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Distance Measurement for Indoor Robotic Collectives

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1. Introduction

Location monitoring is a common problem for many mobile robotic applications covering various domains, such as industrial automation, manipulation in difficult areas, rescue operations, environment exploration and monitoring, smart environments and buildings, robotic home appliances, space exploration and probing.

A key aspect of localization is inter-robot distance measurement. In this chapter we consider the problem of autonomous, collaborative distance measurement in mobile robotic systems, under the following set of design and functional constraints:

a. indoor operation,
b. independence of fixed landmarks,
c. robustness and accuracy,
d. energy efficiency,
e. low cost and complexity.

This work significantly extends and updates the results previously published in (Micea et al., 2010). We present and discuss some of the most relevant state of the art techniques for robot distance estimation. Next, we introduce a framework for collaborative inter-robot distance measurement along with a procedure for accurate robotic alignment. The proposed alignment algorithm is based on evaluating and comparing the strength of ultrasonic signals at different angles, processing (filtering) the measured data and ensuring a good synchronization during the process. Further on, we present the CTOF (Combined Time-of-Flight) method for distance measurement, which brings significant improvements to the classical TOF technique, and we show how this new technique meets the above specified design constraints. Some of the most interesting test and evaluation results are presented and discussed. The experimental data show how the distance estimation accuracy can be increased by applying the Kalman filter algorithm on repetitive measurements. The final remarks and the reference list conclude this chapter.

2. Current techniques for robot distance estimation

The problem of inter-robot distance measurement and location monitoring is considered of key importance in the field and, consequently, a large number and variety of methods have been proposed and studied in the literature. For instance, the GPS system (Ohno et al., 2004; Reina et al., 2007) and landmark-based solutions such as the Cricket Indoor Location System (Cricket Project, 2005; Priyantha, 2005) are well established in the field. On the other hand, they do not comply with the constraints specified in the previous section (i.e. independence of fixed landmarks). In this section we discuss some of the most prominent techniques which can be used for indoor robotic collectives.

Time-Difference-of-Arrival (TDOA) measures the distance between two points by using two different types of signals (usually radio and acoustic) which cover the route connecting the two points with different speeds. To illustrate this technique, consider two points, A and B, located at distance *d* from each other. At a time instance, the transmitter from A sends simultaneously the signals S_1 and S_2, which cover the distance *d* at the speeds v_{S1} and v_{S2}, respectively. If, for example, $v_{S2} < v_{S1}$, then signal S_2 arrives at the receiver B after S_1, with a delay which depends on the distance *d*. This delay is measured at the destination point B and the value of *d* is consequently derived. Cricket Indoor Location System uses TDOA to measure the distance to the reference points. The system consists of several landmark transmission devices, depending on the size of the desired coverage area (at least three modules) and one or more mobile devices that play the role of receptors. In most cases, the transmission devices are attached to the upper part of the room so as to cover a large portion or the entire room. The reception devices are attached to robots, located on the floor. As shown in (Priyantha, 2005), the system relies on two types of signals to calculate distances: a RF (radio) signal and an ultrasonic signal. The radio signal is 10^6 times faster than the ultrasonic signal, and the distance is calculated by applying the principle of TDOA to the difference of the two propagation periods. The localization of mobile robots through this system is made at an accuracy of 1 ÷ 3 cm. Similarly, the system presented in (Fayli & Kleeman, 2004) solves the localization problem based on four transmitters as fixed reference points and a wireless receiver.

Another well known technology used in robotics to calculate distance is based on infrared (IR) sensors. There are several types of IR sensors, each varying according to their parameters (e.g. maximum range and accuracy) and price. In comparison to ultrasonic devices, the IR sensors are cheaper and use light, which is much faster than the acoustic signal. They have nonlinear characteristics which depend on the surface reflectance of the objects. Based on measuring the intensity of light reflected by a target, the IR sensors can calculate the distance to it. This technique is presented and discussed in several works, including (Novotny & Ferrier, 1999; Ha & Kim, 2004; Mohammad, 2009). Hagisonic StarGazer (Hagisonic, 2009) is a location system for mobile robots, based on the analysis of infrared rays which are reflected by a passive landmark with a unique ID. The system works as follows:

1. The IR transmitter is located on the robot. It transmits infrared beams to the fixed landmark attached to the ceiling of the room.
2. The infrared rays are reflected from the landmark and reach the Stargazer, mounted on the robot.
3. Stargazer contains a CMOS camera able to estimate the angle of incidence of the reflected IR waves and the distance between the robot and the landmark.
4. Based on the angle of incidence and on the distance to the landmark, the position of the robot in the room can then be obtained through geometric techniques.

The advantage of such a system is its accuracy, which, according to (Hagisonic, 2009), can reach approximately 2 cm. The system can carry out 20 measurements per second. Its disadvantage is the high price and the reduced coverage area, which ranges from 2.5 to 5 m.

A set of radio-based methods use the power of the received signal to estimate the distance to the source. The mathematical model of the emitted signal power is given in (Fuicu et al., 2009) as:

$$\frac{P_t}{P_r} = \frac{4\pi d}{\lambda^2} = \frac{(4\pi f d)^2}{c^2} \quad (1)$$

where P_t and P_r are the signal power at the emitter and at the receiver, respectively, d is the propagation distance, λ and f are the carrier wavelength and frequency, respectively, and c, the speed of light. The accuracy of such systems though, is around 2-3 m. Another similar technique, based on modeling the signal power for the ZigBee (IEEE 802.15.4) protocol (ZigBee Standards Organization, 2007), is presented in (Grossmann, 2007).

An indoor GPS system, presented in (Kim et al., 2006), consists of two receivers as fixed reference points and a transmitter which uses both ultrasonic and RF signals. The receivers estimate the distance to the transmitter based on the delay between the received RF signal and the ultrasound waves. The two resulting distances are then used to calculate the location of the transmitter, through geometrical formulas. A Linear Kalman Filter is also used to minimize the errors and noise occurring in the measurements of the ultrasound signal.

GPS systems usually calculate the distance between a receiver and multiple transmitters based on the difference in the time-of-flight of the received signals (the TOF method). Through the TOF method, more precise results can be obtained. However, TOF is influenced by the synchronization accuracy of system, environment temperature or other factors which could yield calculation errors. As a result, filtering of measurement values is frequently used. A common solution is the Linear Kalman Filter, as presented in (Kim et al., 2006; Ko et al., 2008; Welch & Bishop, 2006). Other approaches use Bayesian filters (Fox et al., 2003), which estimate the state of a probabilistic dynamic system from observations drowned in noise. Using statistic techniques, they operate in a deterministic manner and are suitable for systems with multiple sensors with different characteristics.

The Building Positioning System (Reynolds, 1999), determines the position of a mobile device by receiving radio signals from fixed devices. These are designed to transmit radio signals in a manner which is similar to the operation of the Cricket or GPS modules. Compared with the GPS, this system uses a much lower frequency, making the radio waves propagate with a relatively low attenuation. The system requires only 4 fixed transmission antennas attached to four different corners of the building. The accuracy of such a system is about 5 cm.

Image processing methods are also widely used, many of them using passive cameras. A microcontroller drives a motor to focus a target image located at a certain distance from the sensor. Based on several parameters, like motor position or lens properties, the distance to the target object can be determined. Some systems are based, for instance, on visual information from a 360 degree camera (Tamimi et al., 2006). Such systems must be trained before being used, by capturing representative images from the environment and associating them with the corresponding locations.

3. Example framework for collaborative inter-robot distance measurement

The proposed distance measurement method and inter-robot alignment algorithm have a common set of requirements for the target robotic system. Such a framework, which has been used to implement and test the proposed techniques, is the CORE-TX platform (Cioarga et al., 2006).

CORE-TX (COllaborative Robotic Environment – the Timisoara eXperiment) is designed to provide theoretical and applicative support for the study of intelligent sensor networks and robotic collectives. Its architecture is structured on three main layers (see Fig. 1):

1. Perception and Operation Layer, consisting mainly of autonomous microsystems with embedded intelligence, called WITs (Wireless Intelligent Terminals),

2. Collaborative Communication Layer, based on ad-hoc wireless data communication techniques (currently, the basic support is provided by the ZigBee protocol), and
3. Background Control and Supervision Layer, with a central node called BRAIN (Background Robotic Activity Induction Node).

