Calibration and Measurement Processing for Ultrasonic Indoor Mobile Robot Localization Systems

Lőrinc Márton, Csaba Nagy, Zalán Biró-Ambrus and Katalin György

Abstract—**This work introduces an indoor localization system for mobile robots using Time-of-Flight measurements between an ultrasound signal emitter mounted on the robot and ultrasonic sensors (anchors) mounted over the workspace of the robot. In the first part of the study a calibration method was proposed for Time-of-Flight measurement based localization systems. The influence of the anchor's position on localization performance was analyzed to show the necessity of precise calibration. The calibration procedure was formulated as an optimization problem and its efficiency was showed through real measurements. In the second part of the study an Extended Kalman Filter based predict - update type estimator was proposed to increase the measurement rate of the localization system. For the state estimator an omnidirectional robot model was developed which inputs are provided by an Inertial Measurement Unit. Experimental results using a KUKA youBot mobile robotic platform are also presented to show the applicability of the proposed indoor localization method.**

Index Terms—**Robot sensing systems, Calibration, Motion estimation, Wireless sensor networks**

I. Introduction

The tracking control of mobile robots requires precise position determination of the moving agent with respect to a reference frame. The localization should also provide the position of the robot with high measurement rate if the control task assumes fast motion. The global positioning systems (GPS) is designed for outdoor navigation and combined with Inertial Measurements Units (IMUs) can assure the localization for outdoor autonomous navigation [1]. However, the GPS based systems are in most cases not suitable in indoor locations, since microwaves will be attenuated and scattered by roofs and walls of the buildings. It is also well known that only the odometry based localization (e.g. position estimation based on wheel mounted sensors) is sensitive on measurements errors such as wheel slipping, and accumulate bias errors over time. It is why in many applications special measurement infrastructure is necessary for precise mobile robot localization.

For mobile robot control applications common indoor localization systems are based on signal receivers - emitter pairs. The emitters or receivers (anchors) are placed over the robot's workspace and its pair is placed on the robot. These systems measure the Time-of-Flight (ToF) of the signals traveling between the synchronized receivers and transmitters. By assuming that the spatial positions of the anchors are known, multiple measurements can be combined with trilateration to find a location of the robot. The ultrasonic emitters and receivers are the most common for these type of localization systems [2].

Other approaches for localization were also presented in literature, such as WiFi signal based [3] or Bluetooth signal based [4] localization. However, these approaches the position measurement accuracy (tenth of centimeters) cannot assure and update rate that are necessary for low level robot control. The passive RFID based localization needs a large number of sensors placed in the floor of the robot's workspace and it can provide a precision in order of centimeters [5].

For complete robot localization, the orientation of the robot should also be determined. The orientation related to a given axis can be determined using dedicated sensors such as well calibrated magnetometers [6]. The other approach is the differential time of arrival technique which is based on ultrasound localization system's measurement [7].

If precise time synchronization and effective signal detection is provided, a well calibrated ultrasound based localization can provide a sub-centimeter position accuracy. However the standard Time-of-Flight ultrasonic range finders are only able to provide tenths of readings per second. This update rate is not enough for fast robot control applications. To handle this problem, the Time-of-Flight measurement based position computation can be fused with inertial measurements to provide much faster position estimation. These sensor fusion methods use the model of the robot and measurements form accelerometers or gyroscope sensors. The method provided in [8] is based on an Extended Kalman Filter (EKF): the proposed estimation method allows the consistent use of the triangulation methods to determine the robot's position at any time during its motion. An EKF-based algorithm with a state/observation vector composed of the robot's position and the orientation is presented in [9] using odometric and ultrasonic distance measurements. The authors of the work [10] developed indoor mobile localization system having high localization performance; specifically, the Unscented Kalman Filter is applied for improving the localization accuracy.

