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INTERNAL CORRECTION OF ODOMETRY ERRORS WITH THE OMNIMATE

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ABSTRACT

This paper presents experimental results of odometric accuracy tests obtained from the first production model of an innovative mobile robot called "OmniMate." The OmniMate is an omnidirectional platform that comprises two individually controllable drive units (called "trucks") that are physically connected by a compliant linkage. The compliant linkage allows relative motion between the two trucks, thereby allowing momentary velocity discrepancies between the two trucks, which would result in wheel slippage if the trucks were linked rigidly. A linear encoder measures the momentary relative distance between the two trucks, and two rotary encoders measure the relative angle between the two trucks and the compliant linkage. Data from these three so-called "internal" encoders, combined with the data from the four wheel encoders in the system, allow for the implementation of a unique odometry error correction method developed earlier at the University of Michigan. Experimental results presented in this paper show that the OmniMate is likely the mobile platform with the most accurate odometry-based positioning system demonstrated to date.

I. INTRODUCTION

The OmniMate, shown in Figure 1 is a new, commercially available mobile robot made in collaboration between HelpMate Robotics Inc. (HRI — formerly TRC) and the University of Michigan (UM). Based on technologies developed at UM and demonstrated first on UM's multi-Degree-of-Freedom (MDOF) "CLAPPER" platform, the OmniMate provides unique odometry error correction as well as fully omnidirectional motion capabilities. HRI redesigned the mechanical components of the CLAPPER, resulting in substantially improved ruggedness and a completely flat loading deck for the end-user's application.

One of the OmniMate's most exclusive and desirable features is its ability to reduce odometry errors significantly. This ability is based on two patented UM inventions: the *compliant linkage and Internal Position Error Correction*.

The compliant linkage is a unique design feature that eliminates the excessive wheel slippage found in other MDOF mobile platforms. Such wheel-slippage results when momentary controller errors cause inevitable discrepancies between the drive- and steer-velocities of the wheels. Wheel slippage necessarily leads to large odometry errors. The OmniMate avoids this problem with the compliant linkage, which absorbs momentary controller errors without wheel slippage. Details about the compliant linkage design are given in [Borenstein 1995a].

Internal Position Error Correction (IPEC) is a novel method with which two collaborating mobile robots mutually correct each other's odometry errors. The two LabMate "*trucks*" that form the basis of the OmniMate are such two collaborating mobile robots. A linear encoder mounted on the compliant linkage and two rotary encoders built into the joints that connect the trucks with the platform provide the data needed to measure the relative position between the two trucks with great accuracy. Details about the IPEC method are given in [Borenstein, 1995b].

Figure 1: The OmniMate is based on two TRC LabMate "trucks," connected by a compliant linkage.

II. MEASURING ODOMETRY ERRORS

When trying to measure and reduce odometry errors, it is important to understand the distinction between "systematic" and "non-systematic" odometry errors. This is because each one of these two groups affects mobile platforms differently, their remediation differs, and, most important, both groups require different measuring techniques in order to obtain meaningful and comparable experimental data. We categorize odometry errors as follows:

- *Systematic errors*
  - Unequal wheel diameters
  - Average of both wheel diameters differs from nominal diameter
  - Misalignment of wheels
  - Uncertainty about the effective wheelbase (due to non-point wheel contact with the floor)
  - Limited encoder resolution
  - Limited encoder sampling rate

- *Non-systematic errors*
  - Travel over uneven floors
  - Travel over unexpected objects on the floor
    - ◊ Wheel-slippage due to:
    - ◊ slippery Floors
    - ◊ over-acceleration
    - ◊ fast turning (skidding)
  - external forces (interaction with external bodies)
  - internal forces (e.g., castor wheels)
  - non-point wheel contact with the floor

A. Measuring Systematic Odometry Errors

To measure systematic odometry errors in differential drive mobile robots, Borenstein and Feng [1995; 1996] introduced the "bi-directional square path test." This test, originally developed at UM, is called "UM Benchmark test" or just "UMBmark." We will summarize the test procedure here, since the experimental results in Section III were obtained from running the UMBmark test.

Figure 2 shows a typical setup for conducting the UMBmark test. The robot starts out at a position x_0, y_0, θ_0, which is labeled START. The starting area should be located near the corner of two perpendicular walls. The walls serve as a fixed reference before and after the run: measuring the distance between three specific points on the robot and the walls allows accurate determination of the robot's absolute position and orientation.

