Fine-Grained Acoustic Positioning with Compensation of CDMA Interference

Fernando Seco, Antonio R. Jiménez and Francisco Zampella
Localization and Exploration for Intelligent Systems (LOPSI) group
Center for Automation and Robotics (CSIC-UPM)
Ctra. de Campo Real km 0,200, 28500 Arganda del Rey, Madrid, Spain
Email: fernando.seco@csic.es

***Abstract*—In this communication we study the accuracy of an acoustic positioning system operating in a robotic cell, and working in sequential (Time-Division Multiple Access, TDMA) and simultaneous (Code-Division Multiple Access, CDMA) operations. In normal room conditions, and operating in TDMA mode with 7 acoustic beacons and 32 bits long binary phase modulated signals, the system achieves a location accuracy (reproducibility) of 2 mm for 90% of measurements in the complete work area, and 1 mm repeatability over small areas and short periods of time. This performance is degraded in CDMA mode, as the interference between the emitted signals causes outliers in the times-of-flight (TOF) of the weaker signals, and, consequently, large positioning errors. We demonstrate that the application of signal processing algorithms that cancel Multiple Access (MAI) and Intersymbol (ISI) Interference effects manages to eliminate most of the TOF outliers, and, as a consequence, the system can nearly replicate the TDMA positioning accuracy in CDMA operation, with the advantage of higher position update rates.**

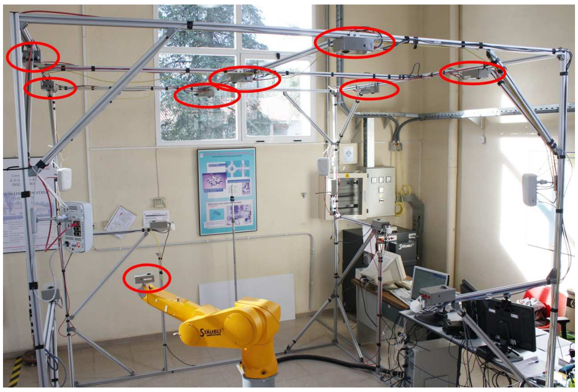

Fig. 1. The 3DLocus acoustic positioning system used in this work. The beacons of the emitting network at the top and the receiver (attached to the point of the robotic arm) are marked with red ellipses.

I. Introduction

Acoustic technology can be used to accurately determine the three dimensional position of mobile objects by distance ranging with signals emitted from fixed, known-location beacons, and use of multilateration algorithms [1]. This is the most accurate of the existing indoor positioning techniques, often achieving centimeter precision, and thus has been used in a wide scope of applications: personal localization, robot navigation, determination of pose, etc (see a recent review in [2]).

Traditional acoustic/ultrasonic positioning systems are based on a TDMA (Time Division, Multiple Access) architecture, in which beacons emit simple pulse train signals in a sequential way in order to avoid interference between them. Current systems gravitate towards the use of CDMA (Code Division, Multiple Access) schemes, in which all beacons emit simultaneously, and signals are identified by individual spread spectrum signals [3], [4]. The advantage of CDMA operation over TDMA lies in higher position update rates and more accurate range estimates, obtained at the expense of higher processing effort [5], [6]. Moreover, CDMA acoustic techniques are well suited to the hardware and processing capabilities of portable devices like smartphones or tablet computers [7], [8] The biggest drawback of CDMA-based systems is the existence of Multiple Access Interference (MAI) between the emitted codes, which may cause the apparition of large deviations in the estimated ranges (outliers), leading to occasional large positioning errors [9].

We have built a high accuracy, CDMA-based acoustic positioning system [10], as well as developed a successful MAI compensation technique [11] which allows to maintain the accuracy results obtained in TDMA mode. We qualitatively call this performance (characterized by millimeter-level repeatability) as "fine-grained" positioning. The device can be used as a general purpose location system in indoor spaces, as well as in industrial or metrological positioning applications requiring millimeter level accuracy.

In the next section we describe the experimental acoustic positioning system and the processing methods necessary for CDMA operation. Section III treats the calibration of the system and the dispersion of range measurements in TDMA operation, as well as the obtained error of the position estimates. Section IV compares the operation of the system in CDMA configuration with respect to TDMA performance. At the end of this paper we present some conclusions.