For robot localization the precise position of the anchors has to be known exactly. The exact position of the anchors has to be determined a-priori the localization measurements. This process is called calibration. The study [11] proposes a three-point extraction algorithm that is used in conjunction with trilateration to compose a new localization method. In the paper [12] the Distribute & Erase self-calibration method for ultrasound based localization systems was proposed. It was successfully applied in the SNoW Bat [13] localization system. The method requires the a-priori knowledge of the

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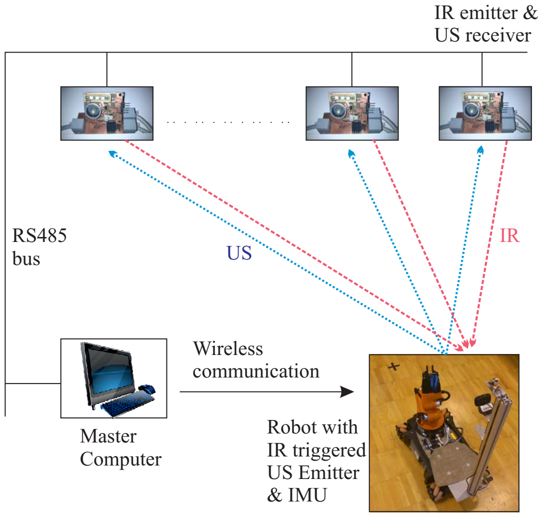

Fig. 1. Bloc scheme of the mobile robot localization system

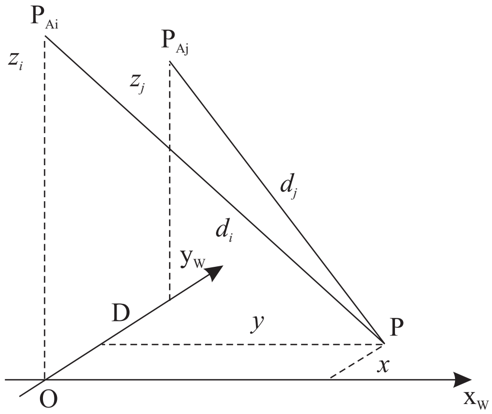

Fig. 2. Simplified localization scheme

exact position of two anchors. In the paper [14] a calibration method was proposed to deal with ambient temperature change which influences the speed of the ultrasound signal.

In this work a localization system is introduced which combines the ultrasound based measurements with an inertial measurement for reliable and fast robot position estimation. The effect of the imprecisely placed anchors on the localization error was analyzed. For precise position measurement a novel optimization based calibration method is introduced which requires no previous exact knowledge on the position of any of the anchors. The method determines all the three coordinates of the anchors. For the calibration only several reference positions in the robot's workspace should be determined a-priori. In addition a sensor fusion technique is also presented to refine the Time-of-Flight based position measurements using IMU sensors. The proposed position estimation method uses Kalman filtering technique and it can also deal with the biases of the IMU sensor. The applicability of the anchor calibration and the sensor fusion based robot control is demonstrated through robot control experiments using a KUKA uouBot robotic platform.

II. Calibration of Anchor Location

A. Short description of the localization system

The block diagram of the localization system is shown in Figure 1. The measurement is initiated by the master computer, which broadcasts a synchronization command for all the anchors through the RS485 bus. The controllers of the anchors receive this signal through their interrupt inputs and transmit a Manchester modulated infrared packet (IR) for the ultrasonic receiver node placed on the robot. Simultaneously the controllers of the anchors start to listen the ultrasonic receiver. The node responds with a phase-modulated ultrasonic (US) chirp signal [15]. The phase change detection offers the precise detection of the arrival time instant. The ultrasonic signal arrives to the anchor's receiver with Time-of-Flight delay. The arrival time is the instant when the phase-change in the received ultrasonic signal is detected.

The distance between the anchor and the robot can be up to 10m. The order of the Time-of-Flight is about 1-10ms. The uncertainty due to the applied infrared synchronization method is under 2μs. It can induce about 0.6mm uncertainty in the ultrasound based distance measurement.

B. The influence of the anchor position on localization

The localization system calculates the anchor-robot distance based on the signal Time-of-Flight measurement. By assuming that the robot moves in a plane, the equations based on which the unknown position can be computed have the form:

$$(x - x_i)^2 + (y - y_i)^2 + z_i^2 = d_i^2 \tag{1}$$

Here x and y denote the robot's unknown position in the plane related to an inertial reference frame. The notations x_i, y_i and z_i stand for the known spatial coordinates of the anchors in the same reference frame. The distance between the anchor and the robot is denoted by d_i. At least two equations (i.e. signal Time-of-Flight measurements) are necessary to calculate the unknown robot's position.

