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The OmniMate Mobile Robot – Design, Implementation, and Experimental Results

by

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ABSTRACT

This paper introduces a new mobile robot for hazardous environments and for industrial applications. The robot, called *OmniMate,* has full omnidirectional motion capabilities, can detect and correct odometry errors without external references, and offers a large 183×91 cm (72×36”) loading deck. A patented, so-called *compliant linkage* avoids the excessive wheel slippage often found in other omnidirectional platforms.

This paper provides an overview over the mechanical and kinematic design of the robot, as well as over the complex, three-level onboard control system. Also explained is the unique, patented odometry error correction method, called *Internal Position Error Correction* (IPEC). The foremost advantage of the OmniMate with IPEC over conventional mobile robots is that the OmniMate’s odometry is almost completely insensitive to even severe irregularities of the floor, such as bumps, cracks, or traversable objects. With conventional mobile robots such irregularities can cause large odometry errors with potentially catastrophic effects (i.e., mission failure), thus mandating frequent external registrations to correct for possible odometry errors. The OmniMate, on the other hand, can travel reliably over larger distances than conventional mobile platforms, thus requiring much fewer external corrections.

1. INTRODUCTION AND BACKGROUND

Omnidirectional vehicles, also called *Multi-Degree-of-Freedom* (MDOF) vehicles, have great advantages for moving in tight areas; they can crab sideways, turn on the spot, and follow complex trajectories. MDOF vehicle designs have been attempted many times, with relevant patents dating back to the 1920's. For strictly manual control or when following a guide path embedded in the floor, many of these designs work adequately. However, under computer control, dynamic errors in wheel orientation and velocity can result in instabilities, excessive wheel slippage, and consequently large position errors in odometry computations.

During the past five years work at the University of Michigan’s (UM) Mobile Robotics Lab resulted in the design of an MDOF vehicle with a *compliant linkage* that overcomes the excessive wheel slippage found in earlier MDOF vehicles. In further work UM used this vehicle to implement a unique method for the detection and correction of odometry errors. Later, researchers at Oak Ridge National Lab, who were in need of a very accurate mobile platform with a large loading area ordered a ruggedized version of the UM vehicle. This vehicle was built in a collaborative effort between UM and HelpMate Robotics Inc. (HRI – formerly TRC) [HRI], the maker of the widely used *LabMate* mobile robot. Thus was born the *OmniMate*.

2. THE OMNIMATE DESIGN

The OmniMate is a Multi-degree-of-Freedom (MDOF) mobile platform with full omnidirectional motion capabilities. The vehicle is made from two differential-drive *LabMate* platforms (here called “trucks”) as shown in Figures 1 and 2. the front truck can rotate around rotational joint A, which is attached to the bottom of a rigid loading deck. The rear truck can rotate around rotational joint B, which is connected to a slider assembly. The slider assembly can linearly move along slider bars that are attached at their ends to the bottom of the loading deck. Rotary encoders mounted on joints A and B measure the relative rotation between each truck and the loading deck, while a linear encoder measures the position of the linear slider assembly, from which the distance between the center points of the two trucks can be computed. As will be explained in Section 2.1, additional joints not shown in Figure 2 allow for limited pitch, roll, and yaw motion of the trucks relative to each other, to accommodate uneven ground.

Because of the linear slider the two trucks can freely move relative to each other. This patented UM design is called “compliant linkage.” The purpose of the compliant linkage is to absorb the inevitable momentary controller errors that can cause wheel slippage in conventional, rigidly-built MDOF mobile robots, as reported by West and Asada [1992], or Pin and Killough [1994].

Figure 1 shows that the OmniMate design provides a completely flat, 180×90 cm (72×36 in) loading deck that is available exclusively for the end-user’s payload. A 24-Volt auxiliary battery pack, designed to power user-installed equipment and the onboard control computer, is installed underneath the loading-deck. This battery pack can provide 300 Watts for 6 hours. In addition, each of the trucks is individually powered by its own 24-Volt battery pack installed inside of each truck. Control and feedback signals to and from the trucks are passed through slip-ring assemblies. The onboard motion control system runs on a 486/100 MHz PC-compatible single-board computer.