II. System description

A. Hardware

CDMA-based acoustic positioning performance will be demonstrated with the 3DLocus location system, developed by our research group, and briefly described here (see [10] and [12] for complete details).

The system consists in a set of 7 emitting beacons placed in the top part of a robotic cell of dimensions $2.8 \times 2.8 \times 2.8$ meters (see figure 1). The receiving beacon is placed on the tip of a robotic arm (Stäubli model RX90), whose movements can be controlled and are repeatable within 30 μm, as stated by the manufacturer. The static beacons transmit the positioning signals through a Visaton CP13 tweeter speaker, and the moving beacon receives the acoustic signals through a Panasonic WM61 microphone.

Beacons are identified through BPSK-modulated 32 bit long Golay codes, using a 15 kHz carrier frequency with 1 cycle per bit. The acoustic signals, amplified and conditioned by the receiver's electronic circuitry, are sampled at 150 kHz, and processed in a TMS320F2812 microcontroller from Texas Instruments for range estimation.

The system can be programmed to operate in TDMA or CDMA mode. Time synchronization is achieved through an RF trigger signal, so spherical trilateration can be used to compute the position of the mobile node (once the system is calibrated). Temperature in the cell is measured with a digital thermometer with resolution 0.1 °C.

B. Signal processing

As stated in the introduction, while computation of the times-of-flight in TDMA operation is straightforward (using simple correlation with the emitted codes), in CDMA operation the situation is more delicate due to the interference between the received codes, which can produce large deviations or outliers of the estimated times-of-flight (TOF). The 3DLocus system permits three possibilities for TOF estimation, which we describe here:

- The simple correlator estimates TOF by directly correlating the received signal with the emitted codes; it is vulnerable to MAI and ISI effects.
- The Parallel Interference Cancelation (PIC) method computes the TOF of a given beacon, but previously subtracts the estimated interfering signals of the remaining beacons [13]. In essence, it operates like an Expectation-Maximization technique [14], where the expected response of all signals but one is subtracted from the received signal, and then the optimum value of the TOF for that beacon is produced.
- The Parallel Interference/Intersymbol Interference Cancelation (PIC/ISI) method improves on the PIC technique by using a rake receiver to estimate each acoustic channel's impulse response as a set of "fingers" or copies of the emitted signal [15]. This has the effect of eliminating more thoroughly the MAI effects and works especially well for weaker signals (offering more resilience to the near-far effect disturbances), but requires longer processing time. In this work we use a rake processor with 5 fingers per beacon.

Both the PIC and PIC/ISI methods are iterative processes which end up when no further improvement on the TOFs is produced. See [11] for a complete description of these techniques.

C. Positioning

The last stage of the system is computation of position estimates. This must done robustly due to the possible presence of TOF outliers. In our application, we discard TOF estimates which differ more than 30 μs (about 10 mm) from their real values, as computed from the robot's position readings. This outlier threshold value can be adjusted depending on the accuracy requirements of an application.

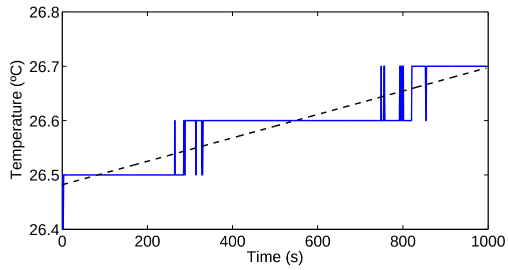

Fig. 2. Temperature variation during one of the experiments of section IV. We have improved on the limited resolution of the measured temperature (blue continuous line) by using instead a linear interpolation (dashed line).

As a figure of merit of the different TOF estimators, we define the System Availability (SA) as the condition that there are at least 4 beacons whose TOFs are correctly determined (free of outliers), since in that case the 3DLocus system is able to perform spherical trilateration and still allow one extra TOF for integrity check [11]. With 7 operating beacons, the 3DLocus system has, in principle, enough redundancy for reliable position estimation.

III. Positioning accuracy: repeatability and reproducibility

This section treats the experimental positioning accuracy of the system in a TDMA setup. After describing the calibration procedure, we study the impact of the dispersion of time-of-flight/range estimates and temperature variations on the system's performance. We also discuss the important distinction between reproducibility and repeatability measurement conditions.