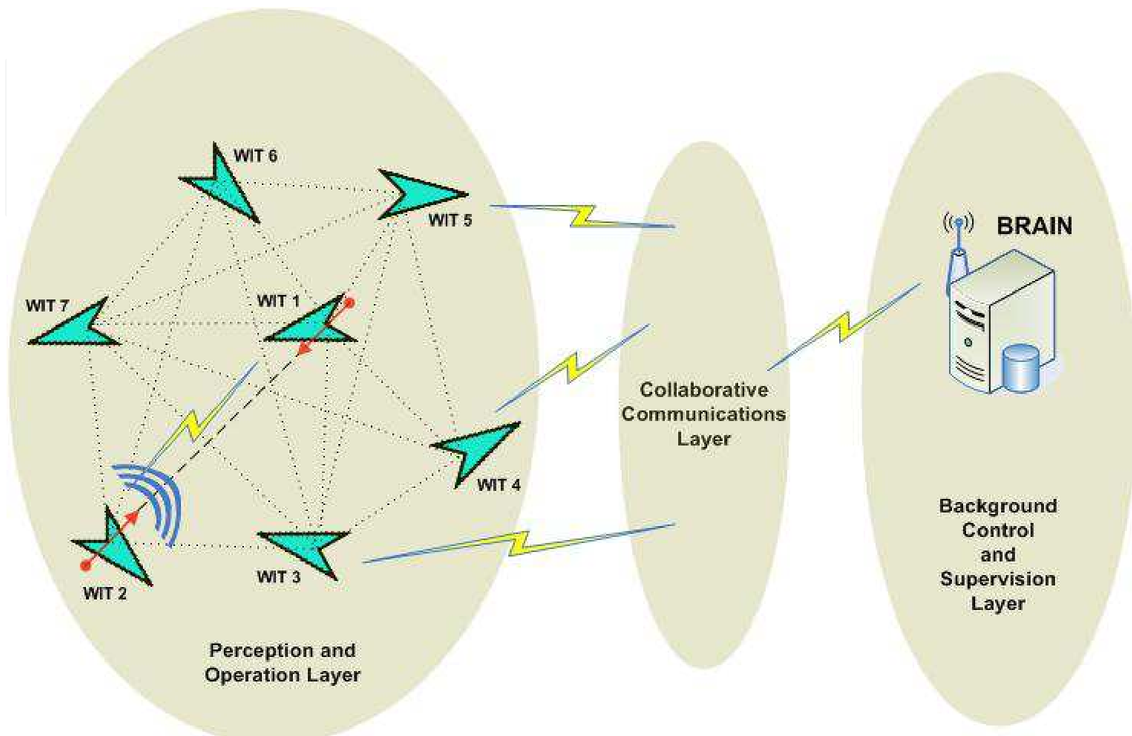

Fig. 1. General architecture of the CORE-TX system

3.1 General architecture of the robotic elements

The WIT elements may have perception functions (intelligent sensors), operating functions (autonomous mini-robots), or combined. They have been designed using a modular approach (Fig. 2) which specifies a motherboard (the Base Processing Module), interconnected through a system bus to a set of specialized daughter boards. Such daughter boards are the Power Management Module, the Perception Module and the Communication Module. The additional Support and Operation Module transforms the WIT, from a static intelligent sensor, into an autonomous mini-robot.
Currently, the WIT communication board uses the XBee wireless module (Digi International, 2009), which is based on the Zigbee protocol. This module provides a unique 64-bit ID. Other features are: size of 2 cm x 3 cm, operating range of up to 30 m indoor and up to 90 m outdoor, with a maximum consumption of 50 mA at a voltage of 3.3 V. Communication uses the 2.4 GHz radio frequency band with 16 channels.

3.2 Design of the perception module

The schematic design of the Perception Module is shown in Fig. 3. The main processor is the ARM7-based LPC2294 (NXP Semiconductors, 2008) which runs the Hard Real-Time Operating Kernel, HARETICK (Micea et al., 2006), for predictable operation. Another important part of the module is the coprocessor ATxmega128A1 (Atmel Corporation, 2010), used for fast, periodic data acquisition and processing operations. It was also chosen for its high ADC performance and multiple resources, such as 16 ADC channels, 4 DMA channels, 8 timers, 24 PWM channels, 4 SPI interfaces and a large set of I/O ports.