The robot is programmed to traverse the four legs of the square path. The path will return the vehicle to the starting area, but, because of odometry and controller errors, not precisely to the starting position. Since this test aims at determining odometry errors and not controller errors, the vehicle does not need to be programmed to return to its starting position precisely — returning approximately to the starting area is sufficient. Upon completion of the square path, the experimenter again measures the absolute position of the vehicle, using the fixed walls as a reference. These absolute measurements are then compared to the position and orientation of the vehicle as computed from odometry data. The result is a set of *return position/orientation errors* caused by odometry and denoted εx, εy, and $\varepsilon\theta$:

$$\begin{aligned} \varepsilon x &= x_{abs} - x_{calc} \\ \varepsilon y &= y_{abs} - y_{calc} \\ \varepsilon\theta &= \theta_{abs} - \theta_{calc} \end{aligned} \qquad (1)$$

where

εx, εy, $\varepsilon\theta$ — Position and orientation errors due to odometry.

x_{abs}, y_{abs}, θ_{abs} — Absolute position and orientation of the robot.

x_{calc}, y_{calc}, θ_{calc} — Position and orientation of the robot as computed from odometry.

The path shown in Figure 2 comprises of four straight line segments and four pure rotations about the robot's centerpoint, at the corners of the square. The robot's end position shown in Figure 2 visualizes the odometry error.

The UMBmark test requires that the square path experiment be performed in both clockwise and counter-clockwise direction, typically five times in each direction.

The result of the UMBmark test might look similar to the one shown in Figure 3 which shows actual results with an uncalibrated LabMate robot (we removed the manufacturer's calibration data for this experiment). In this

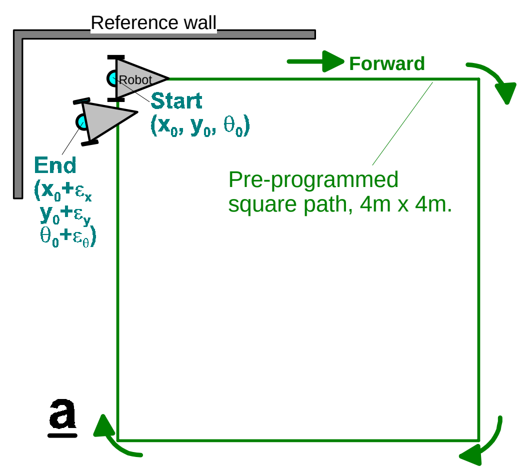

Figure 2: The square path experiment.

experiment the robot was programmed to follow a 4×4 m square path, starting at (0,0). The stopping positions for five runs each in clockwise (cw) and counter-clockwise (ccw) directions are shown in Figure 3. Note that Figure 3 is an *enlarged view* of the target area.

Borenstein and Feng [1996b] defined a single numeric value that expresses the odometric accuracy of a vehicle with respect to systematic errors. This value is derived from the coordinates of the two centers of gravity (c.g.) as shown in Figure 3. The centers of gravity can be computed easily from Figure 3 as

$$x_{c.g.,cw/ccw} = \frac{1}{n}\sum_{i=1}^{n} \varepsilon\, x_{i,cw/ccw}$$

and (2)

$$y_{c.g.,cw/ccw} = \frac{1}{n}\sum_{i=1}^{n} \varepsilon\, y_{i,cw/ccw}$$

where n = 5 is the number of runs in each direction.

The absolute offsets of the two centers of gravity from the origin are denoted $r_{c.g.,\,cw}$ and $r_{c.g.,\,ccw}$ (see Figure 3) and are given by

$$r_{c.g.,cw} = \sqrt{(x_{c.g.,cw})^2 + (y_{c.g.,cw})^2}$$

and (3)

$$r_{c.g.,ccw} = \sqrt{(x_{c.g.,ccw})^2 + (y_{c.g.,ccw})^2}$$

The larger value among $r_{c.g.,\,cw}$ and $r_{c.g.,\,cw}$ is defined as the *measure of odometric accuracy for systematic errors*

$$E_{max,syst} = \max(r_{c.g.,cw}\,;\, r_{c.g.,ccw}) \quad (4)$$

One should note that the UMBmark procedure works just as well with rectangular, oval, or similarly-shaped paths. What is of interest is that the paths have a total of at least 360° of rotation and a total path length of at least 4×4 = 16 meters.