A. Calibration and temperature compensation

System calibration involves determining the position of the beacons (with respect to the robot's framework axes), and follows the procedure in [10]. The receiving beacon is successively moved to 15 positions within the reach of the robotic arm, and TDMA measurements from the network of 7 beacons are recorded. Inverse trilateration is used to locate the beacons from the temperature-compensated ranges. An indicative figure of the expected positioning accuracy is the residue of the experimental ranges minus the expected ranges from the estimated beacon positions. In our case, the maximum range residue is 3.2 mm, and the mean residue is 1.2 mm.

We have identified two factors which compromise the accuracy of our positioning system. The first is the inaccuracy of the emitting beacons' estimated positions obtained during calibration, likely to be improved by taking more calibration points, or repeating calibration regularly. The second factor is due to thermal variations in the room. The temperature is measured with an external probe, so its effects on the propagation speed of sound can be compensated [16], but only to an extent. The resolution of the temperature probe

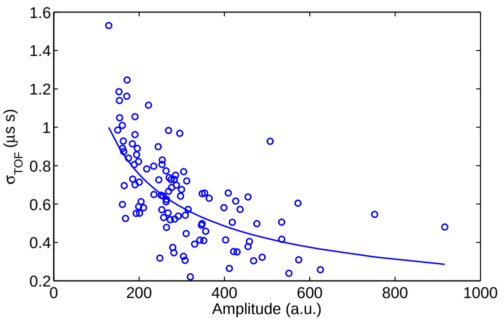

Fig. 3. The dispersion (standard deviation) of the times-of-flight from the acoustic beacons is inversely related to the received signal amplitude.

(0.1 °C) limits the accuracy on the estimation of speed of sound; we have improved somewhat this problem by linearly interpolating the measured temperature, as shown in figure 2. However, as we measure the temperature at only one point, we can not easily compensate for the effects of anisotropy of the propagation medium within the working cell, such as temperature gradients or air motion, which might change the speed of sound enough to degrade the accuracy of range estimates. Additionally, the dilatation of the metallic cell which supports the acoustic beacons causes small displacements in their positions (referred to the robotic frame), which translate to positioning errors.

B. Dispersion of TOFs

We have computed the dispersion of all 7 TOFs at the 15 calibration positions and plotted it as a function of received signal amplitude A in figure 3, in order to determine the TOF's dispersion in typical SNR obtainable in our system. Signal amplitude depends both on the range and the relative angle between emitter and receiver. A linear regression fit (plotted as a continuous line in the figure) shows that $\sigma_{\text{TOF}} \sim 1/A$. Under TDMA conditions, low signal amplitudes are not especially serious, as long as the SNR $\times$ processing gain (obtained from signal coding) remains above 0 dB; however, in the CDMA mode of operation, this near-far effect may lead to large outliers in the TOF estimates from the weaker beacons.

From figure 3 we observe that, at a given point, 90% of TOF measurements are repetitive within 1 μs standard deviation. As the geometric dilution of precision (GDOP) obtained has a maximum value of 1.5 for positions within the reach of the robotic arm, we expect that the dispersion of position estimates will remain below 0.5 mm for 90% of measurements in our experiments.

C. Repeatability and reproducibility measurements

In order to study quantitatively the accuracy of our acoustic positioning system and avoid ambiguities, we will adhere to the guidelines given in the NIST Technical Note 1297 [17]. According to this document, accuracy, which measures the closeness between the result of a measurement and the value of the measurand, is a qualitative term such as, in our case, "fine-grained". Quantitative data for accuracy is determined from the measurement error, obtained as the measurement results minus the "real" value of the measurand. This is actually unknown, but can be substituted by a convenient value, such as the

TABLE I. SUMMARY OF REPRODUCIBILITY AND REPEATABILITY MEASUREMENT CONDITIONS.