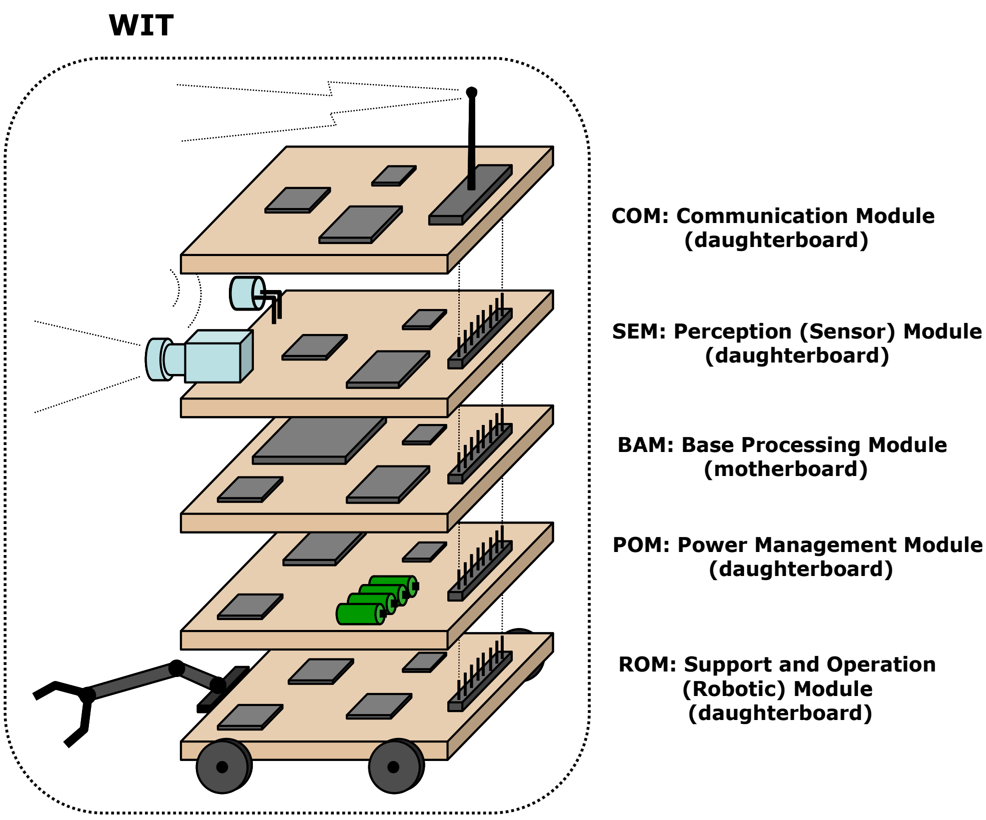

Fig. 2. Diagram of the Wireless Intelligent Terminal

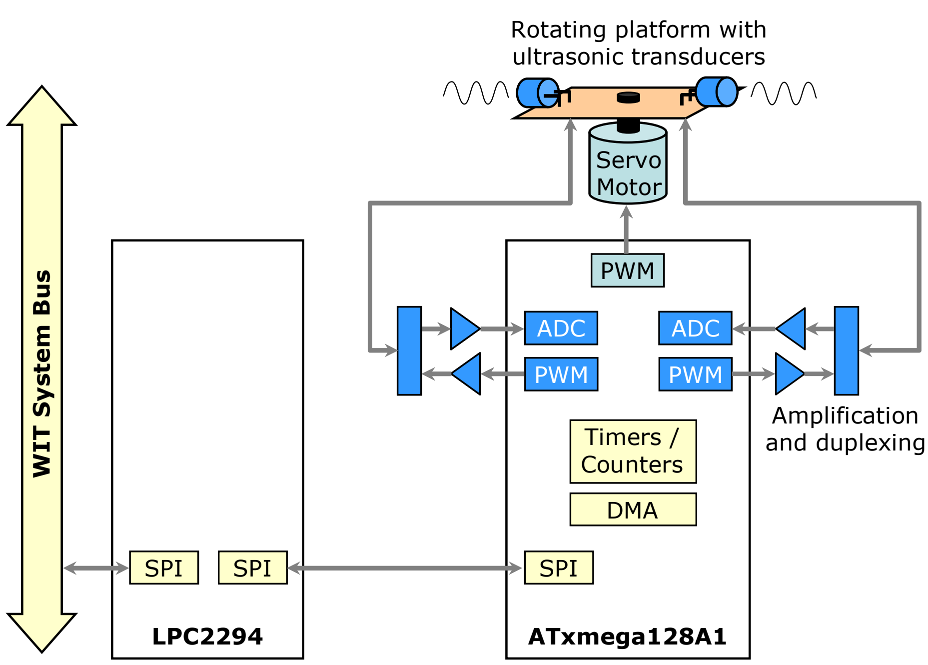

Fig. 3. Schematic of the WIT Perception Module

Two similar transducers are used both for transmitting and for receiving ultrasonic signals. The BPU-1640IOAH12 device (Bestar Electronics, 2006) has been selected, due to its convenient features, which include low cost, bidirectional operation, nominal frequency of 40 kHz, and maximum input voltage of 120 Vpp. Signal duplexing at the transducer level (bidirectional operation) has been implemented using SI4808DY MOSFET circuits.
To perform a fast alignment process, the two ultrasonic transducers are mounted back to back at 180 degrees on a rotating platform, which is driven by a servo motor. The motor is a TowerPro SG-50 (Tower Pro, 2008) with the following specifications: weight 5 g, dimensions 21.5 × 11. 7 × 25.1 mm, speed 0.1 s/60 degrees (at 4.8 V), supply voltage 4 ÷ 6 V. The servo motor is driven by a PWM signal with a period of 20 ms and a variable duty cycle. Rotation is between 0 (minimum pulse duration) and 180 degrees (maximum pulse duration).
Choosing the design based on a turret support for the ultrasonic transducers has several advantages when compared to other designs. On one hand, avoiding the rotation of the entire robots during the alignment process eliminates the inherent positioning errors, while also lowers the power consumption of the system. Other advantages of this solution are the increase of the alignment accuracy at a higher process speed.

4. Inter-robot alignment algorithm

To obtain correct results, the proposed techniques require that the pair of robots performing the distance measurement procedure must successfully complete the alignment algorithm. Correct alignment means the sensing devices (i.e. the ultrasonic transducers) of the robots are facing each other, as close as possible to the straight line between them (see Fig. 4). This procedure also provides key angle values of each robot position and orientation related to the local reference system (Fig. 5):

- a_{12} is the angle between the *orientation axis (Ox_1)* of the first robot (W_1) and the direct line between the two robots.
- φ_1 is the angle defined by the Ox_1 axis and the ultrasonic sensor axis of W_1.
- a_{21} is the angle between the *orientation axis* (Ox_2) of the second robot (W_2) and the direct line between W_1 and W_2.
- φ_2 is the angle defined by the Ox_2 axis and the ultrasonic sensor axis of W_2.

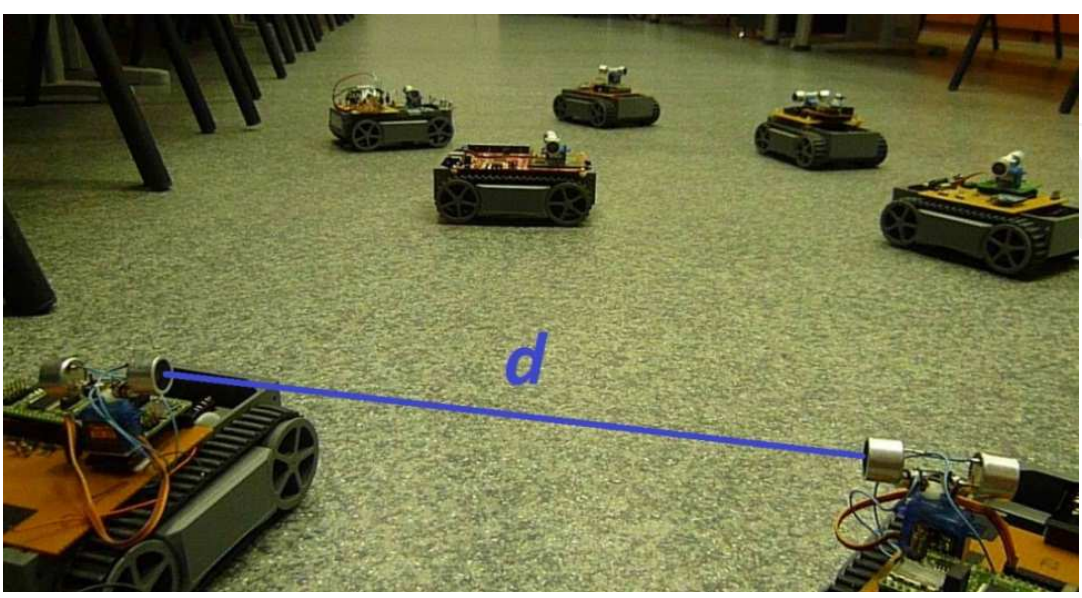

Fig. 4. Inter-robot alignment process

Thus, the ideal alignment situation is when $a_{12} = \varphi_1$ and $a_{21} = \varphi_2$. In this case, the alignment error is 0.

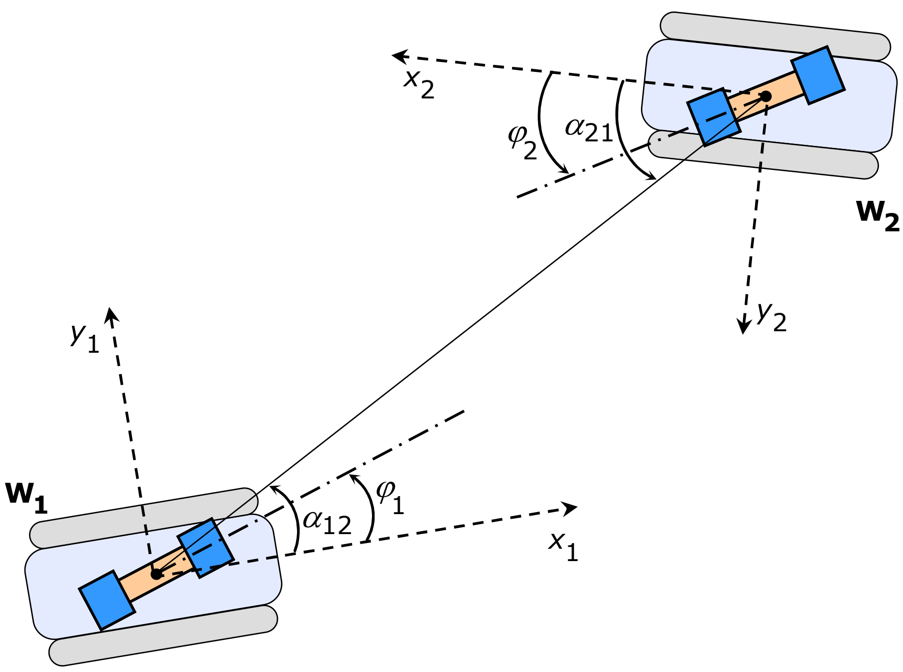

Fig. 5. Key angles on the alignment process

4.1 Description of the algorithm

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 (W_M), while the other robot, the slave (W_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.

The procedure is based on the high directivity of ultrasonic waves used by the Sonar. As the two robot turrets rotate, the master calculates the average strength of the ultrasonic signal received from the slave, at each rotation step of 1 degree. If W_M senses this average signal strength has increased from the previous rotation step, it continues the procedure until a decrease is encountered. Then, the two robots will change the rotation directions of their turrets to return to the previously detected maximum.

Fig. 6 shows all steps of the alignment algorithm. The process starts with the reading of the ADC results. The two decision blocks labeled "done" refer to extracting a predetermined number of samples, respectively, re-reading the values stored in memory. Next, the measured values are optimized by finding the peak amplitude of each period, applying a Kalman filter and comparing the results to each other to determine a global maximum. This global maximum is further used as the amplitude of the signal in the next steps.

