Service Robots: Design and Construction

S. M. Hosseini Monsef, Y. Maddahi and A. Maddahi

Abstract— Nowadays, the service robots have been extensively employed in homes, hospitals and industries. This article addresses the design process and experimental results of a mobile robot with differential drive mechanism which is manufactured as cleaner service robot. The goalie robot is actuated redundancy with two driving wheels and one castor wheel. The design process starts by defining the required robot parameters for the house cleaning purpose. To start the design process, first the kinematics and dynamics equations are derived in a symbolic form assuming that no slip occurs on the wheels in the self-revolute rotation. It is followed by the simulation results performed using Visual Nastran software to calculate the actuators and body characteristics. The design characteristics and control system implemented are then presented. Finally, some experiments are performed on the robot and positioning errors of robot are reduced using commonly used approach called the University of Michigan Benchmark (UMBmark) method. Furthermore, two factors, including radial error and error improvement indices, are statistically defined to measure the workability of benchmark test.

Keywords— Design process, Cleaning machine, Mobile robot, Odometry test, Service robot.

I. Introduction

DIFFERENTIALLY driven wheeled mobile robots are extensively used in robotics, since their motion is easy to program and can be well controlled. This kind of mobile robot is a mobile robot whose movement is based on two separately driven wheels. It can thus change its direction by varying the relative angular velocity of wheels and hence does not require an additional steering motion. If both the wheels are driven in the same direction and speed, the robot will go along a straight line. Otherwise, depending on the robot body angular rotation, the centre of rotation may fall anywhere in the line joining the wheels together (wheelbase). Since, the direction of robot is dependent on the velocity and direction of two driving wheels, these quantities should be sensed and controlled precisely.

There exist several factors such as design purposes and surrounding parameters which affect the design of the mobile robot directly. By using these factors, the design procedure and manufacturing system can be broken into sub-systems including design philosophy (design purposes and existing techniques), technical definitions, modeling and simulation method, quality control (QC and measurement methods) and risk assessment approaches (i.e. FMEA approach), available manufacturing technologies and test/calibration method. To maintain the consistency of the whole system, an interface layer is usually proposed to facilitate the communication between these subsystems and set the protocols that enable the interaction between the subsystems to take place. In spite of the fact that the engineers and researchers usually do their best to implement the best devices and machines to fabricate a robot, existence of some imperfections during the design, manufacturing and assembly processes are unavoidable. This usually creates some positioning errors which by using proper calibration, the accuracy of robot during motion can be increased. Calibration is defined as a set of operations that establishes, under specified conditions, the relationship between the values of quantities indicated by a measuring instrument and the corresponding values realized by standards [1]. There are several methods used for calibration of robotic systems. They include odometry [2], 3D camera error detecting [3], active beacons [4], gyroscope [5] and magnetic compasses [6].

For mobile robots, the organized test procedure remains to be one of the most important means of achieving position error reduction. For instance, benchmark series are the use of data from the movement of actuators to estimate change in position over time [7-12]. They are widely used by various types of mobile robots, whether they be legged or wheeled to estimate (not determine) their position relative to a starting location. On the other hand, the purpose of the experimental tests which are dependant to time is to build an incremental model of the motion using measurements of the elementary wheel rotations. This type of experiment can be applied to measure and reduce the errors of mobile robots which can be categorized into vehicles equipped with wheels such as general robots (automobile-type) and two DOF robots with two parallel wheels (two-wheeled) and some caster wheels (differential drive).

This paper focuses on design, modeling and calibration of a differential drive mobile robot used as vacuum cleaner robot which is motivated by a necessity for researching goals to fabricate cost-effective robot capable of cleaning the defined environments. Section 2 presents the robot measurement system and control algorithm followed by the properties of robot elements. Section 3 addresses the general kinematics and dynamic models for the differential drive wheeled mobile robots. Then, in order to validate the derived equations, the consequences of simulation are carried out in Visual Nastran Software which is presented in Section 3. Section 4 discusses the odometry approach used to measure and reduce robot systematic and non-systematic errors. The conclusions are presented in Section 5.