B. Measuring Non-systematic Errors

Borenstein and Feng [1996] explained that it is difficult (perhaps impossible) to design a generally applicable quantitative test procedure for *non-systematic* errors. However, they proposed an easily reproducible test that allows to compare the *susceptibility* to non-systematic errors between different vehicles. This test, called the *extended UMBmark*, uses the same bi-directional square path as UMBmark, but, in addition, introduces artificial bumps. Artificial bumps are introduced by means of a common, round, electrical household-type cable that has a diameter of about 9 to 10 mm. Its rounded shape and plastic coating allow even smaller robots to traverse it without too much physical impact. In the *extended UMBmark* test the cable is placed 10 times under one of the robot's wheels, during motion.

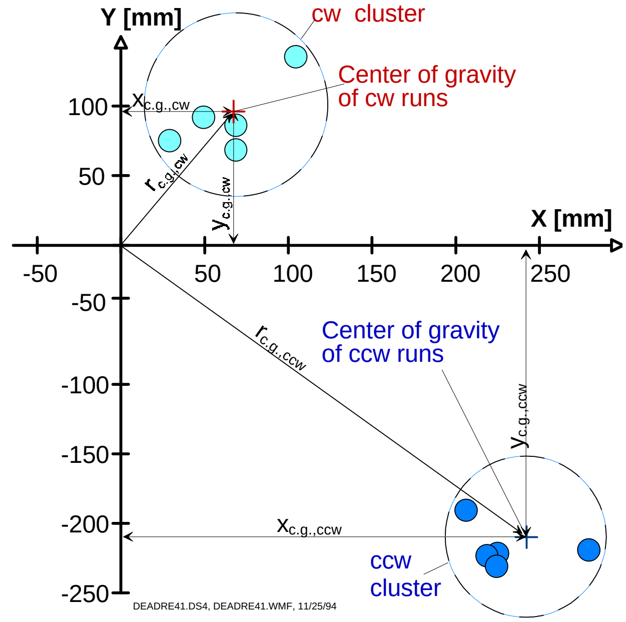

Figure 3: Typical results from running the UMBmark test with an uncalibrated differential-drive robot on a reasonably smooth concrete floor.

Borenstein and Feng [1996] further show that the return *position* error resulting from the extended UMBmark test is *not* a good measure for the susceptibility of a vehicle to non-systematic errors. This is because the resulting return position errors vary with the location at which each bump was introduced. For example, 10 bumps introduce at the very beginning of the square path will cause almost no return position error at all. For this reason, Borenstein and Feng [1996] propose that for comparison purposes one should consider only the return *orientation* error, which does not depend on the position at which the bumps were introduced.

III. EXPERIMENTAL RESULTS

In this section we present the experimental results of the odometric accuracy tests that were performed according to the UMBmark and extended UMBmark tests outlined in Section 3. During these tests the OmniMate was equipped with a so-called "sonar calibrator," a device that uses three ultrasonic sensors to measure the distance between three points on the robot to two L-shaped walls. With the sonar calibrator the absolute position of the vehicle can be measured at the beginning and end of each run fully automatically, and, subsequently, the onboard computer can compute the return position and orientation errors (εx, εy, εθ). Using the sonar calibrator the UMBmark test with multiple laps can be run fully automatically in each direction. Following is a brief summary of the actually employed test procedure, which differed slightly from the formal UMBmark procedure.

A. Summary of the Test Procedure

Experiments were performed in sets of 10 laps along a rectangular path with rounded corners. The total length of the rectangular path (i.e., for one lap) was 18.5 meters (60 ft) and the platform performed a total of four 90°-turns in each lap. Four sets of fully automatic runs were performed:

Set 1: 10 laps with IPEC, cw

Set 2: 10 laps with IPEC, ccw

Set 3: 9 laps without IPEC, cw

Set 4: 9 laps without IPEC, ccw

In each of the four sets the first five laps were run without bumps (i.e., on marginally smooth concrete floor). The remaining laps were run with artificial 9-mm diameter bumps placed under the OmniMate's wheels, as follows:

Lap #6: 20 bumps under the inside wheel, front truck

Lap #7: 20 bumps under the outside wheel, front truck

Lap #8: 10 bumps each under the inside wheels of the front truck and the rear truck, for a total of 20 bumps).