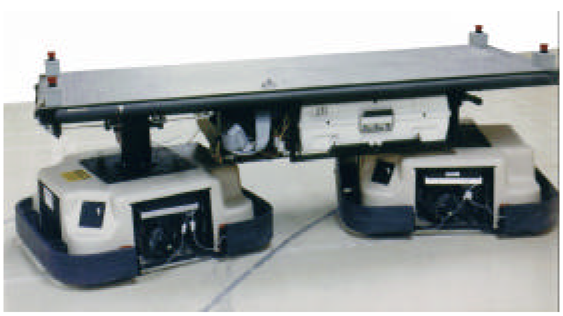

Figure 1: The OmniMate is based on two TRC LabMate "trucks" connected by a compliant linkage. This design provides a free 180×90 cm (72×36-in) loading deck for up to 114 Kg (250 lbs) of payload.

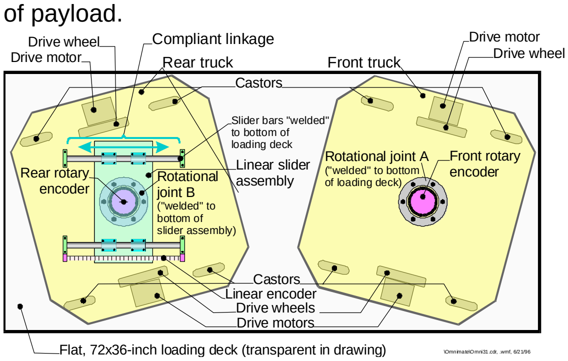

Figure 2: Schematic of the OmniMate mobile robot.

2.1 Kinematic design

The two modified LabMate trucks used in the OmniMate are individually rated at a load capacity of at least 200 kg (440 lbs). With two trucks supporting the payload, the total load capacity is 400 kg (880 lbs). After adding the OmniMate vehicle frame and auxiliary battery pack, there remains a user payload of about 114 kg (250 lbs).

The individual LabMate trucks have their two drive wheels on a separate frame which is spring loaded to provide for each wheel to move up and down and maintain a constant force on the floor surface. This design makes the trucks extremely stable and allows them to traverse uneven surfaces. However, in the OmniMate design, the entire vehicle must provide the same capability: each truck must independently be able to move vertically and to rotate along the pitch and roll axes. The yaw axis, of course, provides the desired agility for the whole vehicle.

The kinematics of the overall vehicle design concept is shown in Figure 3. A three point mount for the vehicle frame is used as the correct kinematic design. This constrains three degrees of freedom, leaving the three degrees of motion desired. The rear truck, with the linear bearings, is attached at two points, with freedom to rotate along the axis through those two points. The front truck is attached at a single point with a universal joint.

To improve the support of the front truck for off-center loads and for roll motions, two compression springs are added to the front support, as widely spaced as possible over the front truck. The two rear truck pivots are fixed to a plate which in turn is supported on the linear bearings with a three point support, two pillow blocks on one rail

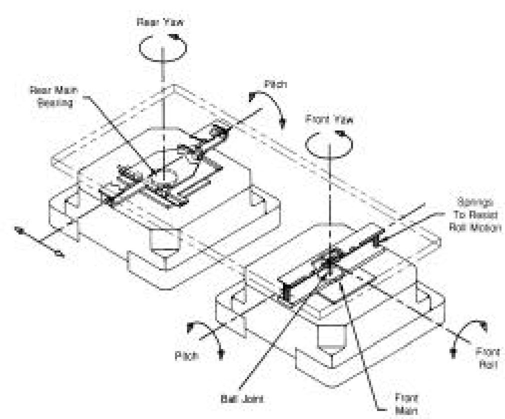

Figure 3: The OmniMate’s kinematic design.

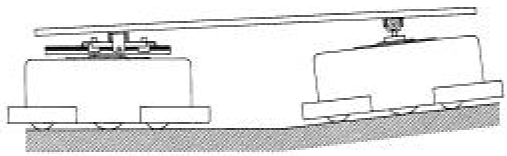

Figure 4: Pitch motion of the rear truck is accommodated in the rotational axis through the two points of suspension, and pitch of the front truck is accommodated at the universal joint.

and one on the other. There is no over-constraint in any of these mountings.

Pitch motion of the rear truck is accommodated in the rotational axis through the two points of suspension, and pitch of the front truck is accommodated at the universal joint as shown in Figure 4.