The block labeled "pre_align==0?" determines whether it is the last alignment phase of the process. If not, the algorithm determines the trend of the signal: if two consecutive increases are detected, "flag_inc" is set and if there has been a previous decrease, the current stage of the algorithm is finished. On the other hand, if there are two consecutive decreases, the

direction of rotation changes and, if "flag_inc" is set, "flag_dec" also will be set. This phase also determines and updates the highest value of the signal reached so far.
In the last phase of the alignment, the algorithm tries to trace back the position with the highest measured values. Thus, if it detects an increase of the measured signal and the current value is larger than or equal to the stored peak, the process ends and the transducers are considered aligned. If, instead, a decrease is detected, the rotation direction is changed. In all cases, if the process doesn't end, the flow of the algorithm goes back to ADC readings.

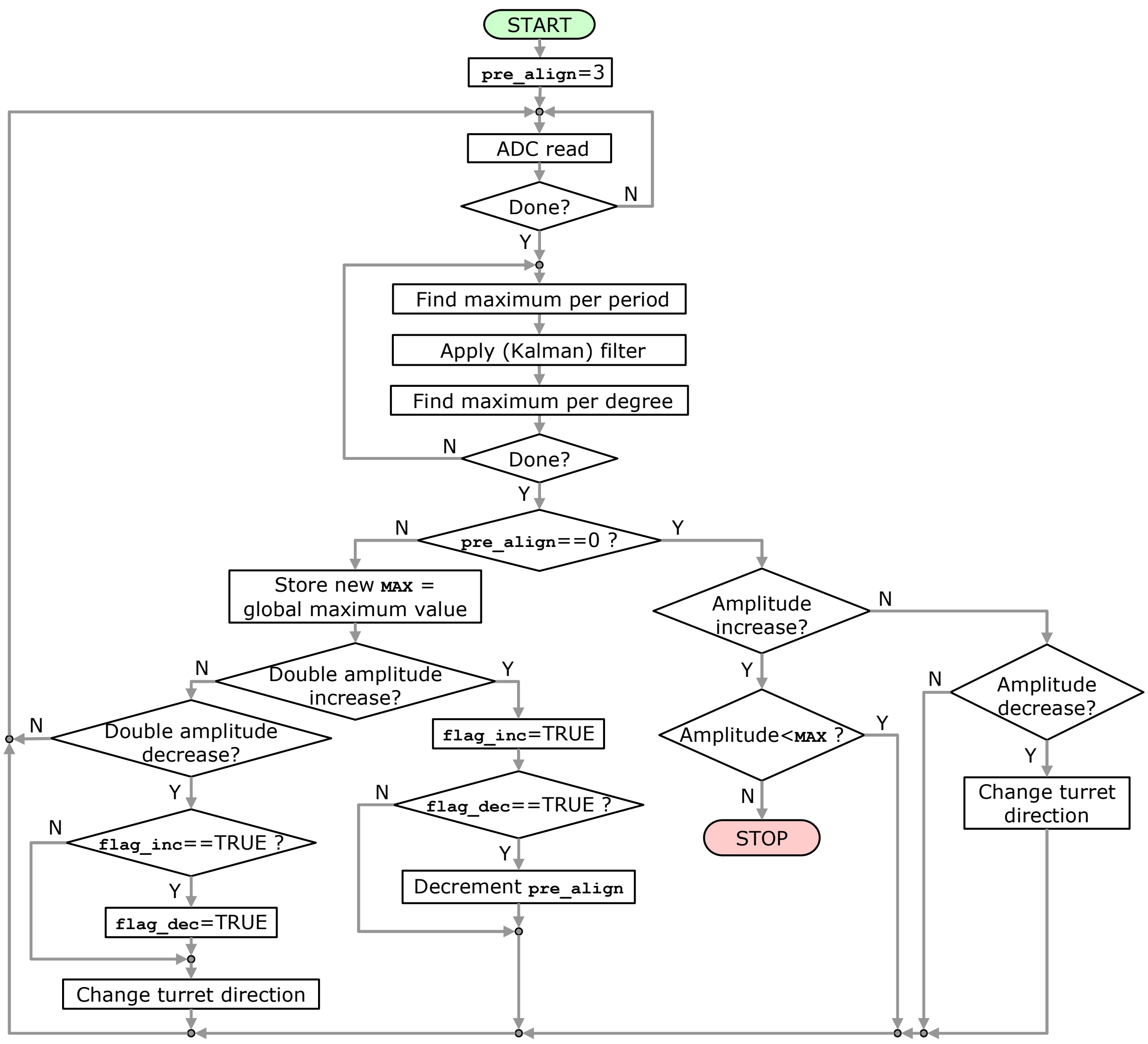

Fig. 6. Robotic alignment algorithm

4.2 Performance evaluation of the alignment algorithm

To evaluate the robotic alignment procedure, a custom simulation application has been developed using the WPF (Windows Presentation Foundation). Two cases have been considered:

1. the ultrasonic transducers are fixed on the robot case and thus the robots rotate themselves (using the wheels) during the alignment process, and

2. the current design in which the robots are equipped with turrets, rotated at 180 degrees by a servo motor.

The data collected was used to improve the alignment algorithm.

To simulate the ultrasonic signal transmission we considered an idealized representation – an isosceles triangle which represents the longitudinal cross-section of the propagation cone. This triangle will represent the "active space" of the robot, and it has an opening of 60 degrees. In this case, the power of the signal (its amplitude) varies with the distance from the bisector of the considered angle. In other words, a perfect alignment takes place when the bisectors of the receiver and transmitter concur (Fig. 7).

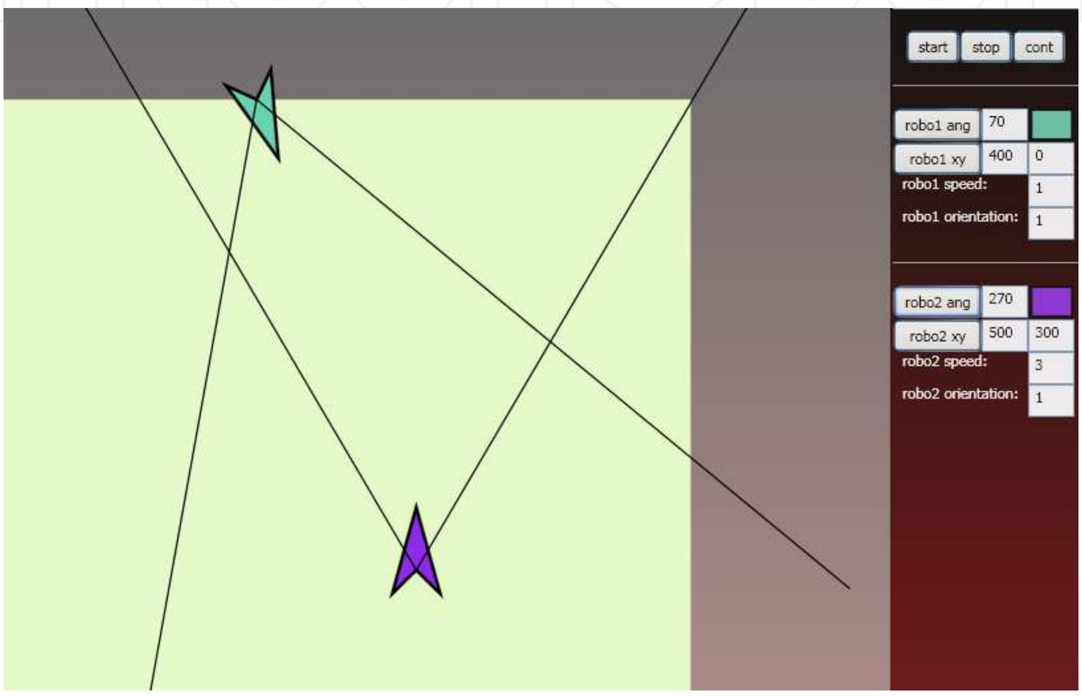

Fig. 7. Robotic alignment simulation tool

Because the distance between the robots is constant throughout the alignment process, its importance in the real case lies in the fact that the receiver may not "read" anything from the transmitter if it is too far away. Also, when further apart, the visibility angle broadens and more precise alignments may occur. In the application, we consider the distance a constant parameter and simulate the most usual scenarios, i.e. where the robots are not too far apart for the angle to broaden.

To be able to determine the position of the robots (of the sensors) relative to each other, we have to calculate the signal strength from both directions and then multiply the results. For the correction of the final alignment, the maximum value of the signal is determined. With the simulator, this maximum value is calculated from the initial conditions. In the real case, the best value must be searched for the signal currently measured, because the distance between robots is unknown.