Lap #9: 10 bumps each under outside wheels of the front truck and the rear truck, for a total of 20 bumps.

Lap #10: 20 bumps placed randomly under all wheels (this test was omitted for runs without IPEC).

Note that the tests performed in Laps #6 through #10 differ from the procedure originally described as the extended UMBmark in Borenstein and Feng [1996]. The reason for this change is that the original extended UMBmark test was designed for basic differential-drive mobile robots. Although the extended UMBmark test *could* be performed with the OmniMate without modification, we noticed during experimentation with the OmniMate that skeptical observers often asked if the placement of bumps under the wheels of the *other* truck would have any negative impact on the odometry error correction. To diffuse these concerns we modified the “with-bumps” procedure to include bumps under both the left and right wheels of the front- and the rear truck. Lap #10, with bumps placed *randomly* under all four wheels, was omitted in the runs without error correction, because the effects of random bumps cancel each other out and thus produce a meaningless result.

As a consequence to this change in the testing procedure it is not meaningful to compute the *average* return orientation error as prescribed by Borenstein and Feng [1996]. Instead, we consider the *worst* orientation error from among any one of laps #5 through #10 as the representative worst error of runs with bumps. For completeness, we also note the worst position error, although this data is not meaningful for comparison purposes.

B. Data Collection

Our experiments were performed under certain conditions and premises that were not explicitly addressed by the original UMBmark procedures. Here is a summary:

- Each set of 10 laps with error correction was performed fully automatically under computer control. Thus, the 10 laps in each set were consecutive runs, not a selection of hand-picked runs. Furthermore, the two sets of cw and ccw runs were run immediately one after the other, without changing any of the robots parameters between sets.
- Laps #5 through #9 of the “no-error correction,” “with bumps” runs were made under human operator joystick control, since the OmniMate would otherwise exit the experimentation area due to the large position errors.
- We deviated from the prescribed extended UMBmark protocol by placing not 10, but rather 20 bumps under the robot’s wheels to produce more noticeable errors and to highlight the unique error resilience of the OmniMate.

An MDOF vehicle like the OmniMate can be programmed to execute a rectangular path in an infinite number of poses (sets of momentary position and orientation). For example, the robot can be programmed to move straight forward for one leg of the rectangular path, then rotate on the spot through 90°, then move straight forward again for the second leg, and so forth. Alternatively, the robot can perform the 90°-turns in a “follow-the leader”-type mode, in which the rear truck tries to follow the exact same trajectory of the front truck. For our experiments we chose yet a different mode, in which we programmed the OmniMate to imitate the kinematic behavior of a car: the rear truck (similar to the rear axle of a car) loosely faced in the direction of the center-point of the front truck. This configuration was the easiest to program and involved the fewest parameters that might have influenced the IPEC error correction system. In informal experiments we ran the robot in other, arbitrary modes of turning under R/C joystick control. The resulting odometry errors were generally slightly worse, but not significantly so. Figure 4 shows the experimental set-up used in all tests. Also shown are the traces of the centerpoints of the front and rear truck as recorded and plotted by the onboard computer for one particular lap. In each lap the robot started and finished in the area labeled "Start/Finish" Figure 4. To produce the rectangular path we pre-programmed the four corner points as via-points for the OmniMate's "*pass_by*" command. The *pass_by* command implies that another motion command will follow and, to produce smooth, continuous motion, does not stop the robot at the *pass_by* location. Instead, the control program executes the next motion command as soon as the centerpoint of the front truck comes within a tolerance range of 50 cm (20 in) from the via-point. This is why in Figure 4 the trace of the front truck doesn't touch the via-points. The four via-points don't form a rectangle exactly, since the exact shape of the trajectory is irrelevant in the UMBmark test. What is important is that the robot turns through a total of 360° in each lap. The somewhat irregular placement of the via points was mandated by the need to keep the robot as far away from obstacles as possible, to allow for the large path deviations in runs without error correction.