Roll motion of the rear truck will result in roll motion of the vehicle bed; roll motion of the front truck is accommodated at the universal joint, with limits imposed by the compression springs outboard of the joint. Figure 5 shows this capability.

2.2 Other design considerations

Each truck is fitted with a rotational joint constructed from a ring bearing with a clear internal diameter of over 7 cm (2.75 in) . That bearing supports a cylindrical housing within which are mounted a slip ring assembly and an incremental encoder. The slip rings are instrument rated and do not carry power for the motors; each LabMate has its own batteries to power the motion of the vehicle while the vehicle frame carries an additional set of batteries for the vehicle controls and the user payload.

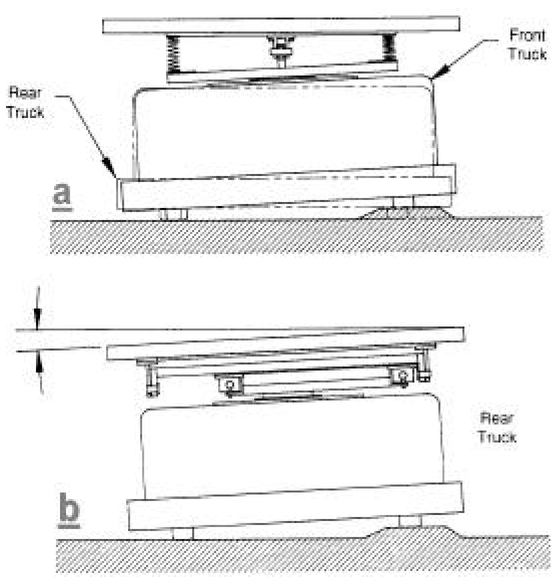

Figure 5: a) Front View: The front truck accommodates roll motion at the universal joint. B) Rear View: Roll motion of the rear truck passes on to the loading deck.

With this design, the trucks are free to rotate continuously under the vehicle frame. The central vehicle control monitors the angle of rotation from the rotary encoder and also monitors the wheel rotations from the encoders on each of the drive wheels.

The slip ring carries motor encoder and bumper data from the trucks to the central control and PWM servo commands to the power amplifiers in each truck. Additional sensor and emergency-stop wiring circuits are also accommodated with the slip ring assembly.

3. THE OMNIMATE CONTROL SYSTEM

The onboard computer controls and coordinates the motion of the two trucks in a user-transparent manner. This means that the user (or a user-written high-level control program) must prescribe the desired translation and rotation of the vehicle only with respect to the loading-deck, without worrying about the motion of the two trucks that would result in the desired motion of the loading-deck.

Another function of the control system is to perform the *Internal Position Error Correction* (IPEC), which is capable of detecting and automatically correcting odometry errors caused by bumps, cracks, or other irregularities on the floor. The IPEC function is described in Section 4, while Section 5 presents some experimental results.

The control system comprises three levels, as shown in Figure 6. The function of each level is discussed below.

3.1 The truck-level controller

At the lowest level of the controller hierarchy is the truck-level controller. The purpose of this controller is to maintain the velocities of each drive wheel, according to reference velocities prescribed by the vehicle-level controller. The truck level controller has an inner velocity feedback loop, which uses the commercially available, programmable *HCTL-1100* motion controller chip [HP]; one for each motor.

The outer loop of the truck-level controller is a modified implementation of the cross-coupled controller developed earlier by Feng et al. [1993] for accurate control of differential drive mobile robots. The purpose of cross-coupling is to maintain an accurate ratio between the velocities of the two drive motors in a differential drive vehicle. The overall effect of the cross-coupled control is the elimination of steady-state orientation errors of a truck, while allowing steady-state errors in the translational velocity of the truck center. This error is of less concern, since it is detected and corrected by the vehicle-level controller.

3.2 The vehicle-level controller

The vehicle-level controller is the central element in our system; its task is to minimize deviations Δl from the nominal link-length L (i.e., the length of the *compliant link* that connects the two trucks). The link-length changes as a function of the speed of each truck ***and*** its orientation relative to the link. This dual dependency creates a difficulty that can be visualized by considering the following two extreme cases:

Case a: both trucks are aligned longitudinally – in this case, the link-length can be controlled by changing the translational speed of the trucks.

