modules (at least three), usually attached to the ceiling of the room to cover a large area or even the entire floor. To calculate distances, the Cricket system uses a method which combines radio-frequency and ultrasonic signals, and applies the Time-Difference-of-Arrival (TDOA) technique for the propagation intervals of the two types of signals. The localization of mobile robots with this system has a good accuracy ($1 \div 3$ cm), but at the cost of several pre-installed landmarks in each corresponding room.

Infrared light (IR) signals and sensors can also be used in distance measurements and location monitoring. IR sensors are able to measure the intensity of the reflected light and/or the angle of incidence at reception. Based mostly on geometric calculation techniques, IR systems can estimate the distance towards the signal transmitter [11], [12]. Hagisonic StarGazer [13] is such a location system for mobile robots. It is based on analysis of infrared rays transmitted by the robot and which are reflected by a passive landmark with a unique ID, mounted on the ceiling of the room. At the receiving end, the robot features a CMOS camera, able to determine the angle of incidence of the IR waves. Based on this angle, the position of the robot is calculated using geometric techniques. The system claims a good accuracy ($\approx$2 cm), at a speed of 20 measurements per second. On the other hand, the disadvantages of this system are its high price, reduced range ($2.5 \div 5$ m) and its requirement of a pre-installed landmark.

III. Accurate Indoor Inter-Robot Distance Measurement

Our distance measurement methods have a common set of requirements for the target robotic systems. First, they rely on inter-robot collaborative procedures and, therefore, a total of more than two robots are needed. On the other hand, the techniques are independent of fixed landmarks. Nevertheless, if the system further requires accurate localization of the mobile robots, at least the initial position of one of the robots must be known prior to the start of the system operation.

Each robot must be equipped with a wireless communication interface. The wireless link is used to initiate the key operation phases of the distance measurement procedures and to exchange synchronization and measurement information. Each robot must also be equipped with an active local Sonar transceiver, which is used to calculate the time delays directly related to the distance between the robots. Since our measurement techniques rely on Sonar, they further require the corresponding robots to have direct visibility and to be within the operating range of their Sonar systems.

To obtain correct results, the proposed techniques also require that the pair of robots performing the distance measurement procedure must operate with synchronized time bases and must be spatially aligned with each other. As time synchronization in wireless robotic environments is a distinct topic, it is not covered in this paper. A generic algorithm for robotic spatial alignment is discussed in the following paragraphs.

A. *Algorithm for Robotic Alignment*

We designed a simple and effective technique to ensure the correct alignment of the two robots to perform the distance measurement procedures. Correct alignment means the robots are facing each other exactly along the straight line between their Sonar transducer elements (see Fig. 1).

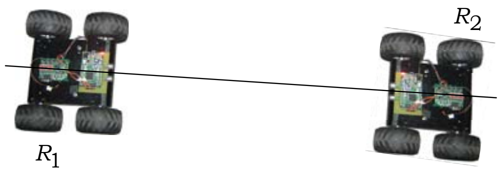

Fig. 1. Correct robot alignment.

The alignment procedure uses the wireless communication interfaces of the robots to enable the two corresponding peers exchange the required commands and messages, and is based on the continuous measurement of the Sonar acoustic intensity. It is initiated and conducted by one of the robots, which acts as the master (R_M), while the other robot, the slave (R_S), executes the commands received from the master through the wireless link. The master will operate in the Sonar receive mode and the slave in Sonar transmit mode.

Algorithm 1. Robotic alignment procedure.

Start Sonar receive mode for R_M and Sonar transmit mode for R_S
Start 360° clockwise rotation for R_M and R_S, at 1° steps
do repeat
  while 1° rotation step **do**
    Average the Sonar signal received from R_S
  end while
  Compare average for current rotation step (Sig_i) with the result of the previous rotation step (Sig_{i-1})
  if $Sig_i \geq Sig_{i-1}$ **do**
    Set the signal increase flag F_{inc} to 1
    if the signal decrease flag F_{dec} already set **do**
      stop
    end if
  else do
    if the signal increase flag F_{inc} already set **do**
      Set the signal decrease flag F_{dec} to 1
    end if
    Change rotation directions of R_M and R_S
  end if
end repeat

As seen in the algorithm sequence above, the alignment procedure is based on the high directivity of ultrasonic waves used by the Sonar. As the two robots rotate, the master calculates the average strength of the ultrasonic signal received from the slave, over each 1° rotation steps. If it senses the increase of this average as compared to the previous rotation step, it will continue the procedure until a decrease will be encountered. Then, the two robots will change the rotation directions to return to the previous position.