II. Design Explanation

A. Measurement System and Camera Positioning

In this study, the camera positioning technique is implemented to obtain the coordinates (position and

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orientation) of robot during the motion in two-dimensional space. To transform the coordinates of cameras to global reference coordinate ($X_R O_R Y_R$), the scaling technique is used which maps the position recorded by center of mass in the photo to the global position of this point. With images taken by these two fixed cameras, the position of robot is calculated and its coordinates in horizontal plane are obtained. As shown in Fig. 1, for this robot, two cameras with a certain distance from each other and test plate are looking at the robot. One of these two stationary cameras is fixed and zooms along X_G-axis (camera 1) and the second one is located in Y_G-axis direction (camera 2). Position of robot is determined in image plane and then transferred to global coordinate by using derived transformation matrices and Denavit-Hartenberg notations [13]. Indeed, the cameras take the sequences of photo from the robot and the encoders count pulses of motors and finally, the taken pictures are scaled and the robot, as a target, is recognized among other objects. Then based on the input desired path and considering the value of pulses read from incremental encoders, the amount of errors, in $X_R Y_R$ plane is calculated. Figure 1 depicts the top view of test plate considered for experiments as well as the control algorithm of position determination of mobile robot during the test.

B. Control System of Robots

The control block diagram of robot works according to diagram is shown in Fig. 2. The external sensors directly affect the robot decision algorithm. Also it denotes that the collection of forward block diagrams can minimize the robot errors in motion using external sensors. The "Jacobian Matrix" block, changes the angular displacement or velocity obtained from "Robot" block to linear displacement or velocity in order to compare them with the path parameters and calculate the error function.

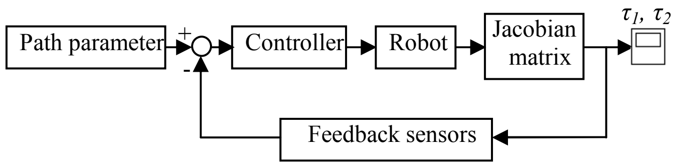

Fig. 2. Control block diagram of robot.

Figure 3 illustrates the decision algorithm of mobile robot. As shown in this figure, the external sensors influence the robot decision algorithm. Also, it noted that the microcontroller can calibrate the robot errors during the robot motion. In Fig. 4, θ_{max}, ω_{max} and τ_{max} are the maximum allowable angular displacement, angular velocity and torque of actuators which are determined by user according to the motors employed in the robot structure. $\delta\omega_i$ and $\delta\tau_i$ represent the error functions of motors angular velocities and torques (Fig. 2).

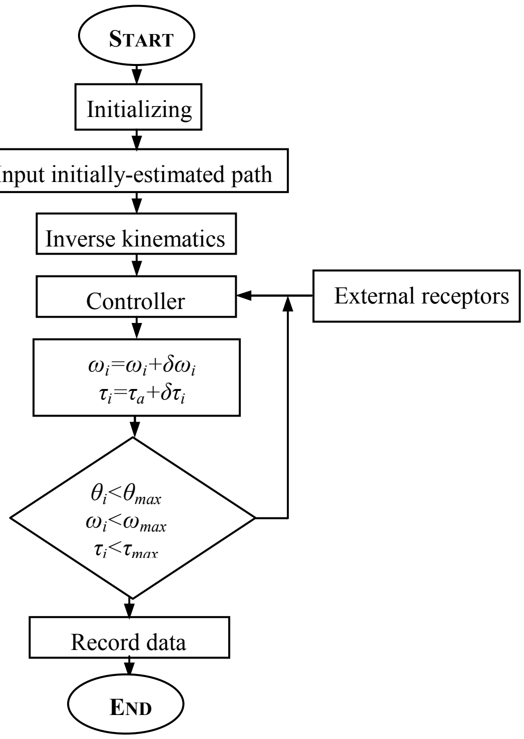

Fig. 3. Decision flow chart of robot.