Case b: both trucks are facing 90^o sideways – *in this case, the relative speed between the two trucks*

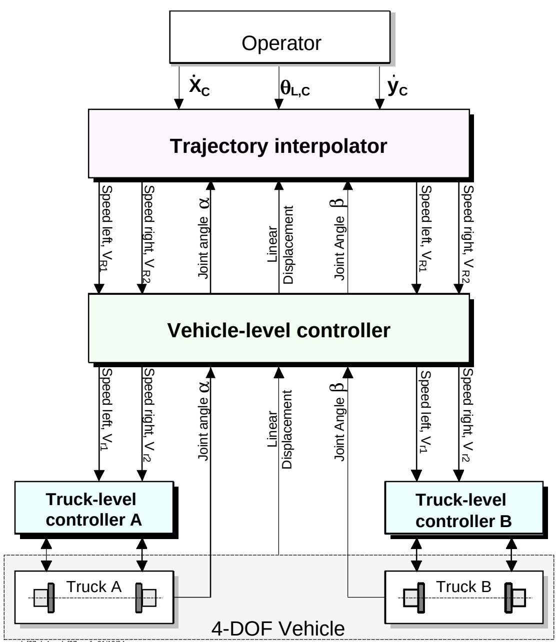

Figure 6: The 3-layer OmniMate control system.

is zero, and the link-length can only be controlled after changing the orientation of the trucks.

In actual operation one will encounter a combination of these two extreme cases. The resulting control problem is rather difficult; it requires that the link-length be controlled by manipulating four motor velocities in a system where two basically different control laws apply (i.e., Cases a and b, above) and where one of the control laws is highly non-linear (Case b, above). Borenstein [1995a] provides a detailed treatment of the controller.

3.3 The trajectory interpolator

The task of the *trajectory interpolator* (TI) is to generate reference velocity signals that direct the vehicle along a specific trajectory. The TI described here is designed for *tele-operator* control of the vehicle, but can be modified easily to allow computer-generated input.

The TI allows a human operator to control the vehicle motion with a 3-DOF joystick. The TI translates joystick control inputs $\dot{x}_C$ and $\dot{y}_C$ into linear Cartesian coordinate motion in vehicle coordinates (e.g., $\dot{x}_C$ causes pure sideways crabbing and $\dot{y}_C$ causes pure forward travel). The third control input, $\theta_{L,c}$, prescribes orientation.

4. Internal Position Error Correction (IPEC)

One unique and seemingly impossible feature of the OmniMate is its ability to measure and correct non-systematic odometry errors (i.e., errors caused by bumps, cracks, or other irregularities on the floor) that occur in one truck by using the other truck as a point of reference. Yet, this error correction method works even while both trucks are in continuous, fast motion.

Figure 7 explains how this method works. We will consider only the case of straight line motion, to keep the example simple. In straight-line motion the internal controllers of each truck try to vary the speed of the motors so that each motor generates exactly the same number of encoder pulses. This simple control law works well on smooth floors, but when one wheel encounters a bump (as shown in Figure 7) then this wheel has to travel an extra distance (namely up and down the bump). Yet, as the encoder pulses of both wheels are being kept equal by the controller, the right wheel (in Figure 7) will cover less horizontal distance. As a result Truck A's orientation will change (a fact unknown to Truck A's odometry computation). Truck A is therefore expecting to “see” Truck B along the extension of line L_e. However, because of the physically incurred rotation of Truck A, the rotary encoder on truck A will report that truck B is now actually seen along line L_m. The angular difference between L_e and L_m is the thus measured odometry orientation error of Truck A, which can be corrected immediately. One should note that even if Truck B encountered a bump at the same time, the resulting rotation of Truck B would not affect the orientation error measurement. One should also note that orientation errors are much more severe than linear odometry errors because even a small orientation error will result in the unbounded growth of a subsequent lateral position error.

The unique error correction capability of the OmniMate is documented in video clips available in [Borenstein, 1995V; Borenstein et al., 1996b].

5. Experimental Results

In order to test the odometric accuracy of the OmniMate the vehicle was programmed to run five laps along a rectangular path in clockwise (cw) and counter-clockwise (ccw) direction, according to a benchmark test called *UMBmark* [Borenstein and Feng, 1996]. 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. Traveling at a maximum speed of 0.3 m/s (11.8 in/s) during straight segments, the robot slowed down near corners but didn't stop. In an additional five laps each in cw and ccw direction 20 artificial 9-mm diameter bumps were placed under the OmniMate's wheels to test the vehicle's ability to correct non-systematic odometry errors. After these runs (i.e., a total of 20 laps) the whole experiment was repeated but with the OmniMate's error correction *disabled*, for comparison.