In practical applications the positions of the anchors are given with a finite precision. Henceforth it will be investigated, how the imprecision of *mounting height of the anchors* and *distances between the anchors* influence the precision of the robot position computation. To answer this question, consider a simplified localization problem presented in Figure 2: the origin of the frame, in which the robot is localized is placed under the anchor i and the y_W axis of the frame corresponds to the line which connects the i'th and j'th anchors that are used for localization.

The computation of the robot position $P(x, y)$ can be performed if the mounting heights of the anchors (z_i, z_j) and the distance between the anchors (D) are known:

$$\begin{cases} x^2 + y^2 = d_i^2 - z_i^2, \\ x^2 + (D - y)^2 = d_j^2 - z_j^2. \end{cases} \tag{2}$$

The equations above stand for $y \geq 0$. Otherwise the second equation should be replaced by $x^2 + (D + y)^2 = d_j^2 - z_j^2$.

However, the procedure of the error analysis is the same for this case as well.

Based on the equations above the robot's position can be computed as:

$$y = \frac{d_i^2 - z_i^2 - d_j^2 + z_j^2 + D^2}{2D}, \quad (3)$$

$$x = \pm\sqrt{d_i^2 - z_i^2 - \left(\frac{d_i^2 - z_i^2 - d_j^2 + z_j^2 + D^2}{2D}\right)^2}, \quad (4)$$

where the sign $\pm$ takes into account the mirror symmetric location.

Let θ, θ^*, $\Delta\theta$ be the vectors comprised of the parameters related to station locations, the real parameters, and relative parameter errors respectively:

$$\theta = \begin{pmatrix} D \\ z_i \\ z_j \end{pmatrix}, \ \theta^* = \begin{pmatrix} D^* \\ z_i^* \\ z_j^* \end{pmatrix}, \ \mathbf{\Delta}\theta = \theta - \theta^* = \begin{pmatrix} \Delta D \\ \Delta z_i \\ \Delta z_j \end{pmatrix}. \quad (5)$$

The position is determined in function of the parameter vector. The vectors of the computed robot position, real position and relative position errors are:

$$\mathbf{p} = \begin{pmatrix} x \\ y \end{pmatrix}, \quad \mathbf{p}^* = \begin{pmatrix} x \\ y \end{pmatrix}, \quad \mathbf{\Delta p} = \mathbf{p} - \mathbf{p}^* = \begin{pmatrix} x \\ y \end{pmatrix}. \quad (6)$$

The computed position can be linearized around the real position using the Taylor expansion as:

$$\mathbf{p} \approx \mathbf{p}^* + \frac{\partial \mathbf{p}}{\partial \theta}(\theta - \theta^*), \quad (7)$$

where

$$\frac{\partial \mathbf{p}}{\partial \theta} = \begin{pmatrix} \frac{\partial x}{\partial D} & \frac{\partial x}{\partial z_i} & \frac{\partial x}{\partial z_j} \\ \frac{\partial y}{\partial D} & \frac{\partial y}{\partial z_i} & \frac{\partial y}{\partial z_j} \end{pmatrix}. \quad (8)$$

From the relation (7) directly results the dependency of the localization error on the relative parameter errors:

$$\mathbf{\Delta p} \approx \frac{\partial \mathbf{p}}{\partial \theta}\mathbf{\Delta}\theta. \quad (9)$$

The elements of the Jacobian are directly computable based on the relations (3) and (4). By evaluating the elements of the Jacobian it can be affirmed that by increasing the mounting height of the anchors, or decreasing the distance between the anchors the sensitivity of the localization error to the relative anchor position errors increases.

Numerical example: Figure 3 shows the dependence of the $\partial y/\partial z_i$ element of the Jacobian on the height parameter z_i and distance parameter D. It was considered that both z_i and D belongs to the interval $[0.5\text{m}, 3\text{m}]$. As the figure shows, the investigated element can take values over one thus amplifies the effect of the inexactly known anchor position on robot's localization.