C. Robot Structure

The construction of the cleaner robot consists of two driving wheels with associated gear boxes, two shafts that connect the wheels to gearbox, three sensors to detect the

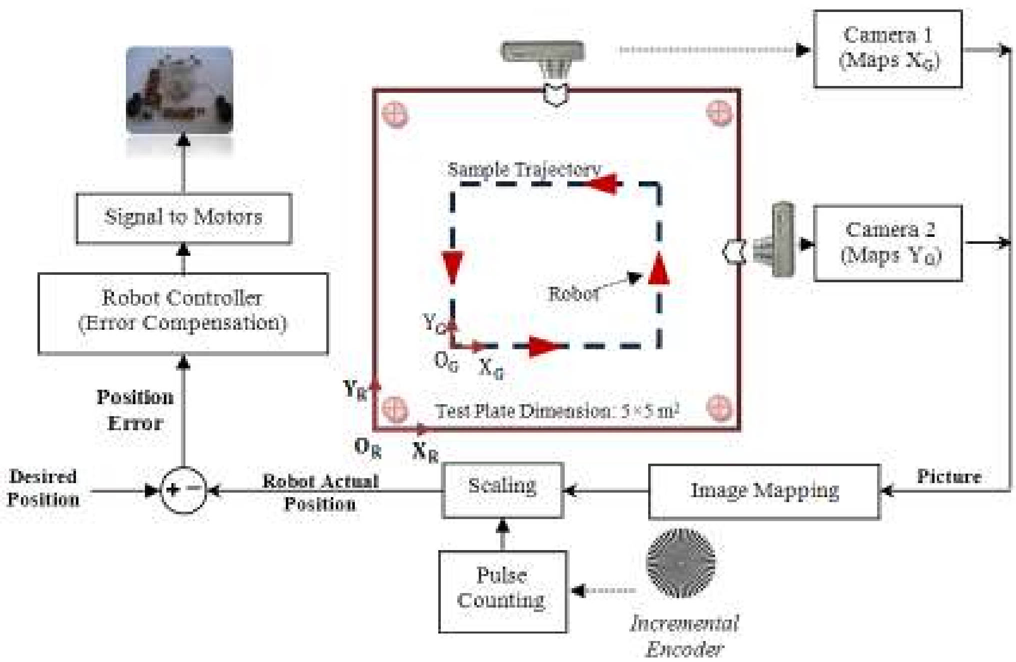

Fig. 1. Position-based control structure of robot.

collision and vacuum board as shown in Fig. 4. The vacuum cleaner works in two self-controlled and remote control modes. This robot is designed for navigation with high maneuverability on flat and low friction surfaces. Robot specifications are presented in Table I.

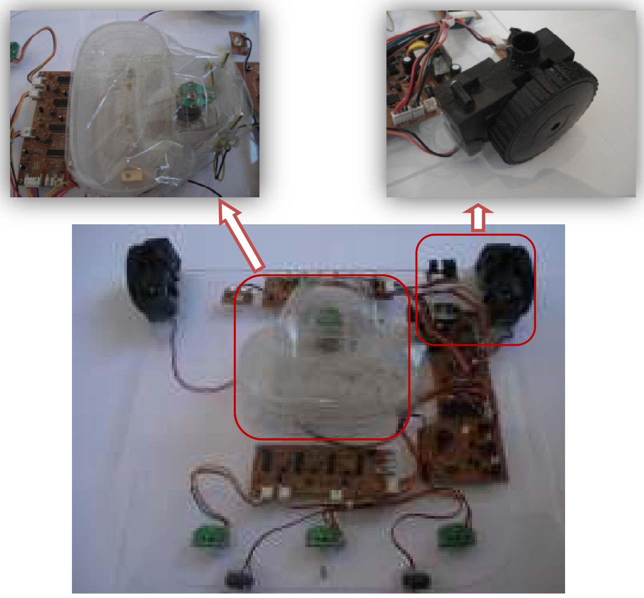

Fig. 4. Vacuum cleaner service robot.