Fig. 8 and Fig. 9 show the elapsed time for the alignment, versus the initial angles of the robots, at various ratios of the rotation speed (calculated as $[rad/(s \cdot 10^3)]$). The thick lines mark the best two series, which minimize the alignment duration, at a corresponding rotation speed ratio.

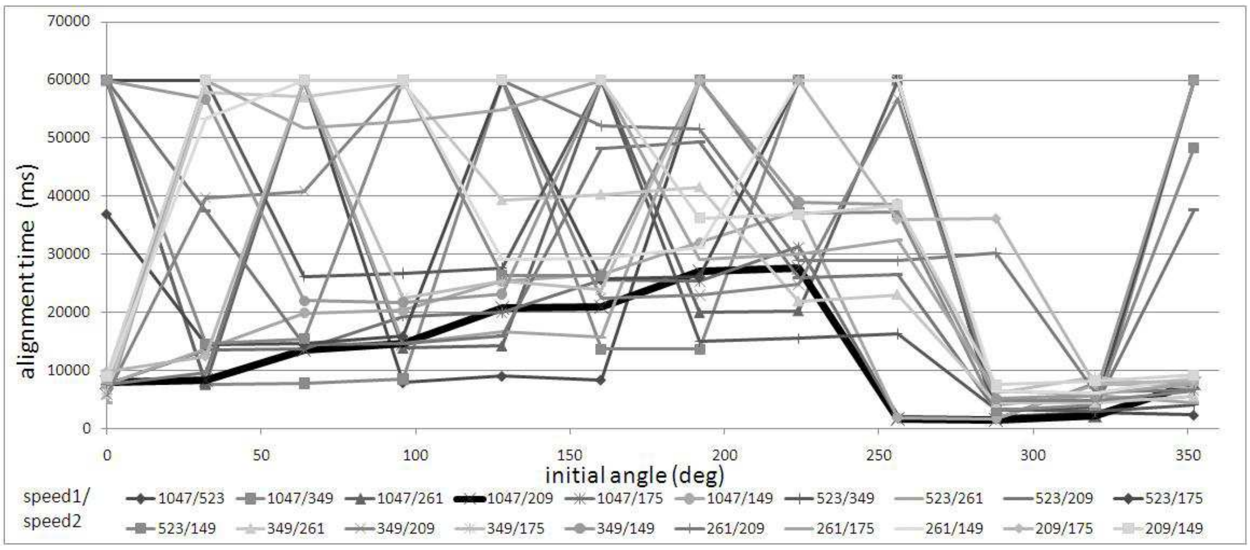

Fig. 8. Inter-robot alignment in the case of the fixed transducers (rotating robots)

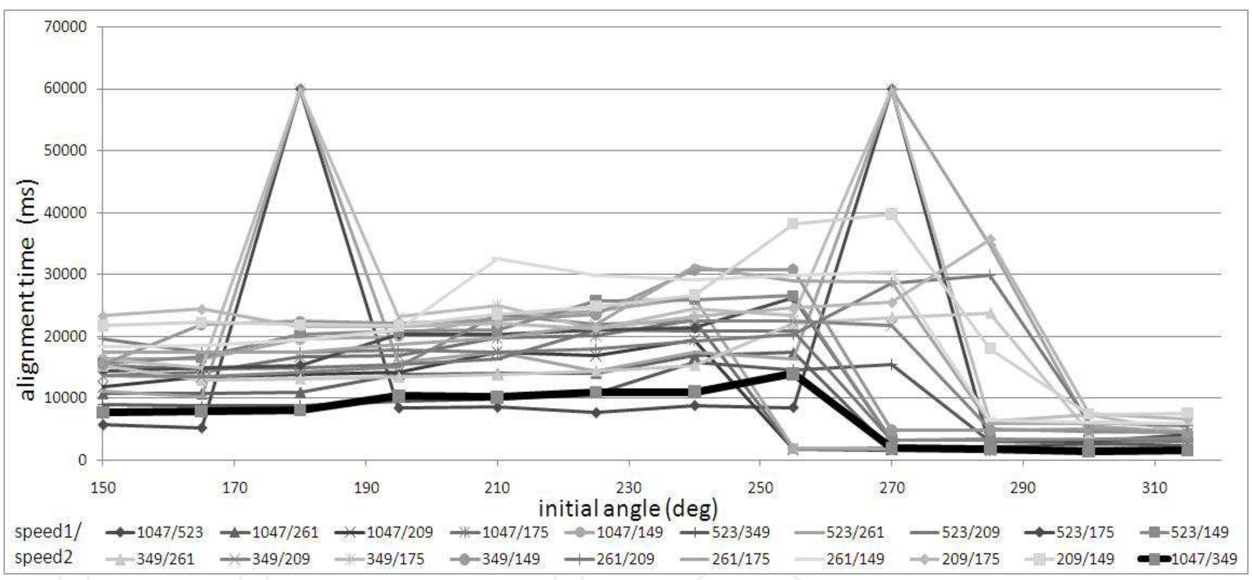

Fig. 9. Inter-robot alignment in the case of the transducers mounted on the turret

For the design without turrets, most of the rotation speed ratios have cases in which the alignment time exceeds the limit imposed (60 s). They are shown on the graph as being equal to the limit. For the turret case, the sensors have to scan only half of the circle and, consequently, they find each other more quickly.

In many cases of small rotation ratios, the sensors cannot find each other, because they are "following" each other closely behind. On the other hand, for increased values of the rotation ratios, the entire process is becoming slow. Considering these facts, the simulations found an optimal rotation ratio of 1047/209 (i.e. 5/1) for the case in Fig. 8 and 1047/349 (i.e. 3/1) for the rotating turret (Fig. 9). Taking also into consideration the alignment time, its maximum value is about 27 s in the first case and 14 s for the second. These results prove that by using the turret design, the alignment time can be almost reduced to half.

5. Distance measurement with the CTOF method

CTOF, Combined Time-of-Flight, is based on the TOF technique and involves two robots. Although a little more complicated, CTOF has several advantages over the MTDOA method, proposed in (Micea et al., 2010). Thus, the CTOF procedure does not require an additional robot (the third one) to coordinate the distance calculation. It also does not depend on the delays implied by the wireless communication interfaces of the robots.