Situation	Conditions	Measurement error
Reproducibility	Arbitrary positions Arbitrary time Any system configuration	$\|\|\mathbf{b_x}\|\|^2 + \mathbf{R_x}$
Repeatability	Small regions Short periods of time Fixed system configuration	$\mathbf{R_x}$

position as measured by the encoders of the Stäubli robotic system. When a number position estimates of position $\mathbf{x}$ are produced, the three dimensional quadratic positioning error $\mathbf{E_x}$ can be given as [18]:

$$\mathbf{E_x} = \mathcal{E}\{(\mathbf{x} - \mathbf{x}_{\text{real}})(\mathbf{x} - \mathbf{x}_{\text{real}})^T\} = ||\mathbf{b_x}||^2 + \mathbf{R_x}, \quad (1)$$

where $\mathbf{x}_{\text{real}}$ is the real position and $\mathcal{E}\{\cdot\}$ is the expected value of the quantity between the brackets. Notice that the error in Eq. 1 has two contributions. The first:

$$\mathbf{b_x} = \mathcal{E}\{\mathbf{x}\} - \mathbf{x}_{\text{real}} \quad (2)$$

corresponds to a bias or systematic error, and the second,

$$\mathbf{R_x} = \mathcal{E}\{(\mathbf{x} - \mathcal{E}\{\mathbf{x}\})(\mathbf{x} - \mathcal{E}\{\mathbf{x}\})^T\} \quad (3)$$

stands for random fluctuations caused by the dispersion of the TOFs. The relative contributions of systematic and random errors depend on the measurement conditions of the positioning system (see table I).

Under *reproducibility* conditions, the measurement situation may change significantly during the process. Referring to the 3DLocus system, reproducible conditions imply operating in large regions of the robotic cell, at different periods of time, or with different configurations of the system. In this case, the term $\mathbf{b_x}$ must be included in the positioning error, since it will fluctuate randomly, depending on both measurement position and time (like the real value of the measurand, systematic error and its causes cannot be completely known). However, if the 3DLocus system is operated in a confined region of the robotic cell, during a relatively short period of time (some minutes), and a fixed configuration, we achieve *repeatability* conditions. In this case, the measurement error can be lowered by subtracting the systematic error or bias $\mathbf{b_x}$, which remains constant during the measurement time. This scheme is used for example in differential global positioning (DGPS), where fixed ground stations broadcast local corrections of measured pseudoranges to a mobile GPS terminal, so it can compensate for bias errors and greatly increase positioning accuracy [19].

The difference between reproducibility and repeatability conditions is illustrated with the next two positioning experiments obtained with the 3DLocus system operating in TDMA mode. The first (shown in figure 4) corresponds to four positioning experiments in which we drove the robotic tip to point $(700, -50, 600)$ mm in the workspace, in two different days, at two different times each. It is apparent that each set of measurements is affected by a systematic bias, which is different in each case (see table II). Under our experimental conditions, this bias is itself a random variable, which depends on position, temperature, etc in an unpredictable way.

The second experiment, illustrating repeatability conditions, is shown in figure 5, for which we moved the robot

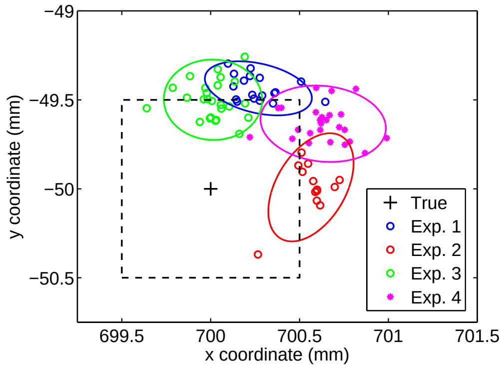

Fig. 4. TDMA positioning estimates (x, y coordinates) at point $(700, -50, 600)$ mm in four different experiments carried at different times (reproducibility conditions). We include the 90% confidence ellipses and a 1 mm side square bound centered in the true position.

TABLE II. EXPERIMENTAL CONDITIONS AND MEASUREMENT BIAS OF THE REPRODUCIBILITY EXPERIMENT OF FIGURE 4.