A special case is also considered, i.e. when the two robots are already aligned prior to the start of the procedure. In this case, the master senses a decrease of the received signal strength from the start and changes the rotation directions of the two robots, until a maximum will be reached again.

Although simple and effective, this algorithm has its own drawbacks. It is vulnerable to the presence of walls or other large and flat surfaces which can reflect the ultrasound waves. It also implies the rotation of robots, which is in many cases a source of positioning errors. Nevertheless, this procedure is highly cost effective. An improvement we are considering for the near future is to use multiple transducer Sonars (e.g. Sonars with 8 transducers, oriented at 45°), to cover multiple viewing angles for each robot. In this way, the rotation of robots during the alignment procedure could be significantly reduced.

B. Distance Measurement with the MTDOA Method

MTDOA, Modified Time-Difference-of-Arrival, is the first distance measurement method we have developed and tested. It is derived, as the name states, from the TDOA method, but with a set of modifications to overcome some of the problems which occur when using several wireless communication interfaces. This is especially the case of more complicated communication interfaces, with a consistent protocol stack, such as the ZigBee protocol, used in our robot implementations. In such cases, there are important delays employed by the protocol stack at transmission and at reception, which will corrupt the TDOA results. Moreover, the transmission delays are significantly longer than the reception counterparts and have also a much larger standard deviation. As a result, the MTDOA technique focuses only on wireless reception for the two robots involved in the distance measurement process.

To illustrate the operating principles of the MTDOA method, suppose robot R_1 decides to measure its distance to another robot, R_2. First it initiates the alignment procedure, described in the previous paragraphs, as the master, while R_2 becomes the slave. After R_1 and R_2 are correctly aligned with each other, R_1 finds a third robot, R_C, to play the temporary role of coordinator (see Fig. 2). R_C sends a wireless message to both R_1 and R_2, which starts the measurement tasks on the two peers. Upon its reception, R_2 sends an ultrasonic signal burst towards R_1 while, at approximately the same time, R_1 starts counting the time elapsed until the reception of the ultrasonic signal. This delay is directly proportional to the distance between the two robots.

We used the term "at *approximately* the same time", because of the possible variations of the time needed for different robots to receive and process the message over the wireless link. The maximum variation, denoted here with θ_W, can be empirically measured. The distance d between R_1 and R_2 results as

$$d = c_{air}(\Delta t - \theta_W), \quad (1)$$

where c_{air} = 343.4 m/s is the velocity of acoustic waves in air at room temperature and at normal pressure, Δt is the time elapsed from the moment R_1 receives the radio message from the coordinator until the reception of the ultrasonic signal from R_2, and θ_W is the maximum delay employed by the message reception at the wireless interface. For example, the measurements conducted for the XBee wireless modules [14] resulted in θ_W = 0.352 ms.

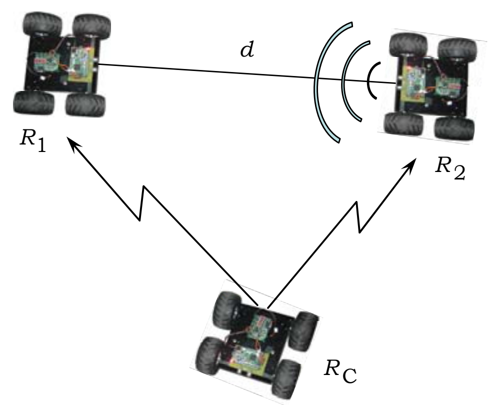

Fig. 2. Hypothetical configuration for the MTDOA procedure.

C. Distance Measurement with the CTOF Method

CTOF, Combined Time-of-Flight, is the second method proposed in this paper. At its principle, it is based on the TOF technique. Although a little more complicated, CTOF has several advantages over the MTDOA method. Thus, the CTOF procedure does not require an additional third robot as coordinator. It is also does not depend on the delays implied by the wireless communication interfaces of the robots.