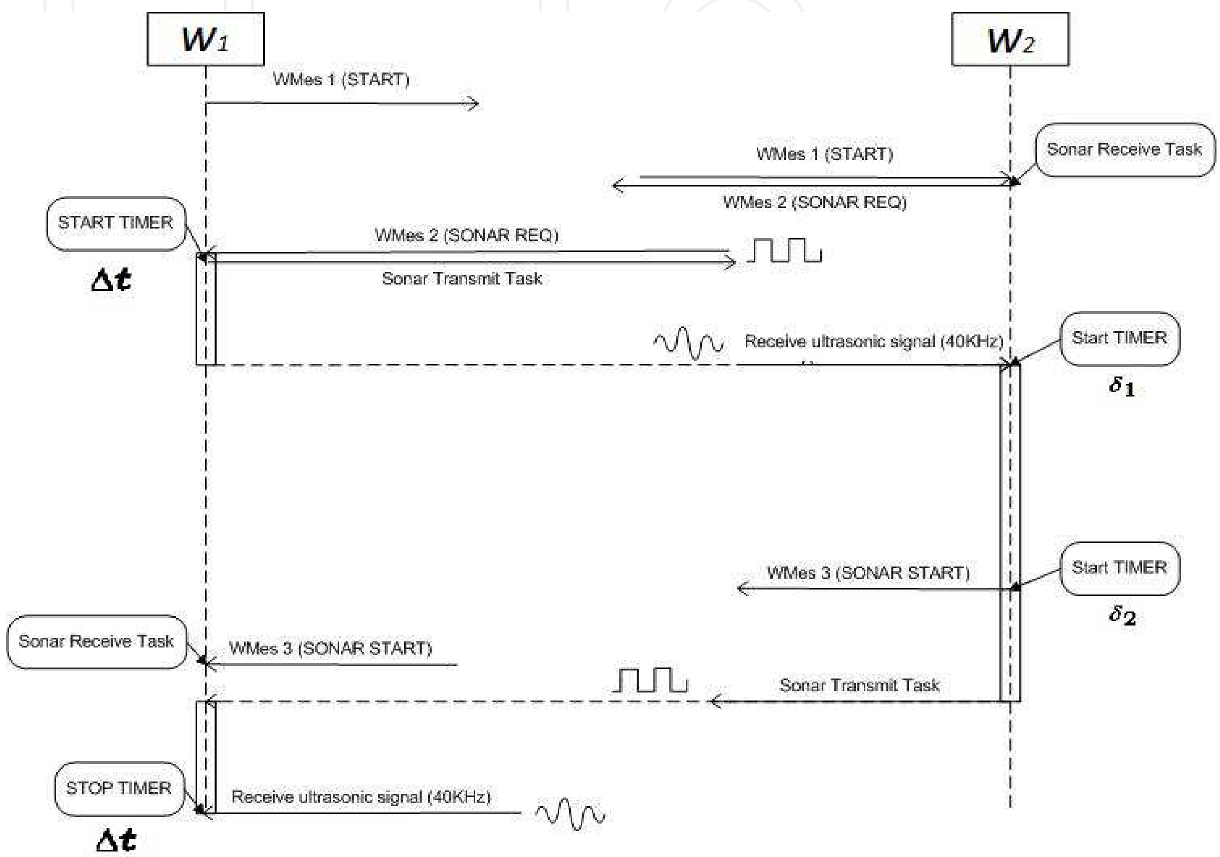

Fig. 10. Distance measurement with the CTOF method

Fig. 10 depicts the CTOF technique. Robot W_1 initiates the procedure by sending a "START" wireless message (abbreviated "WMes" in Fig. 10) to its peer, W_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, W_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, W_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 W_1. After the δ_U delay, W_2 sends a "SONAR START" message to W_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 W_1 receives the "SONAR START" message, it launches its Sonar Receive Task. After the δ_W timer expires, W_2 starts its Sonar Transmit Task and sends the corresponding ultrasonic signal towards W_1. Finally, when W_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 W_1 to W_2 and backwards. Based on this ultrasound propagation delay, the distance between the two robots can be derived:

$$d = \frac{c_{\text{air}}\left(\Delta t - \delta_U - \delta_W\right)}{2} \tag{2}$$

where c_{air} = 343.4 m/s is the velocity of acoustic waves in air at room temperature and at normal pressure. 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):

$$d = \frac{c_{\text{air}}\left(\Delta t - \delta_U - \delta_W - \theta_{UC}\right)}{2} \tag{3}$$

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

6. Experimental results

An extensive set of experiments have been conducted in the DSPLabs using the robotic system of the CORE-TX platform. The experimental setup consisted in several mobile robots, out of which two of them were randomly chosen to perform the alignment and the distance calculation procedures for each experiment. The robots have been placed at a distance ranging from 100 mm to 3000 mm and, for each 100 mm in this range, a set of over 50 pairs of measurements have been performed. Before each measurement, the robots have been positioned in random directions with respect to each other.

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 (2) and (3).

Fig. 11 shows several periods for the raw received ultrasonic signal, at the output of the LM6134 amplification circuit. Further on, the values of the signal peaks (which occur every 25 μs) are extracted and interpreted as the received Sonar signal.

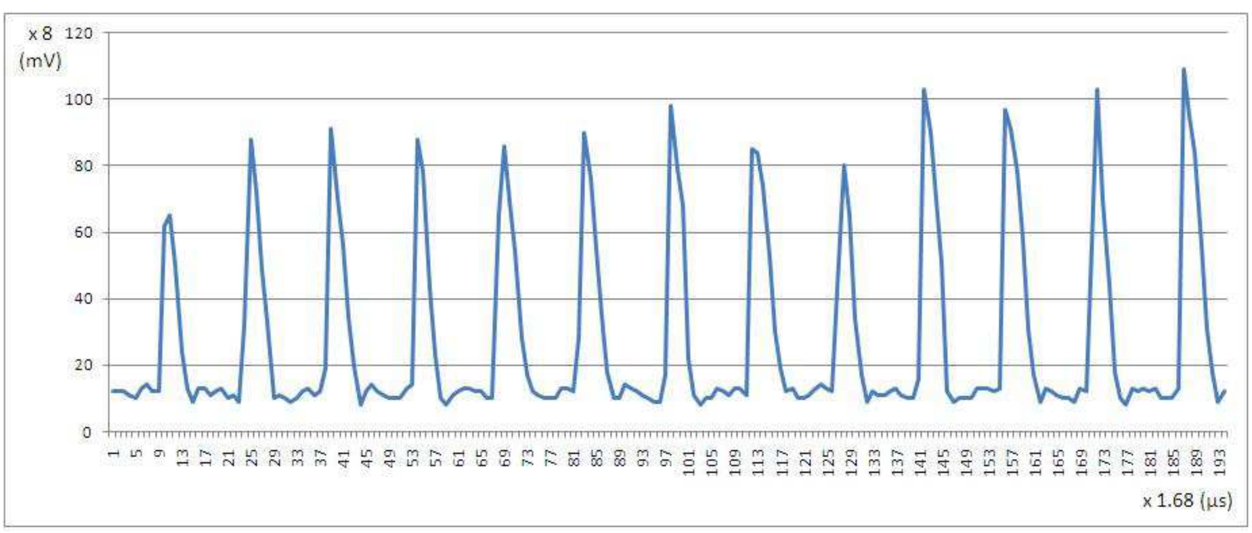

Fig. 11. Amplitude of the received ultrasonic signal, after amplification

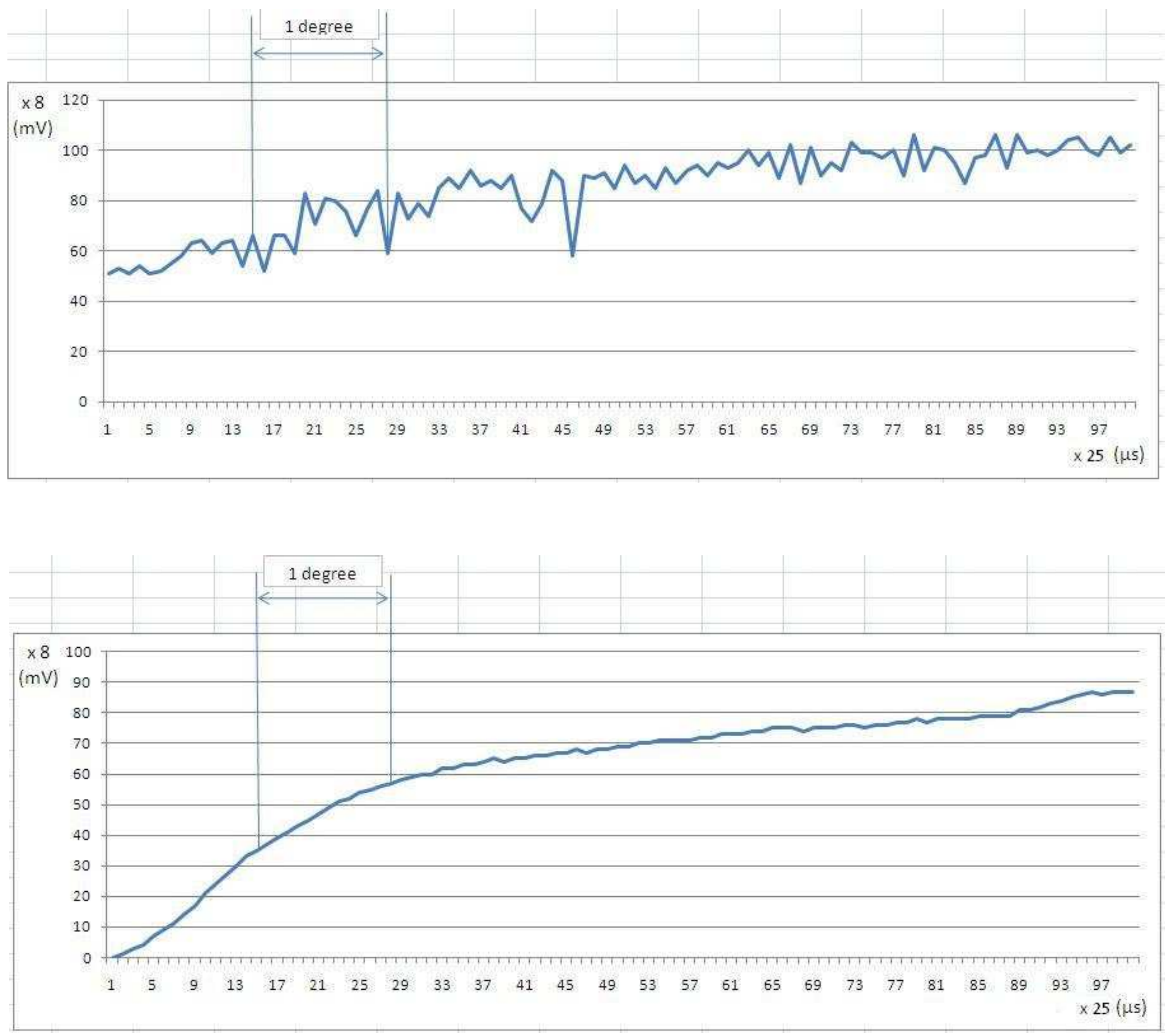

Fig. 12. Received signal without filtering (up) and after the Kalman filtering (down)