TABLE I
ROBOT SPECIFICATION

Characteristic	Value
Maximum tool-tip speed of C. G.	3.5 m/min
Number of motors	3
Stall torque	0.28 Nm
Wheelbase	135 mm
Wheel diameter	35 mm

III. Mathematical Modeling of Mobile Robot

The general diagram of a planar differential drive mobile robot is shown in Fig. 5. Each wheel is assumed to rotate independently and without slippage. The kinematics equations of this robot are obtained using Denavit-Hartenberg notation [13]. Based on these equations, independent non-holonomic constraints due to instant no-slip wheel conditions are written as follows:

$$\dot{x}\,cos(\theta) + \dot{y}\,sin(\theta) - 0.5\left(r_R\dot{\theta}_R + r_L\dot{\theta}_L\right) = 0 \quad (1)$$

$$\theta = \left(\frac{1}{l}\right)(r_R\theta_R - r_L\theta_L) \quad (2)$$

$$\dot{x}\,sin(\theta) = \dot{y}\,cos(\theta) \quad (3)$$

where l indicates the wheelbase, x and y are the generalized coordinates of the frame with respect to the reference coordinate $\{X_R Y_R\}$, θ represents the orientation of the robot with respect to the initial position of robot at the start of motion and r is the radius of wheels. The parameters are illustrated in Fig. 5.

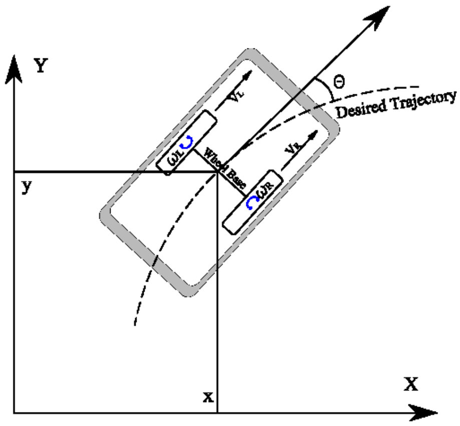

Fig. 5. Coordinate system of mobile robot.

Using the Lagrangian method, the dynamic formulations of robot are expressed by the following equations [14]:

$$M[\ddot{x}\,cos(\theta) + \ddot{y}\,sin(\theta)] + 0.5mr\left(\ddot{\theta}_R + \ddot{\theta}_L\right) = (\tau_R + \tau_L)/r \quad (4)$$

$$l\ddot{\theta} = 0.5mrl\left(\ddot{\theta}_L - \ddot{\theta}_R\right) + l(\tau_L - \tau_R)/r \quad (5)$$

where M and m are the masses of the robot and each wheel, respectively and r is the radius of wheels. Also, τ_L and τ_R are the input torques of left and right actuators, $(\dot{\theta}_R, \dot{\theta}_L)$ and $(\ddot{\theta}_R, \ddot{\theta}_L)$ denote the angular velocities and accelerations of robot motors.

In order to validate the kinematics and dynamics equations, a model of cleaner robot was analyzed using Visual Nastran software. The robot is programmed to move along different trajectories and the results were compared with the theoretical values. In this study, the small-detailed components such as electrical wires were ignored. Figure 6 shows a typical trajectory obtained using software simulation study. As can be seen, there exist some differences between the desired and actual paths. The errors are originated from this fact that in theoretical modeling, some effective parameters such as misalignment in joints and friction force are usually neglected.

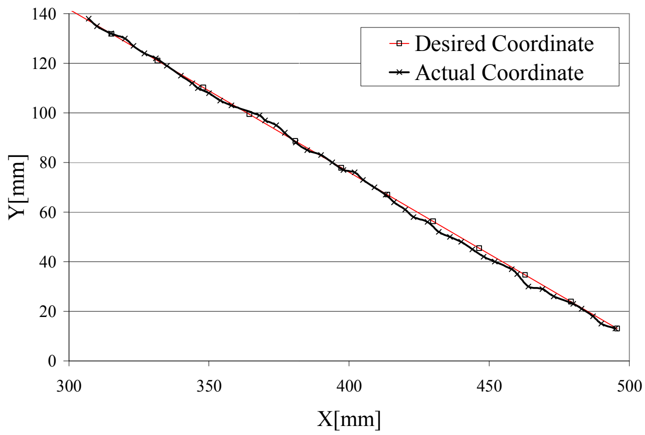

Fig. 6. Typical desired and actual trajectories.