Accordingly, in order to perform a precise localization, it is necessary to obtain the accurate spatial positions of the anchors in the reference frame.

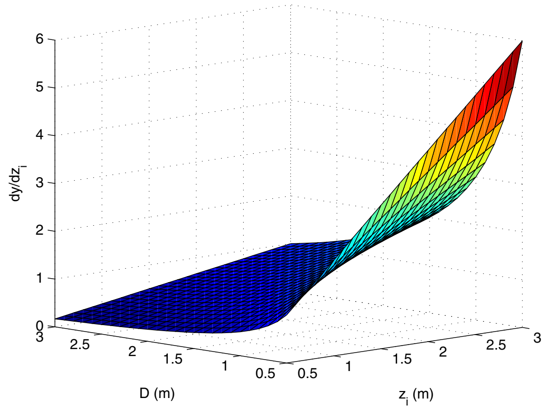

Fig. 3. An element of the Jacobian in function of anchor position

C. Optimization based calibration

In the calibration approach proposed in this Section it was considered that inexact initial estimates of the anchors' positions are available (in order of tenth of centimeters). In real applications it is realistic to know an approximate of the positions of the mounted anchors. However, these anchors can be mounted with millimeter precision with difficulty. With the calibration process the exact position of the anchors is determined.

The calibration can be performed in function of known reference points in the robot's workspace ($P_{ref}(x_{ref}, y_{ref})$). These reference positions are considered to be in the line of sight of $N_A \geq 3$ anchors. The position of these anchors can be calibrated.

For the calibration a cost function is formulated. The first part of the proposed cost function is formulated in function of the distances between the reference points and the anchors' position ($P_{Ai}(x_i, y_i, z_i)$). Further anchor - robot distance measurements are also performed in the vicinity of the reference points. These are called here test points ($P_T(x_T, y_T)$) and the coordinates of them should not be known for calibration. A position of these test points can be determined based on measurements performed by two anchors. Denote the obtained test point by an anchor pair by $\hat{P}_{Ti}(\hat{x}_{Ti}, \hat{y}_{Ti})$. In the same test point all the different anchor pairs should compute the same $\hat{x}_{Ti}$, $\hat{y}_{Ti}$ coordinate values. The second part of the cost function is formulated in function of the distances between the obtained test points by the different anchor combinations in a test point.

By combining these two criteria, the cost function based on which the calibration is performed can be written as:

$$J = \sum_{k=1}^{N_R}\sum_{i=1}^{N_A} \delta(P_{Ai}, P_{ref}) + \alpha \sum_{k=1}^{N_T}\sum_{i=1}^{N_A}\sum_{j=1, j\neq i}^{N_A} \delta(\hat{P}_{Ti}, \hat{P}_{Tj}), \quad (10)$$

where $\delta(\cdot)$ represents the Euclidean distance between the points and α is a weighting factor to combine the two costs. The notations N_R and N_T stand for the number of applied

Anchor	Initial (m)	Calculated (m)	Real (m)	|Error| (m)
P_{A1} - x	1.5180	1.3828	1.382	0.0008
P_{A1} - y	2.4805	2.2637	2.263	0.0007
P_{A1} - z	2.3540	2.1450	2.146	0.0010
P_{A2} - x	1.3938	1.3834	1.384	0.0006
P_{A2} - y	1.3178	1.2565	1.257	0.0005
P_{A2} - z	1.3178	2.1446	2.144	0.0006
P_{A3} - x	0.1	0.0050	0.006	0.0010
P_{A3} - y	0.1	0.0020	0.003	0.0010
P_{A3} - z	2.2660	2.0660	2.066	0.0000

TABLE I
RESULTS OF THE CALIBRATION

reference points and the number of test points respectively. The set of test points can also include the reference points.

D. Calibration Measurements

The anchors' positions in the localization system were calibrated using the optimization procedure described in the previous subsection. The ultrasound transmitter node was fixed at the end of a pole, which was attached to the mobile platform. The height of the node related to the plane of the reference frame is 0.89m.