Fig. 3 depicts the CTOF technique. Robot R_1 initiates the procedure by sending a "START" wireless message (abbreviated "WMes" in Fig. 3) to its peer, R_2. The latter acknowledges the start of its part of the procedure with the "SONAR REQ" message, while simultaneously launching its own Sonar Receive Task. As a response to the second message, R_1 starts the Sonar Transmit Task and activates the timer which will count the elapsed time of the entire procedure, Δt. Upon receiving the ultrasound signal, R_2 activates a delay timer with a predefined value, δ_U, which is empirically determined to cover the total duration of the ultrasonic transmission from R_1. After the δ_U delay, R_2 sends a "SONAR START" message to R_1 and starts a second timer, with a value δ_W empirically established to cover the maximum communication delay over the wireless link and the corresponding interfaces. When R_1 receives the "SONAR START" message, it launches its Sonar Receive Task. After the δ_W timer expires, R_2 starts its Sonar Transmit Task and sends the corresponding ultrasonic signal towards R_1. Finally, when R_1 receives the signal, it stops the timer to produce the Δt period.

As a result, the Δt period contains the two predefined delays, δ_U and δ_W, and twice the propagation delay of the ultrasound signal, from R_1 to R_2 and backwards. Based on this ultrasound propagation delay, the distance between the two robots can be derived:

$$d = \frac{c_{air}(\Delta t - \delta_U - \delta_W)}{2}, \quad (2)$$

where c_{air} has the same meaning as in (1).

When considering the threshold-based detection method of the received ultrasonic bursts and the fact that the ultrasonic measurements are not perfectly linear, an additional calibration offset is needed for the distance formula in (2):

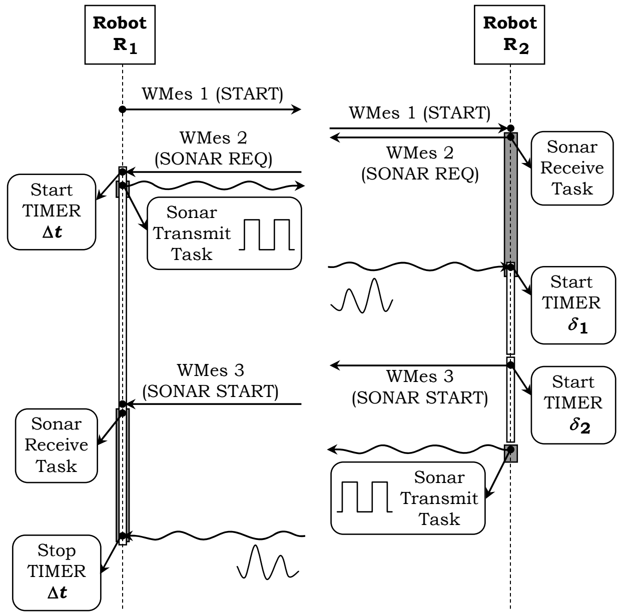

Fig. 3. Distance measurement with the CTOF method.

$$d = \frac{c_{\text{air}}\left(\Delta t - \delta_{\text{U}} - \delta_{\text{W}} - \theta_{\text{UC}}\right)}{2}, \qquad (3)$$

where θ_{UC} is the ultrasonic signal calibration offset and has an experimentally determined value (in our case studies, $\theta_{UC} = 290$ μs).

IV. Case Study with the CORE-TX Platform

The robot alignment and distance measurement techniques previously described have been implemented and tested on the CORE-TX system [15], a project of the Digital Signal Processing Laboratories (DSPLabs), "Politehnica" University of Timisoara. CORE-TX (COllaborative Robotic Environment – the Timisoara eXperiment) is developed as a complex platform for the study of collaborative robotic environments and intelligent wireless sensor networks. It is composed at the architecture level of a set of autonomous microsystems with embedded intelligence, called WITs (Wireless Intelligent Terminals), a collaborative communication environment and a central entity with the role of configuration, control and supervision of the whole system.

The WIT elements may have perception functions (intelligent sensors), operating functions (autonomous mini-robots), or combined. A modular architecture has been used for the WIT design, consisting of a motherboard (the Base Processing Module) and a set of specialized daughter boards such as the Power Management Module, the Perception Module and the Communication Module (see Fig. 4). The additional Support and Operation Module transforms the WIT, from a static intelligent sensor, into an autonomous mini-robot.