The sonar calibrator, with two sonars installed at the corners of the left side and one sonar in the rear of the OmniMate, uses the four stationary walls as absolute references. For cw runs the walls on the left-hand side and bottom of Figure 4 are used, while for ccw runs the walls at the center and top of Figure 4 serve as absolute references. Because of the relatively large distance between the rear sonar and the respective rear walls, measurements in y-direction are less accurate, on the order of ±3 cm (1.2 in). The accuracy of the side-facing sonars is better, on the order of ±3 mm (0.12 in), because of the shorter distance to the respective reflector walls. Using the two side-facing sonars, the sonar calibrator can determine the robot's true orientation with respect to the reflector walls with an accuracy of about ±0.1°.

At the beginning of each lap the OmniMate determined its absolute position with the sonar calibrator and initialized the odometry system with that data. Traveling at a maximum speed of 0.3 m/s (11.8 in/s) during straight segments, the robot slowed down near via-points. Then, when within the tolerance range of 50 cm (20 in) and while still moving, the robot would begin to align itself with the direction to the next via-point and, simultaneously, aim its front truck toward that new via-point. At the end of each run the sonar calibrator measured the robot's actual position and compared the result to the vehicle's internal position, based on odometry. The error, expressed as εx, εy, and $\varepsilon\theta$, was automatically recorded, the internal position (i.e., odometry) was reset to the actually measured one, and the robot continued with the next lap.

C. Test Results

The quantitative results of our tests are summarized in Table I. Graphical representations of these results are shown in Figures 5 through 8.

Table I includes results required by the UMBmark test and some additional results that are not required by the UMBmark test. As mentioned before, the UMBmark procedure is designed to allow developers to compare the performance of different robots, or to help developers fine-tune the odometry parameters of a single robot. However, we recognize that end-users of mobile robots may want to know the worst accuracy of a robot for a given test. These worst-accuracy results are printed on shaded background in Table I.

It is interesting to note that for the variety of results shown in Table I the IPEC error correction method provides consistently one order of magnitude greater accuracy than that obtained from running the same vehicle without IPEC. The graphical representation of our results in Figures 5 through 8 confirms this observation visually.

Table I: Summary of numeric results. Results printed on shaded background are not required by the UMBmark test but are included to demonstrate the *worst* accuracy of the OmniMate with and without IPEC error correction in each type of experiment.

Worst of cw and ccw runs:	$r_{c.g.}$ [mm]		$r_{individual}$ [mm]		$\varepsilon\theta_{\lvert avrg \rvert}$ [deg]		$\lvert\varepsilon\theta_{individual}\rvert$ [deg]		$\lvert\varepsilon\theta_i^{nonsys} - \varepsilon\theta_{avrg}^{sys}\rvert$ [deg]	
	With IPEC	Without IPEC	With IPEC	Without IPEC	With IPEC	Without IPEC	With IPEC	Without IPEC	With IPEC	Without IPEC
No bumps	25	205	30	275	0.3	3.7	0.4	5.3	Not meaningful	
With bumps	Not meaningful		44	465	0.8	8.0	1.3	11.3	1.2	13.3

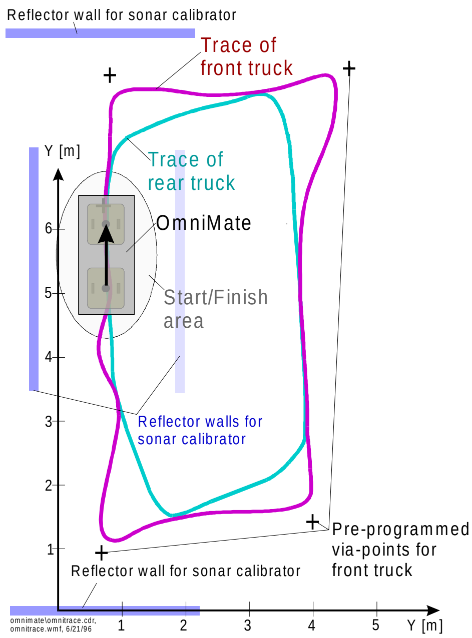

Figure 4: Experimental setup for the OmniMate experiments. Traces of the front and rear trucks as recorded and plotted by the onboard computer are also shown.

IV. CONCLUSIONS

This paper presents results of odometric accuracy tests performed with a new, commercially available mobile robot called "OmniMate." The OmniMate provides true omni-directional (i.e., holonomous) motion and its kinematic design eliminates the excessive wheel-slippage often associated with omni-directional platforms. One of the OmniMate's most unique features is its ability to employ *Internal Position Error Correction* (IPEC) to dramatically improve its odometric accuracy.