Experiment	Date & time	Temperature	Bias (b_x, b_y, b_z)
1	Day 1, 11h 49m	26.7 °C	(0.24, 0.59, 0.14) mm
2	Day 1, 13h 33m	27.9 °C	(0.52, 0.11, -0.46) mm
3	Day 2, 12h 48m	29.9 °C	(0.03, 0.48, -0.25) mm
4	Day 2, 17h 55m	32.2 °C	(0.62, 0.41, -1.03) mm

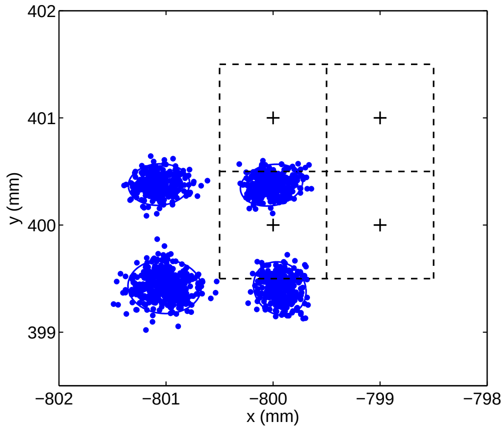

Fig. 5. Performance of the positioning system under reproducibility conditions. A positioning resolution better than 1 mm is obtained, but the measurement is affected by an error bias $(b_x, b_y, b_z) = (-0.9, -0.6, 0.7)$ mm.

arm three consecutive times over a 1 mm step, 2×2 points plane square grid, producing 1400 point estimates in a time interval of 13 minutes. It is seen that the resolution of the positioning system is better than the 1 mm grid step, a result which is consistent with the dispersion in the TOFs and the GDOP bound given in section III-B; however, the position estimates are affected by a systematic bias error $(b_x, b_y, b_z) = (-0.9, -0.6, 0.7)$ mm.

A comparison of the positioning error found in reproducibility and repeatability conditions, with data obtained from eight grids at different regions in the robotic cell (a total of 5600 position estimates), is shown as cumulative density functions (CDF) in figure 6. Under reproducibility conditions we obtain a median error of 1.20 mm and a 90% error of 1.90 mm; under repeatability conditions, the median error is reduced to 0.30 mm and the 90% error to 0.70 mm.

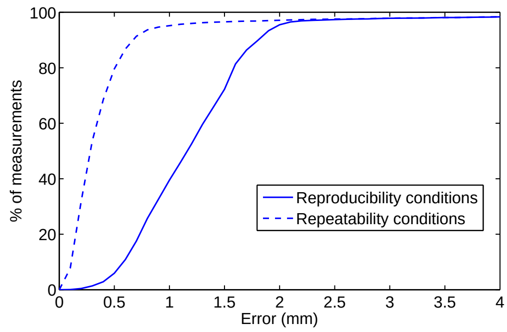

Fig. 6. Cumulative density function (CDF) of the positioning error of the acoustic system in TDMA operation. Reproducibility conditions encompass both systematic and dispersion errors, while repeatability conditions include only the dispersion error.

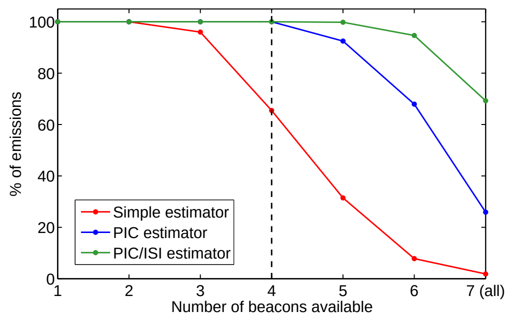

Fig. 7. Statistics with the number of beacons free of outliers and available for positioning, for three different CDMA estimators. The condition for System Availability (4 beacons are available) is shown with a vertical dashed line.

IV. CDMA CONFIGURATION POSITIONING PERFORMANCE

The results of the previous section were obtained in a TDMA setup, and match the previously found performance of the system [10]. In the CDMA setup, we expect degradation of range estimates due to the MAI effects between the emitting beacons. We study this situation experimentally in this section.

A. *Number of outliers and system availability*

To quantify the effect of interference in position estimation, we moved the robot's tip in a grid arrangement of 11×10 points, at xy steps of 10 mm, for 973 total measurements, while remaining at a constant height (600 mm). Figure 7 shows statistical results of the number of beacon estimates free of outliers and usable for positioning, for all three CDMA estimators. For the simple estimator, 42.5% of TOF measurements resulted outliers, and the System Availability (SA) condition was achieved for only 65.5% of emissions. Outliers were reduced to 16.2% with the PIC estimator and to 5.2% with the PIC/ISI estimator; in both cases, SA was 99.1%. Furthermore, use of the PIC/ISI estimator over the PIC estimator results in more TOF estimates being available for positioning computation at any given point.