At the beginning and end of each lap an on-board "sonar calibrator" (a device that uses three ultrasonic sensors to measure the distance between three points on the robot to two L-shaped walls) was used to measure the absolute position and orientation of the vehicle. Comparing this "true" measurement to the position and orientation from odometry at the end of each lap allows the onboard computer to compute the return position- and orientation errors (εx, εy, $\varepsilon\theta$). After determining the odometry errors at the end of each lap, the odometry system was re-initialized with that data (i.e., odometry errors were not allowed to accumulate from lap to lap).

Noting the return position and orientation errors after each lap, errors εx and εy were plotted in Figures 8 and 10, and errors $\varepsilon\theta$ were plotted in Figures 9 and 11. It is evident from these results that the OmniMate's error correction provided consistently one order of magnitude greater accuracy than that obtained from running the same vehicle without IPEC.

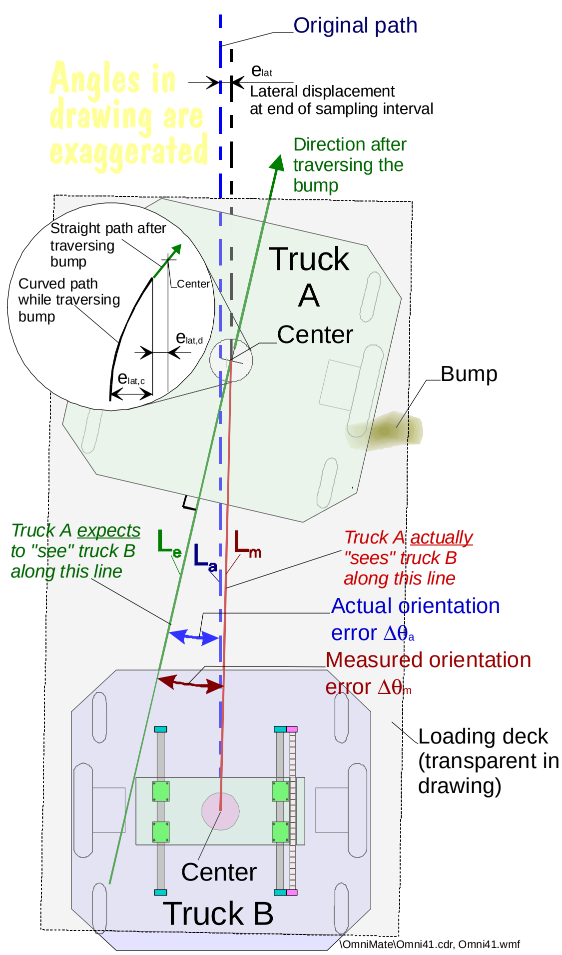

Figure 7: After traversing a bump, the resulting change of orientation of Truck A can be measured relative to Truck B.

6. Conclusions

This paper presents an overview over the design of a new, commercially available omnidirectional mobile robot called *OmniMate*. The OmniMate provides true omnidirectional motion and its kinematic design eliminates the excessive wheel-slippage often associated with omnidirectional 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.

Acknowledgment:

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7. References

1. Borenstein, J., 1995a, "Control and Kinematic Design for Multi-degree-of-freedom Mobile Robots With Compliant Linkage." *IEEE Transactions on Robotics and Automation*, February, Vol. 11, No. 1, pp. 21-35.

2. Borenstein, J., 1995b, "Internal Correction of Dead-reckoning Errors With the Compliant Linkage Vehicle." *Journal of Robotic Systems*, Vol. 12, No. 4, April, pp. 257-273.

3. Borenstein, J., 1995V, "The CLAPPER: A Dual-drive Mobile Robot With Internal Correction of Dead-reckoning Errors." ***Video Proceedings** of the 1995 IEEE International Conference on Robotics and Automation*, Nagoya, Japan, May 21-27.