Moreover, Fig. 7 illustrates the torques of left motor for this robot in the trajectory considered in Fig. 6. As illustrated,

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in simulation study, the robot needs extra torque to move in the defined path compared to the theoretical value of torque. For instance, as shown in Fig. 7, the torque of left motor has the maximum value of 52 Nmm while the minimum torque is about 40 Nmm.

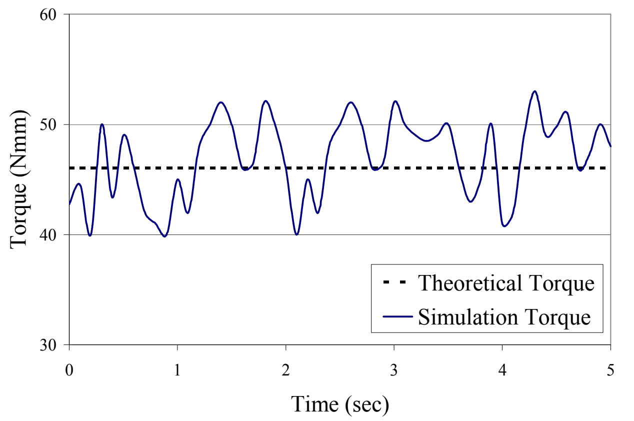


Fig. 7. Typical desired and actual torques derived for left actuator.

IV. EXPERIMETAL RESULTS

One of the methods for measuring odometry errors is benchmark series test which allows the experimenter to draw conclusions about the overall odometric accuracy of the robot. The first benchmark method applied on robot for error correction is called "UMB mark" with sub-test named "Uni-Directional square path (UDT) Test. The robot starts out at a position which is labeled "Start" and move on a 4×4m uni-directional square path. The robot is programmed to travel the four legs of the square path but because of odometry and controller errors, not precisely to the starting position [6].

Another UMBM sub-test called "Bi-Directional square path Test (BDT)". In BDT the robot is programmed to follow a 4×4 m square path in clockwise (CW) and then counter-clockwise (CCW) directions. Upon completion of the square path in each direction, the experimenter again measures the absolute position of the vehicle. Then these absolute measurements are compared to the position and orientation of the vehicle as computed from odometry data [6]. The coordinates of the two centers of gravity are computed as follow:

$$X_{cw,ccw} = \frac{1}{n}\sum_{i=1}^{n} x_{cw,ccw} \quad (6)$$

$$Y_{cw,ccw} = \frac{1}{n}\sum_{i=1}^{n} y_{cw,ccw} \quad (7)$$

where n is the number of test runs in each direction and supposed to 10 in the following experiments.

A. Error Classification

We categorized these errors into type A and type B. Type A errors are caused mostly by E_b and cause too much or little turning at the corners of the square path. The amount of rotational error in each nominal 90 turn is denoted by α and β measured in radian. Type B errors are caused mostly by the ratio between wheel diameters E_d and they cause a slight curved path instead of a straight one during the four straight legs of the square path. Because of the curved motion, the robot will gain an incremental orientation error β, at the end of each straight leg (Fig. 8).