In the experiment above three anchors were calibrated. To perform the calibration, three reference points were considered in the robot's workspace. (P_{R1}(0m, 0m), P_{R2}(0.1m, 0.4m) P_{R3}(-0.1m, 0.4m). Over these one more test point was taken into consideration during the calibration process.

The cost function (10) was formulated using the anchors - reference (and test) point distance measurements. The weighting parameter in (10) was chosen $\alpha = 0.5$. For the minimization of the cost function the simplex search method was applied (`fminsearch` Matlab function).

The convergence of the cost function during the optimization is presented in Figure 4. The obtained results are presented in the Table I. To confirm the validity of calibration, the exact position of the anchors were also measured by independent measurements. In the table the initial anchor positions used for optimization, the calculated anchor positions by the optimization procedure, the real anchor positions and the anchor position errors are also presented. As the results show, the optimization guarantees the precise calibration of the anchor's position.

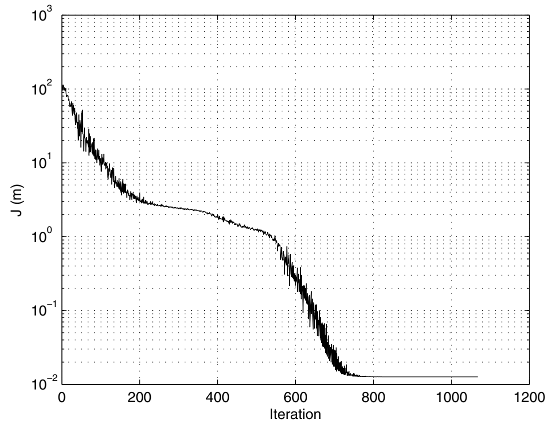

Fig. 4. Convergence of the cost function

III. EXTENSION OF THE LOCALIZATION WITH IMU MEASUREMENTS

A. Robot model for position and velocity estimation

The update rate provided by the Time-of-Flight measurements based localization could not be enough for fast robot control applications. To improve the update rate IMU measurements can be used to estimate the location of the robot. The IMUs have higher measurement update rate than the Time-of-Flight measurement based localization systems. In order to exploit this, predict-update type position estimation can be applied, i.e. between the Time-of-Flight based position measurements the estimator provides the robot's location based on the robot model and the available IMU measurements.

Consider a moving robot which position has to be determined in a reference frame ($y_W O x_W$). The ultrasonic localization also provides the position of the robot in this frame. Another local frame is attached to the robot's body ($y_R O x_R$) which origin can be the center of gravity of the robotic platform. The robot equipped with an accelerometer, placed in the origin of the robot's frame, that can compute the acceleration along the axis of the robot's frame (a_x, a_y) and a magnetometer. Using magnetometer measurements, the orientation of the robot can also be determined. The orientation is defined as the angle (α) between the x_R and x_W axes of the robot's frame and the reference frame, see Figure 5.

In the case of omnidirectional robots the heading direction does not necessarily correspond to the x axis of the robot's frame, see Figure 5. The kinematic model that describes the robot's motion in the reference frame is:

$$\begin{cases} \dot{x} = \|v\| \cos(\theta), \\ \dot{y} = \|v\| \sin(\theta). \end{cases} \tag{11}$$

The magnitude of the velocity ($\|v\|$) and the heading angle (θ) can be computed in the robot's frame as it is presented in Figure 5:

$$\begin{cases} \|v\| = \sqrt{v_x^2 + v_y^2}, \\ \theta = \alpha + \beta = \alpha + \arctan(v_y/v_x). \end{cases} \tag{12}$$

The components of the velocity vector in the robot's frame are given by the integral of the measured accelerations. It should also be taken into consideration that the acceleration measurements are generally corrupted by a bias that can be considered almost constant. Accordingly the robot's model can be extended with the following measurement equations:

$$\begin{cases} \dot{v}_x = a_x + b_x, \\ \dot{v}_y = a_y + b_y, \\ \dot{b}_x = 0, \\ \dot{b}_y = 0, \end{cases} \tag{13}$$

where a_x, a_y are the accelerations along the axis of the robot frame and b_x and b_y represent the constant biases of the acceleration measurements.