As depicted in the upper diagram of Fig. 12, the received Sonar signal contains a relatively significant amount of noise, which can be reduced by applying a Kalman filter. As shown in the lower diagram of Fig. 12, the filter significantly reduces the random variations of the signal, while retaining its trend. Even with the filtering process, accidental variations of the signal can occur. Therefore, empirical thresholds have been specified to establish when the signal amplitude changes. Setting the threshold values is a key calibration step of the alignment procedure.

The results for a full scan of the ultrasonic transducer, i.e. a rotation of 180 degrees, are presented in Fig. 13, both with and without applying the Kalman filter. The target robot is detected at around 93 degrees, with a maximum of the Sonar signal occurring at approximately 116 degrees.

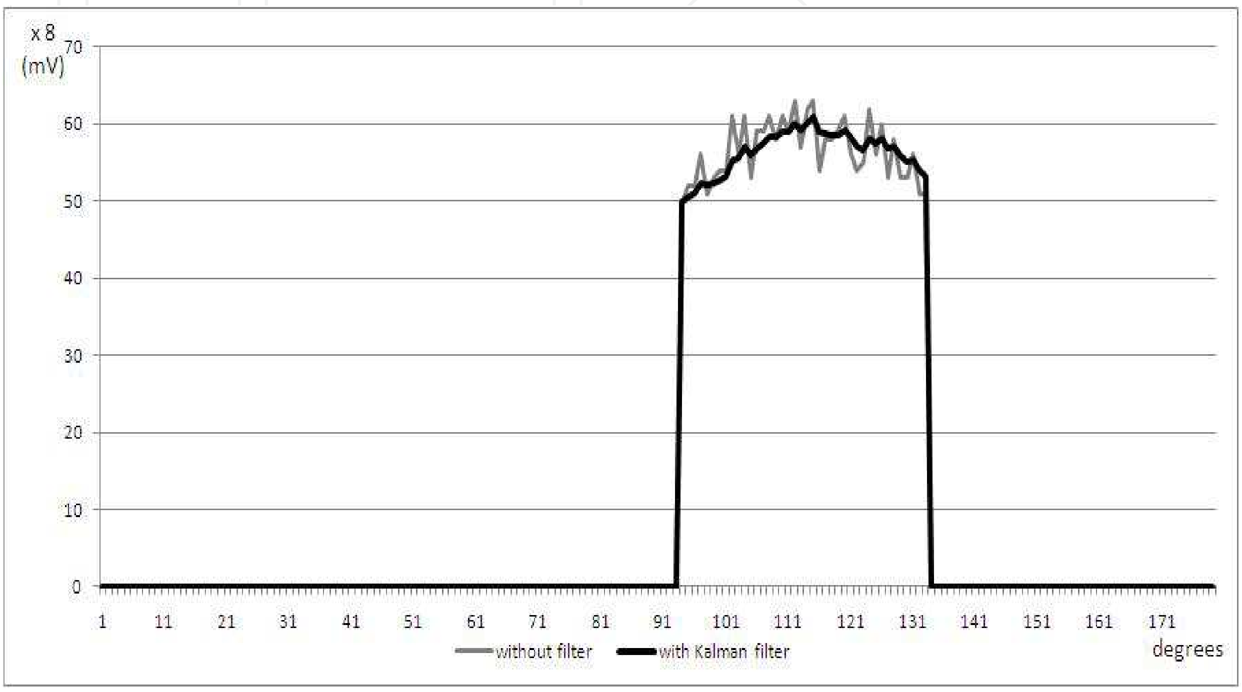

Fig. 13. Reading of the Sonar signal for a 180 degree rotation (scan) of the transducer

Some of the most interesting experimental results for the alignment process are depicted in Fig. 14. The alignment accuracy varies even for the same distance between the robots, due to the frequent changes of the turrets rotation and to the different time instances the transmitted ultrasonic signal is acquired. With few exceptions, the alignment correction angle remains lower than 10 degrees. The results presented in Fig. 14 also show the improvement of the alignment accuracy with the increase of the distance between the two robots.
Table 1 presents the distance measurement results for the proposed CTOF method. The maximum absolute error is 4.8 cm, when the robots are 3000 mm apart. The result and error analysis of the CTOF procedure show that, after the necessary calibrations, the measurement characteristics are linear and follow very closely the real distance. It proves also to be independent from the random delays introduced by the wireless modules.

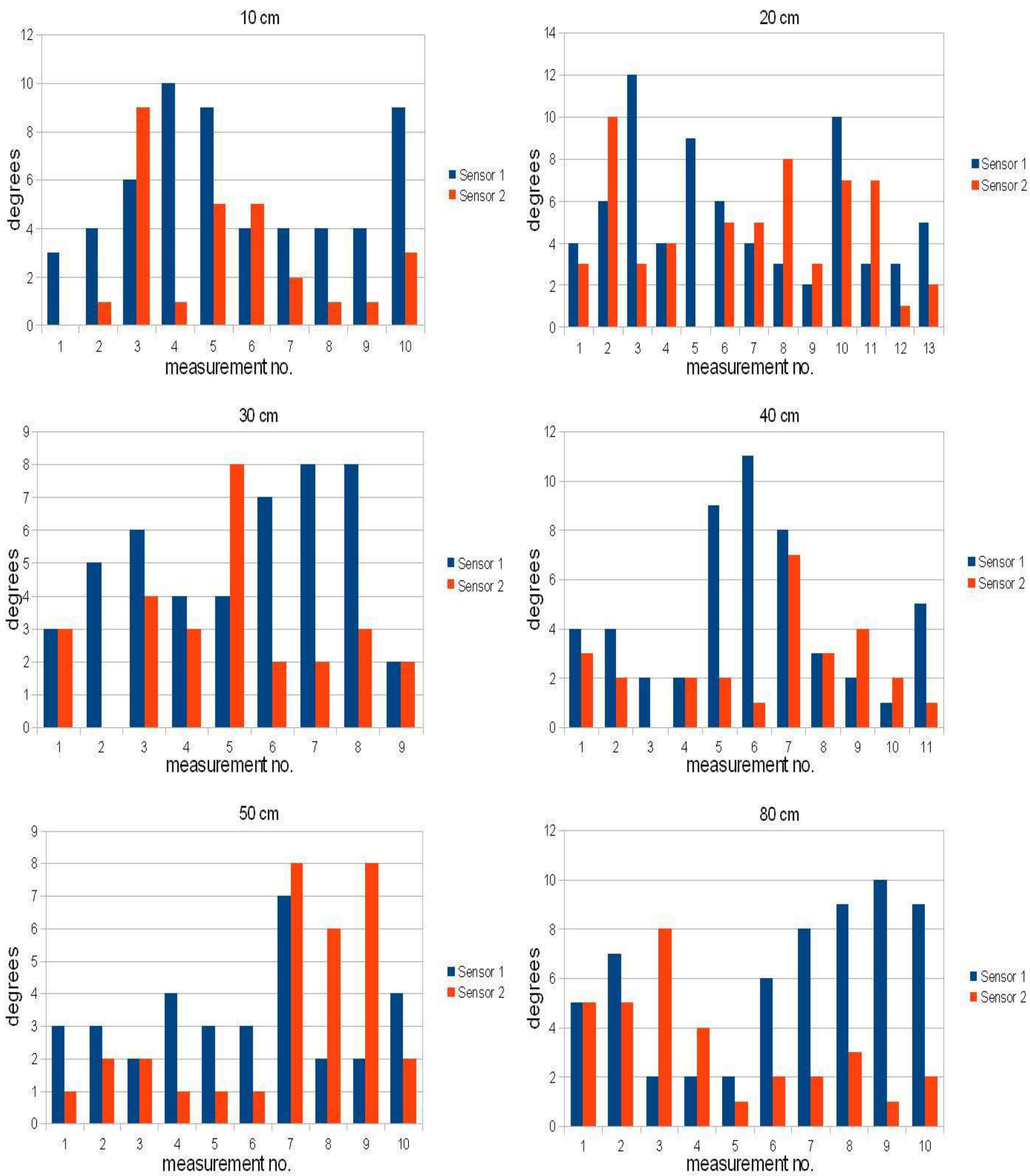

Fig. 14. Maximum variation of the correction angle for experimental alignment procedures

Table 2 presents distance measurements with the CTOF method, after applying the Kalman filter to the results. As we can see, the results are very good in terms of accuracy. The disadvantage is the time of measurement, which increases for repetitive measurements. Some comparative distance evaluation results with and without filtering the data are depicted in detail in Fig. 15. From the experiments we conclude that the system provide optimal results for approximately 10 repetitive measurements.