α and β can be found from simple geometric relations.

$$\alpha = \frac{180}{n} \cdot \frac{X_{CW}+X_{CCW}}{-4L} \quad (8)$$

$$\beta = \frac{180}{n} \cdot \frac{Y_{CW}-Y_{CCW}}{-4L} \quad (9)$$

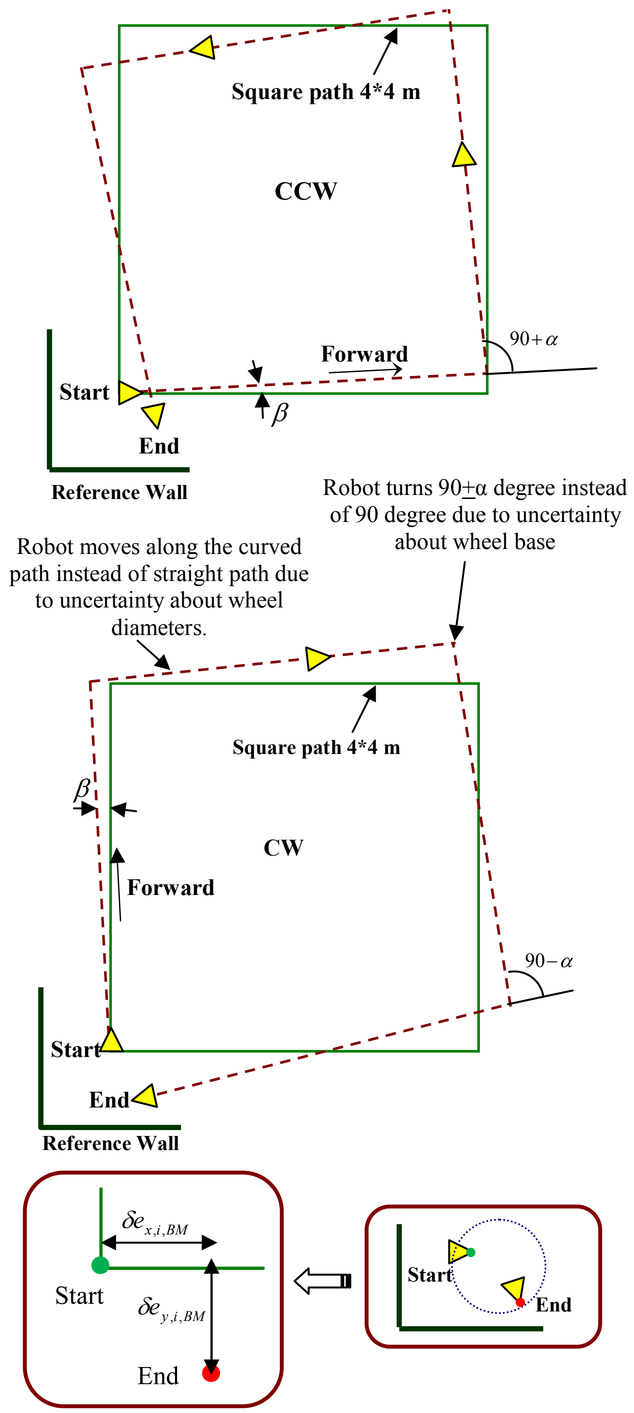


Fig. 8. UMBmark test path in CW and CCW directions.

where L is straight leg of the square path and considered 4 m for this study.

Finally, two correction factors can be defined by [7]:

$$c_L = \frac{2}{E_d+1} \tag{10}$$

$$c_R = \frac{2}{\frac{1}{E_d}+1} \tag{11}$$

Figure 9 shows the schematic of experimental results in two CW and CCW directions, before and after calibration. Also it demonstrates the contribution of two type errors (Types A and B) labeled with α and β angles.

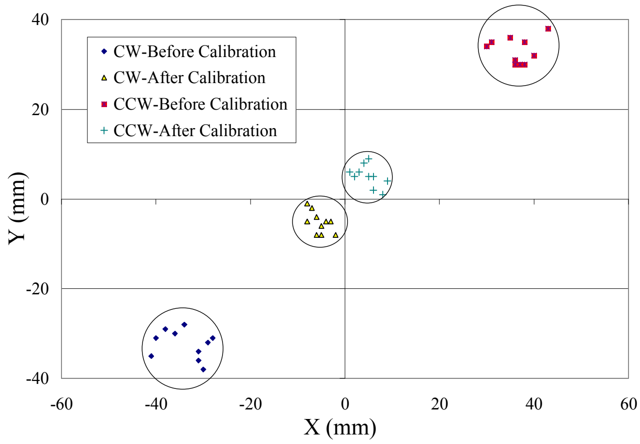


Fig. 9. Experimental results of UMBmark test.