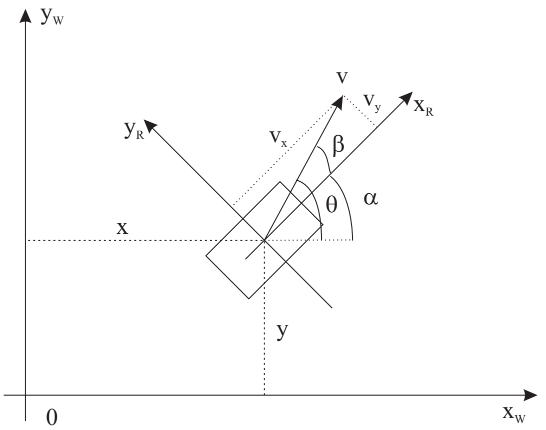

Fig. 5. Omnidirectional robot - Kinematic model

Note that in the measurement model above, used to support the robot's position estimation, the angular velocity was not taken into consideration. The extension of the model with the angular velocity can be done by considering the measurement of the IMU's gyroscope.

During state estimation it should also be taken into consideration that the measurements are affected by noise (w). In this work Gaussian measurement noises are assumed in the form: $w_{ax}, w_{ay} \sim N(0, \sigma_a)$; $w_{\alpha}, \sim N(0, \sigma_{\alpha})$; $w_x, w_y \sim N(0, \sigma_x)$.

In order to cope with these measurement noises and the nonlinearities in the robot model, an *Extended Kalman Filter* can be designed for state estimation. The model given by the relations (11), (12) and (13) with the available acceleration and magnetometer measurements was applied for prediction. The robot model is linearized by using the Euler method with a sampling period corresponding to the measurement period of the IMU. The inputs of the prediction model are $\mathbf{u} = (a_x\ a_y\ \theta)^T$, the state vector is $\mathbf{x} = (x\ v_x\ y\ v_y\ b_x\ b_y)^T$, the outputs (measured states) are $\mathbf{y} = (x\ y)^T$. The update phase of the Kalman filtering can be performed when a new (x, y) measurement set comes from the ultrasonic localization system.

B. Motion experiments

The applicability of the localization system combined with IMU measurements was tested on a KUKA youBot omnidirectional mobile robotic platform. The IMU was placed on the robot platform.

The applied accelerometer is able to measure the acceleration along three axes with 10 bit resolution. It provided the inputs a_x and a_y for the state estimator's model. The orientation angle α was measured using a three axis magnetometer with 12 bits resolution. Both sensors have $T = 10$ms measurement period.

The position of the robot is measured by the ultrasonic localization system. During its motion the robot was in the viewing angle of three anchors. The position information was provided with $T_P = 120$ms sampling period.

The kinematic model of omnidirectional robot in the reference frame is given by $\dot{x} = u_x,\ \dot{y} = u_y$, where u_x and u_y are the control velocities. The control algorithm along the x axis was computed using the formula $u_x = u_{dx} + K(x_d - x)$. Here x_d and $u_{dx} = \dot{x}_d$ are the prescribed position and velocity of the robot along the x axis. A control law with the same form was applied along the y axis.

The position measurements (x, y), necessary to implement the control law, was provided by the Kalman filter. The prediction step of the filter provided an estimate of the robot's position with the measurement rate ($T = 10$ms). Whenever a new position measurement arrives from the ultrasonic localization system, the update (correction) step of the Kalman filter is executed.

Figures 6 and 7 show the performances of the estimation during the control experiment. The initial position of the robot was (x_0, y_0) = (0.4m, 0.1m). The final prescribed position of the robot was $x_d = y_d = 0$m. The results show that even in the presence of significant acceleration measurement noise the state estimation works properly: the biases of the accelerometers are correctly estimated and between the position updates the robot's position is correctly determined by the predictor. In addition the components of the velocity vector are also provided by the state estimator. When new position information arrives from the ultrasonic localization system, the Kalman filter executes the position update (correction) for more precise position computation. With this measurement strategy the positioning problem of the robot can be solved with the update rate of the Inertial Measurement Unit.