4. Borenstein, J. and Feng. L., 1996, "Measurement and Correction of Systematic Odometry Errors in Mobile Robots." IEEE Transactions on Robotics and Automation, Vol 12, No 6, December 1996, pp. 869-880.

5. Feng, L, Koren, Y., and Borenstein, J., 1993, "A Cross-Coupling Motion Controller for Mobile Robots." *IEEE Journal of Control Systems*. December, pp. 35-43.

6. Pin, F. G. and Killough, M., 1994, "A New Family of Omnidirectional and Holonomic Wheeled Platforms for Mobile Robots." *IEEE Transactions on Robotics and Automation*, Vol. 10, No. 4, August 1994, pp. 480-489.

7. West, M. and Asada, H., 1992, "Design of a Holonomic Omnidirectional Vehicle." *Proceedings of the 1992 IEEE International Conference on Robotics and Automation.* Nice, France, May, pp. 97-103.

Commercial Companies

8. HP — Hewlett Packard, 19310 Pruneridge Ave., Cupertino, CA, 800-752-9000

9. HRI — Helpmate Robotics Inc., (formerly TRC - Transitions Research Corp.) Shelter Rock Lane, Danbury, CT 06810, 203-798-8988.

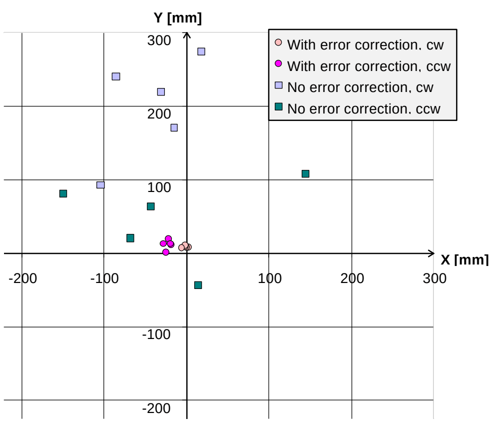

Figure 8: OmniMate return position errors after completing the 18.5 m rectangular path on a smooth concrete floor without bumps.

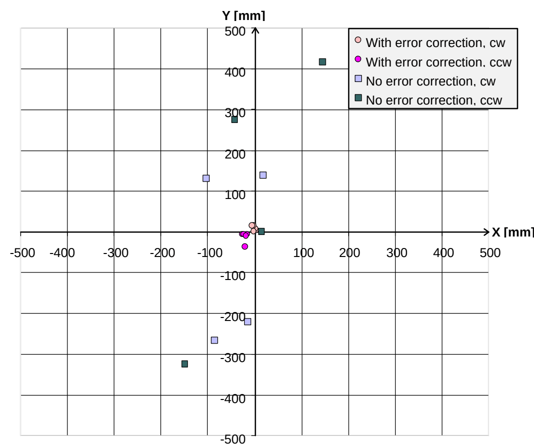

Figure 10: OmniMate return orientation errors after completing the 18.5 m rectangular path on a smooth concrete floor with 20 artificial bumps.

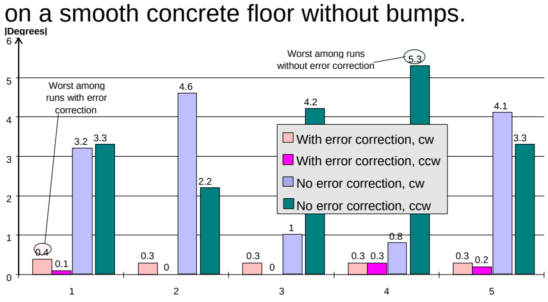

Figure 9: OmniMate return orientation errors after completing the 18.5 m rectangular path on a smooth concrete floor without bumps.

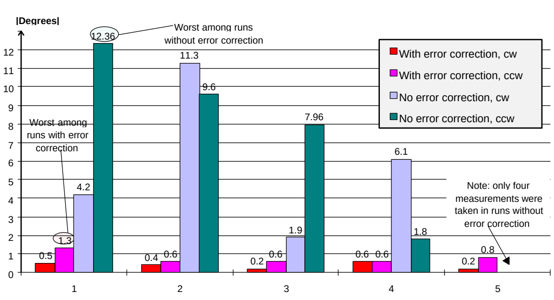

Figure 11: OmniMate return position errors after completing the 18.5 m rectangular on a smooth concrete floor with 20 artificial 9-mm bumps.