Currently, the WIT communication boards are based on the XBee wireless module. For our case study, several mobile WITs have been implemented, to compose a collaborative robotic environment. The robotic perception modules are based on identical Sonar systems, with a pair of front-mounted ultrasound transducers, one for transmission and the other for reception.

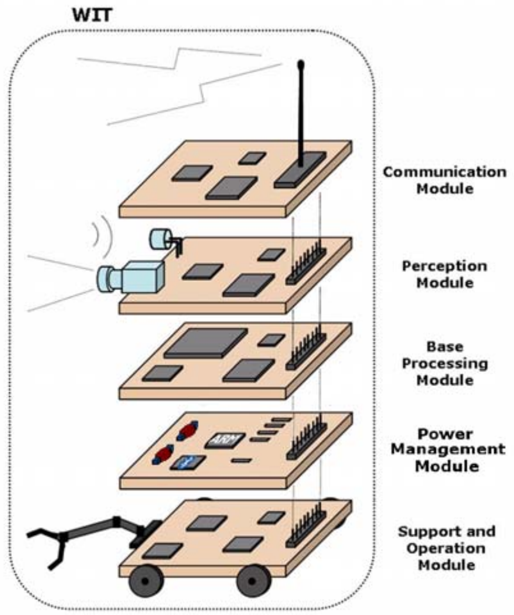

Fig. 4. Modular architecture of the WIT.

A. Ultrasound Signal Transmission

A periodic ultrasound signal is constructed on the robot perception boards to be transmitted through the corresponding Sonar transducer. The total duration of this signal is $T_{BURST} = 200$ μs and consists of 8 signal pulses of 25 μs period, each (40 KHz). The voltage level of the generated signal is 3.3 V (Fig. 5). A MAX232CPE circuit has been used to raise the signal level at the input of the transducer to 13.2 Vpp, as seen in Fig. 6.

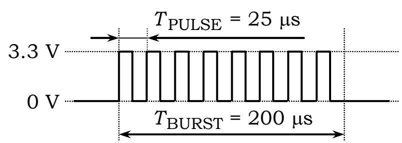

Fig. 5. Periodic pulse signal to be transmitted by the Sonar transducer.

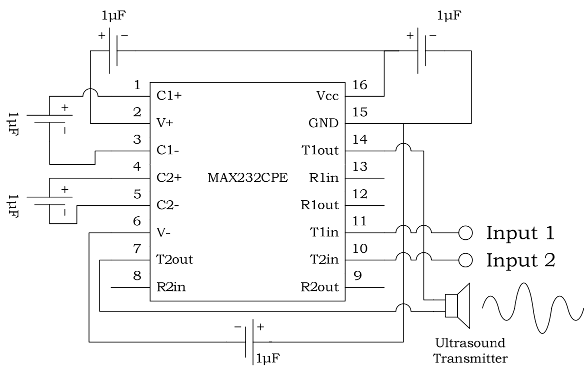

Fig. 6. Schematics of the ultrasound signal transmission logic.

B. Ultrasound Signal Reception

A four-stage, LM6134-based amplifier logic has been implemented for the reception of the ultrasound signal. The gain factor of all the amplifiers is 11 and each output is associated to a distinct input channel of the LPC2294 microcontroller ADC circuit [16], including the output signal of the reception transducer. Thus, depending on the strength of the ultrasound signal coming from the transducer, the reception logic is able to select the channel which best amplifies the signal, without saturating it.

V. Experimental Results

An extensive set of experiments have been conducted in the DSPLabs using the robotic system developed as a case study and presented in the previous section. The experimental setup consisted in three mobile robots, out of which two of them were randomly chosen to perform the distance calculation for each experiment. The robots have been placed at a distance ranging from 100 mm to 3000 mm and, for each 10 mm in this range, a set of over 50 pairs of measurements have been performed, with both the MTDOA and the CTOF methods. Before each measurement, the robots have been positioned in random directions with respect to each other, to verify the robot alignment procedure discussed in Section III.

Since the proposed techniques are based on Sonar and are specifically designed for indoor measurements, the experiments, evaluations and results consider normal room values for the air parameters (such as temperature, humidity, pressure, etc.). These parameters could otherwise influence the speed of ultrasonic waves used in equations (1) – (3). Such influences are a distinct topic and are not covered in this paper.

Fig. 7 exemplifies the reception of the ultrasound signal over the second channel of the Sonar receiver module. The signal is fairly clear from noise and, therefore, the threshold-based technique has been applied to determine the signal arrival delay at reception.