Figure 8 shows the corresponding positioning results in the grid. The empty spaces in the top part (a), are grid points where the SA condition was not achieved with the simple estimator. Application of the PIC or PIC/ISI methods provides almost complete coverage of the grid, as shown in parts (b) and (c).

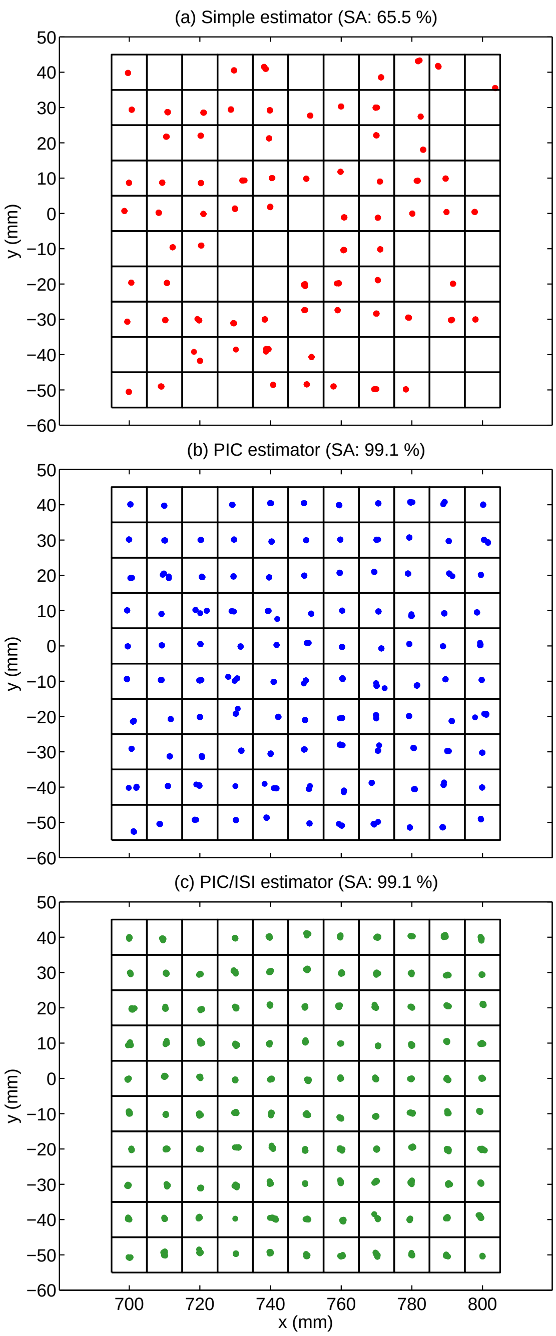

Fig. 8. CDMA performance of the positioning system over a 11×10 grid with step 10 mm. Position computed with (a) the simple, (b) PIC, and (c) PIC/ISI estimators. Empty grid points correspond to regions where the System Availability condition was not reached.