Using rigorous test procedures, called "UMBmark" and "extended UMBmark," the OmniMate and its implementation of IPEC were carefully tested at our lab. The results show an improvement of one order of magnitude in odometric accuracy over the accuracy of a conventional odometry system.

The foremost strength of the IPEC method is its ability to reliably and accurately detect and correct *non-systematic* odometry errors such as those caused by bumps, cracks, or other objects on the floor. In conventional mobile robots the encounter of one or more such irregularities could have a catastrophic effect on the performance of the robot, i.e., cause the mission to fail completely. With the OmniMate and IPEC, on the other hand, floor irregularities have virtually no detrimental effect on the odometric accuracy of the vehicle at all.

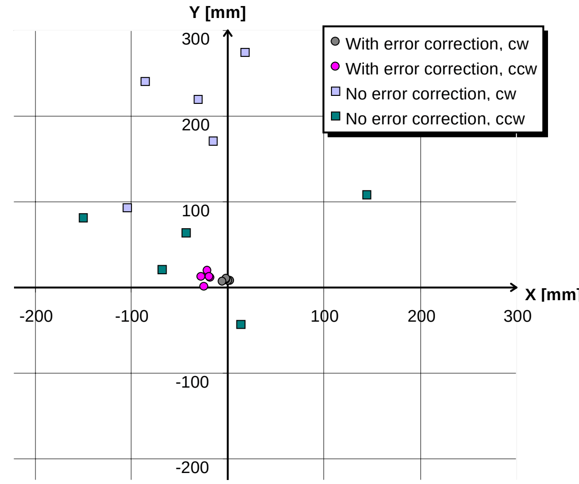

Figure 5: OmniMate return position errors after completing the 18.5 m rectangular path of Figure 4 on a smooth concrete floor *without* bumps.

Figure 6: OmniMate return orientation errors after completing the 18.5 m rectangular path of Figure 4 on a smooth concrete floor without bumps.

Video footage o f the OmniMate as well as references cited in this paper are available on CD-ROM and can be requested from the author [Borenstein, 1996].

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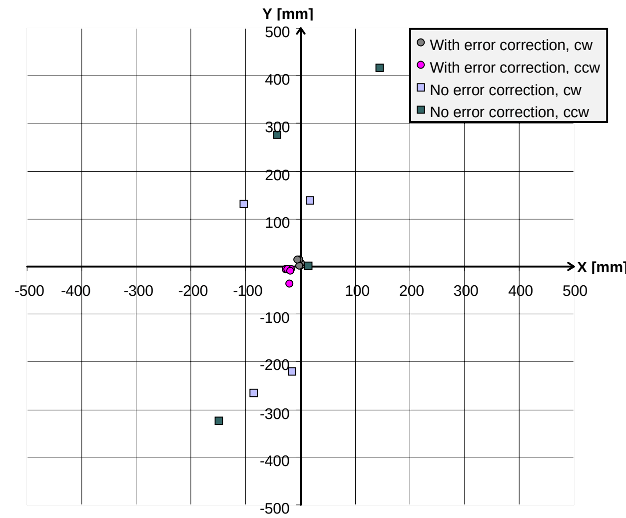

Figure 7: OmniMate return orientation errors after completing the 18.5 m rectangular path on a smooth concrete floor with 20 artificial bumps.

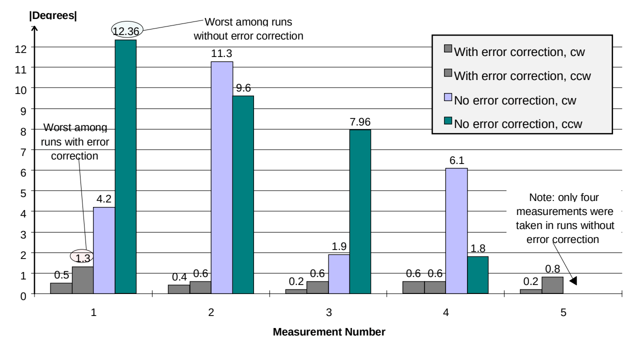

Figure 8: OmniMate return position errors after completing the 18.5 m rectangular on a smooth concrete floor with 20 artificial 9-mm bumps.