Real Distance [mm]	CTOF 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

Table 1. Distance measurement results for the CTOF method

Real Distance [mm]	CTOF Measured Distance with Filtering [mm]			Procedure Duration [ms]	Error reduction with Filtering [%]
	Min	Average	Max		
100	98	100	101	208÷688	66
200	198	200	205	215÷708	29
300	298	300	301	220÷727	62
400	397	399	401	226÷747	50
500	498	500	508	232÷767	63
600	598	599	601	238÷786	68
700	697	699	703	244÷805	19
800	796	800	802	250÷825	56
900	897	899	901	256÷845	56
1000	997	1001	1004	262÷865	49
2000	1997	2002	2006	321÷1060	40
3000	2993	3000	3006	379÷1252	57

Table 2. Distance measurement results for the CTOF method with Kalman filtering

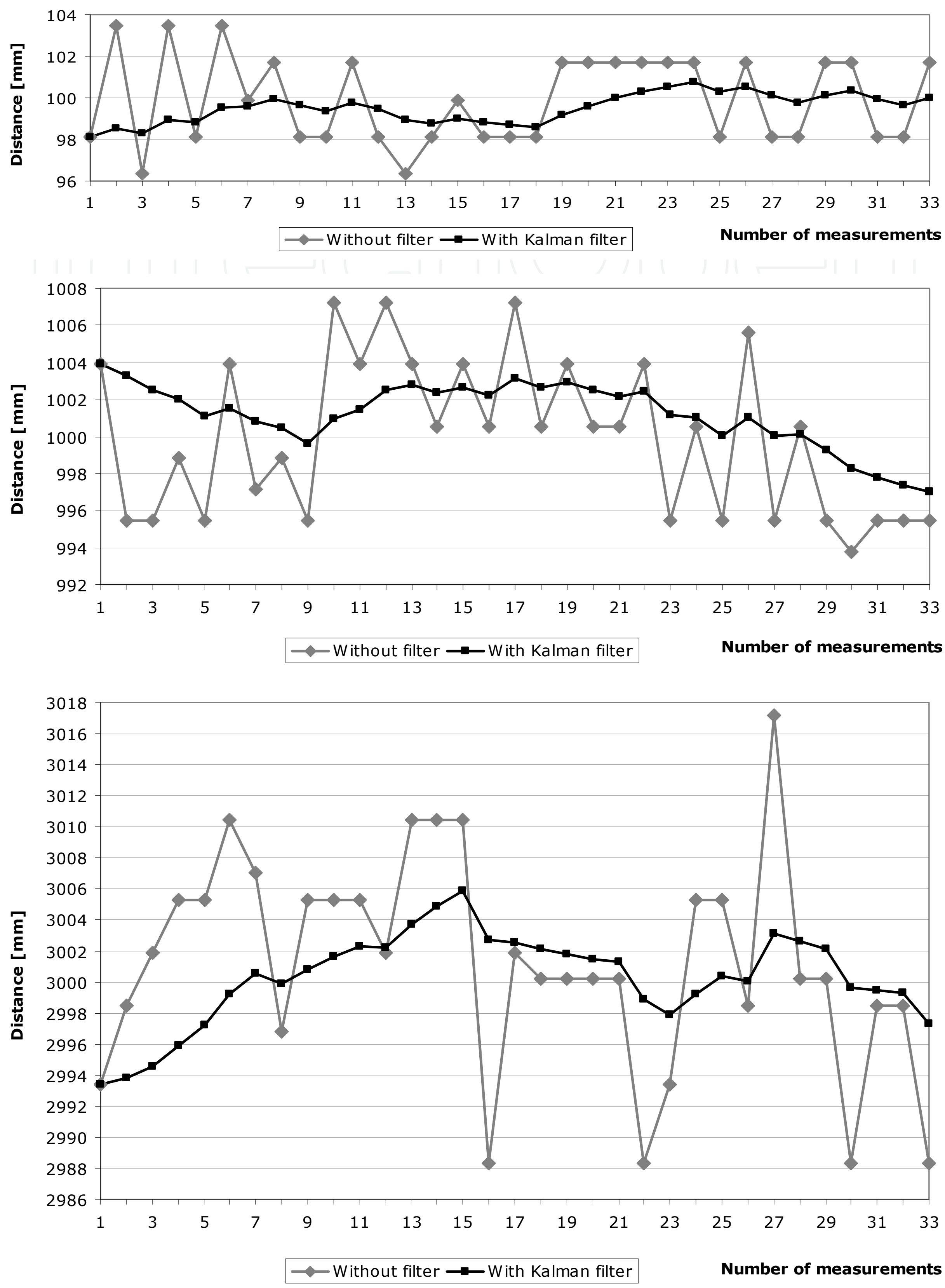

Fig. 15. Repetitive CTOF distance measurements with and without Kalman filtering, for various distances between robots (100 mm – top, 1000 mm – middle, and 3000 mm – bottom)

7. Conclusion

This work extends the discussion on the CTOF method of inter-robot distance measurement, introduced in (Micea et al., 2010). An extended discussion has also been made on the prerequisite sensor (robot) alignment procedure. The custom designed software simulation application provided the optimal ratio between the rotation speeds of the robots or their turrets with the ultrasonic transducers.
After the alignment process, the distance between two robots can be measured with the CTOF method. It has been shown that CTOF is independent of the communication propagation errors. We have also shown how the CTOF method meets the requirements of indoor, low-cost, energy-efficient robotic applications, reaching an accuracy of 4.8 cm for distances of 3 m. Furthermore, by applying the Kalman filter to repetitive distance measurements, an accuracy of 1 cm has been achieved for distances of 3 m, without the need of fixed landmarks.
The proposed distance measurement method and inter-robot alignment algorithm rely on inter-robot collaborative procedures and, therefore, these 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.

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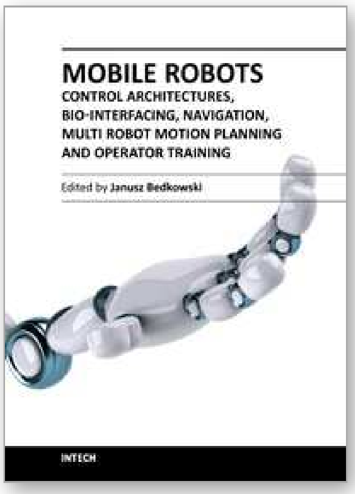

Mobile Robots - Control Architectures, Bio-Interfacing, Navigation, Multi Robot Motion Planning and Operator Training

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The objective of this book is to cover advances of mobile robotics and related technologies applied for multi robot systems' design and development. Design of control system is a complex issue, requiring the application of information technologies to link the robots into a single network. Human robot interface becomes a demanding task, especially when we try to use sophisticated methods for brain signal processing. Generated electrophysiological signals can be used to command different devices, such as cars, wheelchair or even video games. A number of developments in navigation and path planning, including parallel programming, can be observed. Cooperative path planning, formation control of multi robotic agents, communication and distance measurement between agents are shown. Training of the mobile robot operators is very difficult task also because of several factors related to different task execution. The presented improvement is related to environment model generation based on autonomous mobile robot observations.