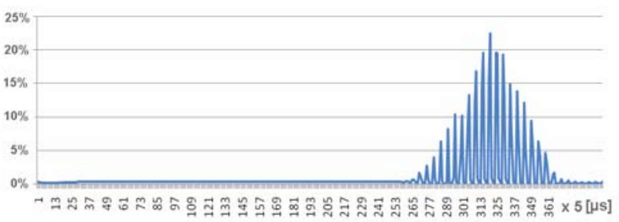

Fig. 7. Received ultrasound signal.

The difference between the packet reception times for the XBee modules of the two robots involved in the distance measurement procedures has been measured with a logic analyzer. This difference varies randomly each time, mostly due to the operation of the XBee modules and their corresponding protocol stack. We obtained a maximum value of 86 μs, which corresponds to a distance measurement error of 30 mm.

Fig. 8 and Table I present the experimental results obtained for the MTDOA distance measurement method, whereas Fig. 9 and Table II represent the results for the CTOF method. A statistical analysis of the data has also been performed. The maximum absolute and relative errors for both techniques are depicted, in a comparative manner, in Fig. 10. For the MTDOA method, the maximum absolute error has been obtained when the two robots were positioned at a distance of 100 cm from each other and has a value of 7.3 cm. In the case of the CTOF method, the maximum absolute error is 4.8 cm, when the robots are 300 cm apart.

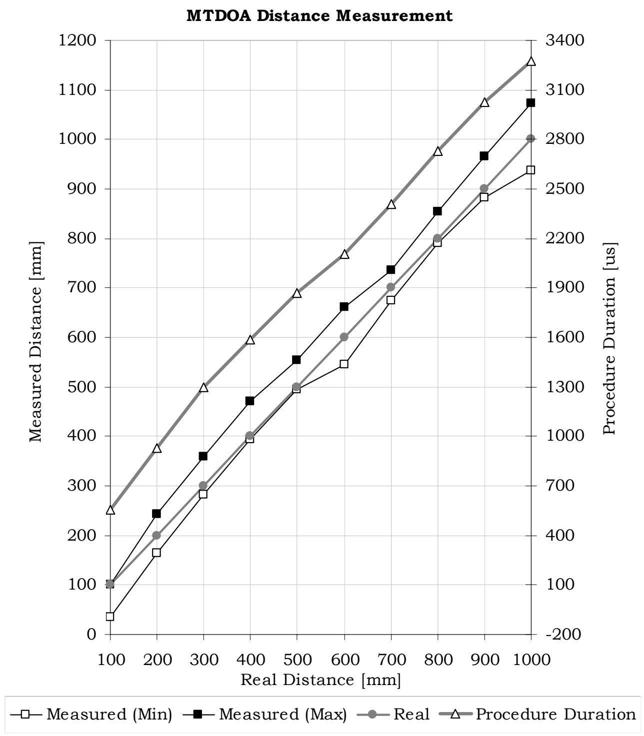

Fig. 8. Combined chart with measured distance and procedure duration vs. real distance, for the MTDOA method.

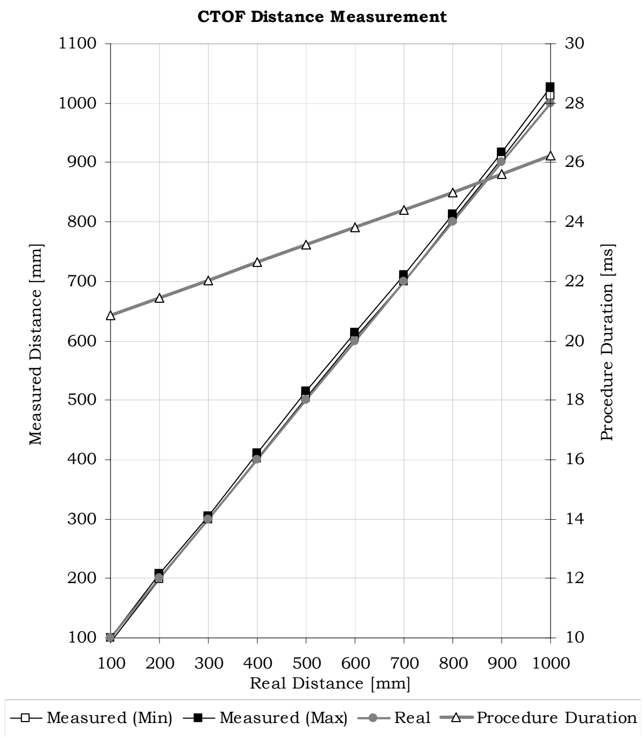

Fig. 9. Combined chart with measured distance and procedure duration vs. real distance, for the CTOF method.