IV. Conclusions

In this work we have developed an indoor localization method for mobile robots that extends the Time-of-Flight based localization with sensor fusion techniques to obtain the position of the robot with high measurement update rate, suitable for control applications. Firstly, the effect of slight anchor misplacements on the Time-of-Flight based position computation was shown. To avoid the necessity of the precise anchor mounting, an anchor position calibration method was proposed. The calibration requires a set of reference points in the robot's workspace in which the anchor-robot distances are measured. Than the anchor positions were computed by minimizing a cost function, which was formulated in function of reference point measurements. As the ultrasound based measurements can offer a relatively low update rate, the position measurement was extended with sensor fusion techniques. The sensor fusion was solved by applying a Kalman filter type estimator for which a robot model was developed. The inputs of the prediction model were generated by an Inertial Measurement Unit. Real-time experimental measurements showed that the localization system can effectively be applied for mobile robot control.

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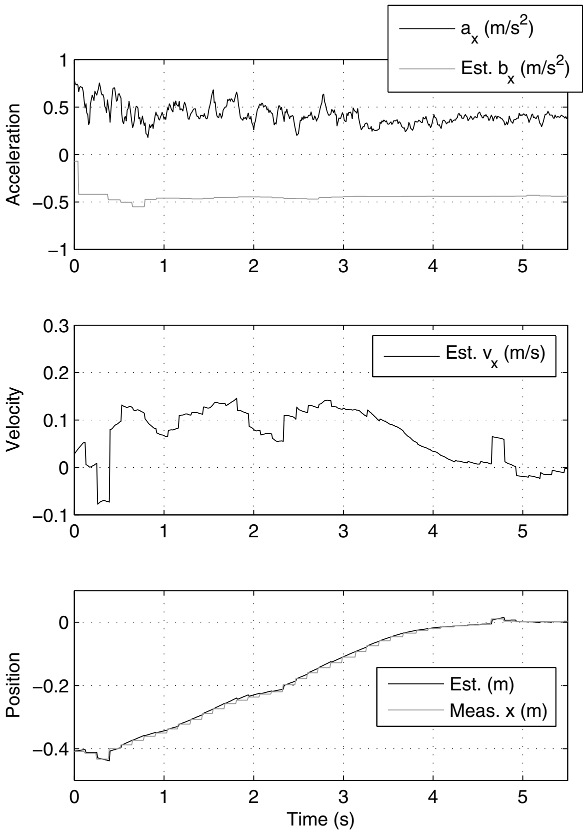

Fig. 6. Motion of the robot along the x axis

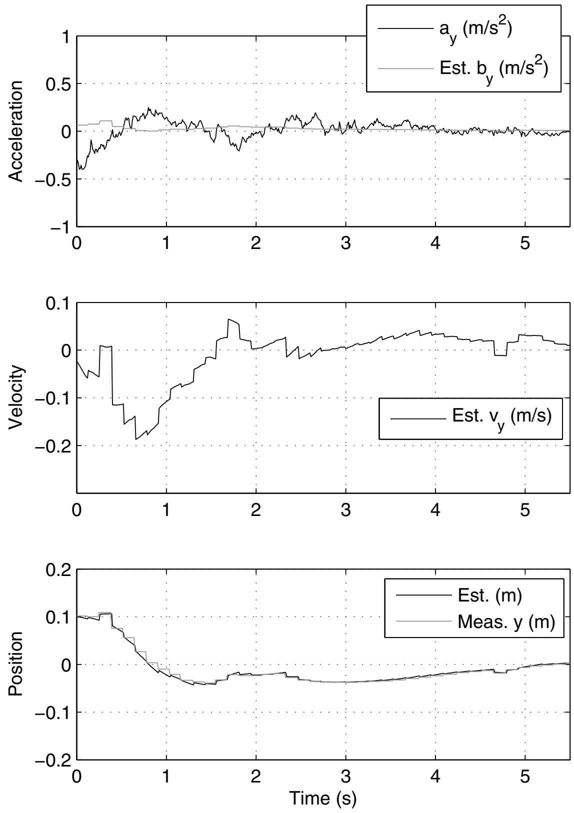

Fig. 7. Motion of the robot along the y axis

Market Introduction of Advanced Information and Communication Technologies (subproject I.6).

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