B. Statistical Indices

To compare the robot errors during the experiments and better presentation of robots position in each trial, the radial error of robot center (δe_r) is defined as follows:

$$\delta e_r = \sqrt{(\delta e_x)^2 + (\delta e_y)^2} \tag{12}$$

where δe_x and δe_y are depicted in Fig. 8. Moreover, the mean error improvement index ($\delta \bar{r}_m$) is expressed as:

$$\delta \bar{r}_m = \left[\frac{\delta \bar{r}_{BF} - \delta \bar{r}_{AF}}{\delta \bar{r}_{BF}}\right] \times 100\% \tag{13}$$

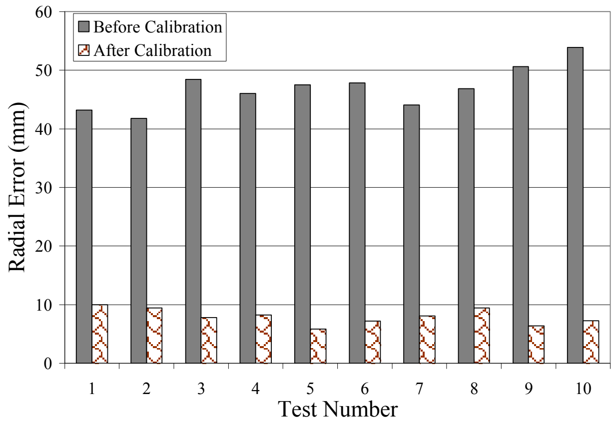
In (13), AF and BF represent the state of the measurement in after and before applying the corrective actions.

Fiugure 10 shows the radial positioning error of robot in both CW and CCW directions. As shown, in each trial, the radial errors was reduced after calibration which shows the effectiveness of the calibration method. Based on the UMBmark test results, the mean error improvement index was obtained equal to 83.0% and 84.4% for CW and CCW tests, respectively, which shows the effectiveness of calibration process.

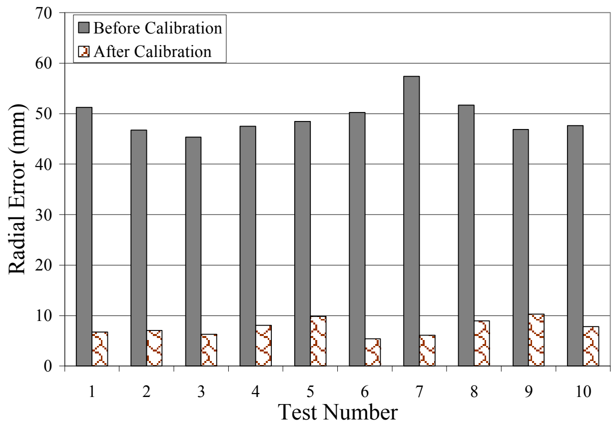
V. Conclusions

In this paper design, modeling, simulation and bechmark tests of cleaner wheeled mobile robot were presented. The focus was on explanation of modeling and design process as well as the correction of positioning errors. Using kinematics and dynamic equations, the equations of motion were derived in symbolic forms and then simulation studies were performed based on the mathematical formulations. To overcome the positioning errors, the mobile robot was tested and moved in some certain trajectories. As shown in this paper, the systematic errors were modified and reduced using UMBmark method. Using this method, the absolute measurements of errors were compared to the desired position and orientation of the robot. Specifically, the results derived from experimental analyses concede that in the mean error improvement was at least 83% in both CW and CCW directions.

As a new work, the non-systematic errors can be obtained from some tests such as UMBmark method to predict the behavior of robot in movement on the surfaces with some irregularities. The non-systematic error can be measured and reduced by designing some artificial obstacles in the test plate and performing the tests.



CCW direction



CCW direction

Fig. 10. Radial error in both CW and CCW directions, before and after calibration.

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