The measurement results and error analysis show that, although the MTDOA method generates relatively high absolute errors, the average follows closely the real distance and has a linear evolution, after the corresponding calibration adjustments. Moreover, the maximum relative errors tend to decrease with the measured distance. This is another indication of the predominant contribution of the XBee operating delays which influence the results. An improvement to this technique could be to take more than a single measurement for a particular position of the robots and, if the results differ significantly, to repeat the process.

On the other hand, the CTOF method behaves much better. After the necessary calibrations, its measurement characteristics are linear and follow very closely the real distance. The corresponding maximum errors have also a natural evolution, as seen in Fig. 10. This is a direct result of the independence of this technique from the random delays introduced by the XBee modules.

TABLE I. DISTANCE MEASUREMENT RESULTS FOR THE MTDOA METHOD.

Real Distance [mm]	Measured Distance [mm]			Procedure Duration [μs]
	Min	Average	Max	
100	36	71	101	559
200	164	198	243	929
300	281	324	358	1296
400	394	423	470	1584
500	494	522	554	1872
600	546	602	661	2105
700	674	705	736	2405
800	789	817	855	2731
900	882	919	966	3028
1000	937	1003	1073	3273
2000	1931	1983	2046	6127
3000	2948	2978	3023	9024

TABLE II. DISTANCE MEASUREMENT RESULTS FOR THE CTOF METHOD.

Real Distance [mm]	Measured Distance [mm]			Procedure Duration [μs]
	Min	Average	Max	
100	92	96	99	20849
200	199	201	207	21461
300	298	300	303	22037
400	401	404	410	22643
500	504	508	515	23249
600	604	607	612	23825
700	700	706	710	24402
800	803	807	813	24990
900	906	911	916	25596
1000	1013	1019	1026	26225
2000	2024	2033	2043	32130
3000	3018	3031	3047	37943

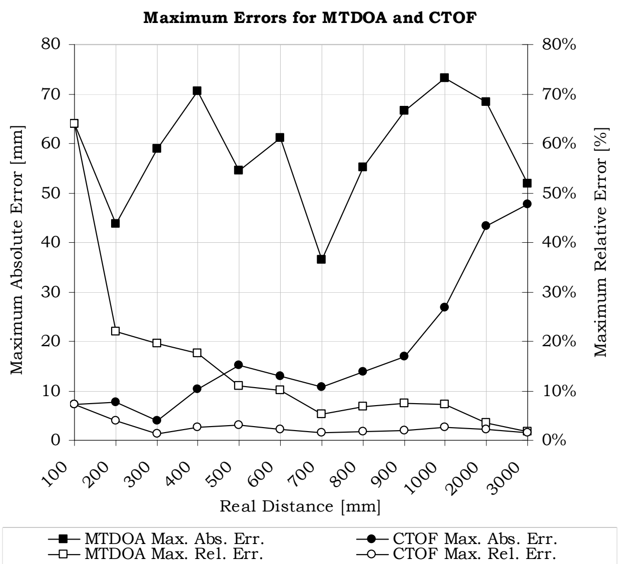

Fig. 10. Comparison of the maximum errors (absolute and relative) for the MTDOA and CTOF techniques.

VI. CONCLUSION

In this paper we propose and discuss two distance measurement techniques for collaborative robotic indoor environments. We have shown how the MTDOA and the CTOF methods meet the requirements specified by indoor, low-cost, energy-efficient, inter-robot distance measurement applications, without the need for pre-installed, fixed landmarks.

The experimental results indicate that the CTOF method, with its accuracy of 4.8 cm for distances of 3 m and its linear behavior, outperforms the MTDOA and other similar techniques which are applied to state of the art location monitoring systems. The only exception is the procedure duration, which is roughly four times longer in the case of CTOF as compared to the MTDOA method. Nevertheless, at its maximum duration of 38 ms, the procedure allows a theoretical rate of 26 measurements per second.

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