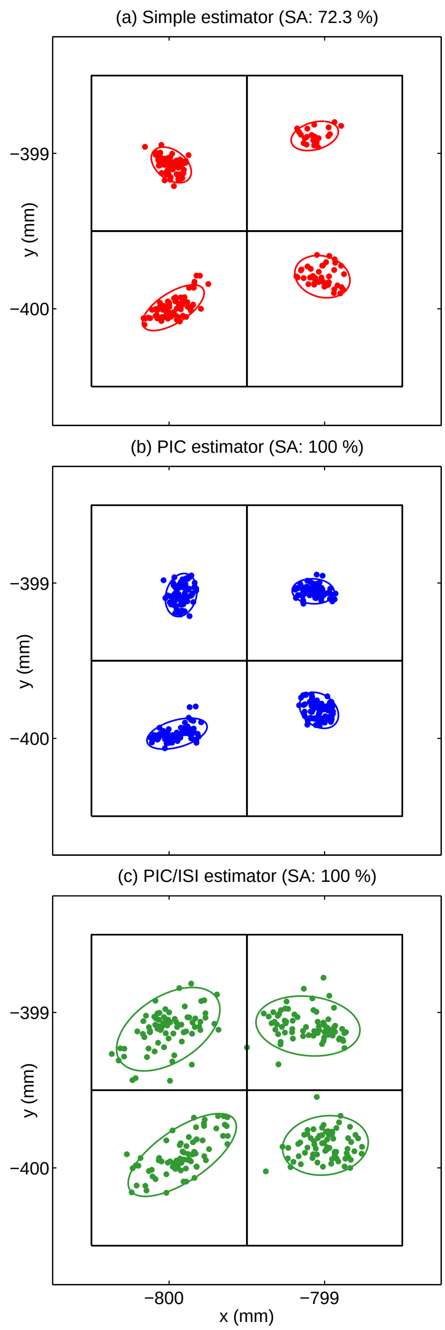

Fig. 9. CDMA positioning over a small 2×2 grid of 1 mm size. Results of the (a) simple, (b) PIC, and (c) PIC/ISI estimators, and 90% confidence ellipses. Repeatability estimates with systematic error removed.

B. CDMA positioning accuracy

We are also interested in the accuracy of the system in CDMA operation. As an example, we again cover a 2×2 square grid with 1 mm step in figure 9), and subtract the systematic error. With the simple estimator (part (a)), the SA condition is achieved for only 72.3% of instances, which increases to 100% with either PIC and PIC/ISI estimators (parts (b) and (c)), which is consistent with our previous result. It is interesting to note that the positioning estimates of the PIC/ISI estimator have a higher dispersion (random error) than the PIC version, which is probably due to imperfect estimation of the channel response of the transducers, and it is a matter for further research.

CDF results for CDMA operation are provided in figure 10, along with TDMA results for comparison. As in section III-C, they have been collected from 11 different position grids at several points in the workcell (around 5500 position estimates in all), and systematic bias has been removed (repeatability conditions). The first thing to be noticed is that the simple

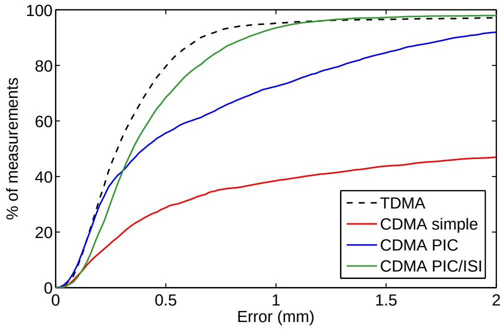

Fig. 10. CDF of the TDMA and CDMA positioning error results compared (under repeatability conditions, systematic bias has been removed).

estimator (correlator) only provides valid positioning results for approximately 50% of points, establishing the need for MAI/ISI compensation methods. The median and 90% error values of the PIC estimator are 0.50 mm and 1.90 mm, while for the PIC/ISI estimator we achieve 0.40 mm and 0.90 mm, respectively. These results are similar to those obtained under TDMA operation (0.30 and 0.70 mm), which proves that CDMA can nearly replicate TDMA accuracy if MAI and ISI effects are compensated for. Regarding the relative performance of both MAI compensation methods, the PIC technique has less valid TOF estimates for position estimation than the PIC/ISI technique (see figure 7), however, the individual TOF estimates have less dispersion (see figure 9). This situation results in the PIC method being more precise in the low error portion of the CDF curve (below 0.3 mm), but being outperformed by the PIC/ISI method at larger error values.

V. Conclusions

The results offered here demonstrate that similar accuracy can be obtained with our acoustic positioning system working in a CDMA setup than was found with a TDMA setup, with the advantage of a higher position update rate. The system positioning precision in reproducibility operation, is 2 mm for 90% of measurements in the robotic cell, which improves to 1 mm in repeatability conditions (operation in small areas, during a period of time of a few minutes). Of the two interference cancelation techniques demonstrated here, we have found experimentally that, although the PIC/ISI algorithm provided better TOF outlier rejection than the PIC method, the overall repeatability was degraded, probably due to the method making wrong estimates of the transducer's impulse response. We are investigating this issue further.

While reproducibility measurement conditions are in general more versatile for instrumentation, repeatability conditions can also be useful for positioning tasks carried over a limited time or in a confined region, or in applications where only relative displacement measurements are significative. Further study and correction of the sources of error pointed out in this work would presumably bring the accuracy (reproducibility) of our system closer to its 1 mm repeatability, opening many possibilities for acoustic positioning as a precise metrological tool in industrial processes.

Acknowledgment

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