inaccuracy of the orientation error measurement would be $\epsilon = 2\times0.01^o = 0.02^o$, which translates into 0.02/0.44×100 = 4.5% inaccuracy in measuring the orientation error of truck A relative to truck B.

4. INTERNAL POSITION ERROR CORRECTION (IPEC)

The principle of operation of the IPEC method is best explained with the help of Fig. 5, which shows truck A's "direction of travel after traversing a bump." Since this direction differs from the intended (straight ahead) direction as the result of a dead-reckoning error, truck A still "believes" it was traveling straight ahead. Consequently, truck A would expect the center of truck B straight behind, along the dotted line labeled L_e in Fig. 5. Using dead-reckoning data from both trucks, truck A can always compute this *expected direction* to the center of truck B, whether both trucks are traveling straight or along a curved path. This *expected* direction can then be compared to the *measured* direction, which is readily available from the absolute rotary encoder on truck A. The difference between the *expected* direction and the measured direction is the *measured* orientation error $\Delta\theta_m$. The orientation error of truck B can be determined in a similar way, relative to the center of truck A.

4.1 Correction of orientation errors

In this section we explain the actual implementation of the IPEC method on the CLAPPER. With its three *internal* encoders, the CLAPPER performs relative position measurements every T_s = 40 ms. This sampling rate allows each truck to detect the *fast-growing* orientation errors caused by bumps. The *slow-growing* lateral position errors of both trucks have no significant effect on this measurement, as was shown in Section 3. Note that the sampling time is not critical for the performance of the system.

The IPEC method performs the following computations once during each sampling interval: At first, trucks A and B compute their momentary position and orientation based on dead-reckoning:

$$
\begin{aligned}
x_{A,i} &= x_{A,i-1} + U_{A,i}\cos\theta_{A,i} \\
y_{A,i} &= y_{A,i-1} + U_{A,i}\sin\theta_{A,i} \\
&\text{and} \\
x_{B,i} &= x_{B,i-1} + U_{B,i}\cos\theta_{B,i} \\
y_{B,i} &= y_{B,i-1} + U_{B,i}\sin\theta_{B,i}
\end{aligned}
\tag{9}
$$

where

$x_{A,i}, y_{A,i}$ - position of centerpoint of truck A, at instant i;

$x_{B,i}, y_{B,i}$ - position of centerpoint of truck B, at instant i;

$U_{A,i}, U_{B,i}$ - incremental displacements of the centerpoints of trucks A and B during the last sampling interval;

$\theta_{A,i}, \theta_{B,i}$ - Orientations of trucks A and B, respectively; computed from dead-reckoning.

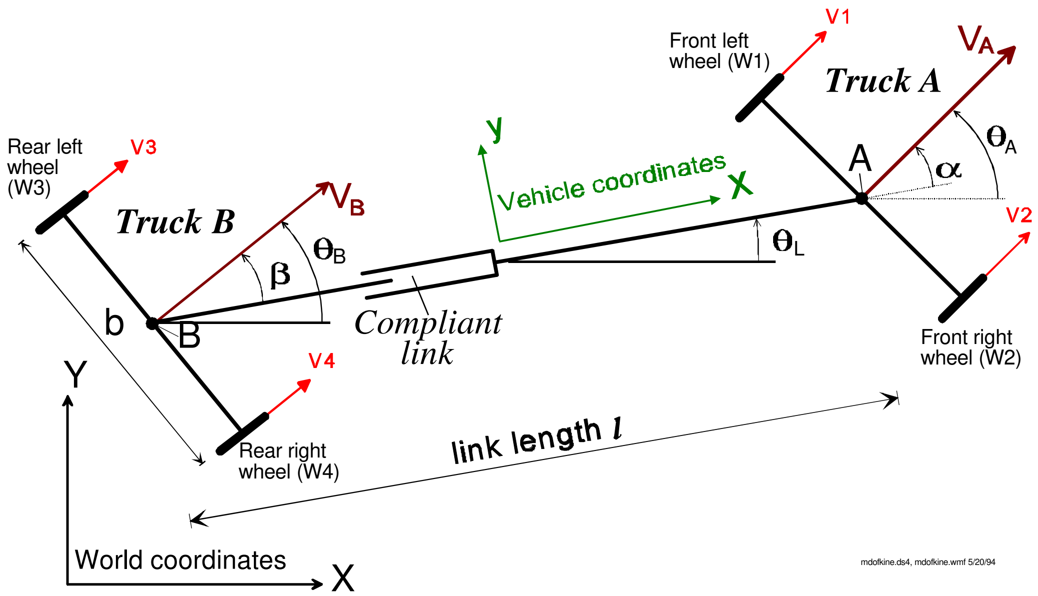


Figure 6: Kinematic definitions for the CLAPPER.

Note that the dead-reckoning equations for U_i and θ_i are well known and not repeated here (see [Banta, 1988; Everett, 1995]). Also note that we will skip the index i in the following equations.

Next, the orientation θ_L of the compliant linkage is computed

$$\theta_L = \operatorname{atan}\left(\frac{y_B - y_A}{x_B - x_A}\right) \tag{10}$$

Using the kinematic relations defined in Fig. 6, we can now compute the *expected* angles α_{exp} and β_{exp} between the compliant linkage and trucks A and B respectively.

$$\alpha_{exp} = \theta_A - \theta_L \tag{11a}$$

and

$$\beta_{exp} = \theta_B - \theta_L \tag{11b}$$

Note that the index "*exp*" indicates that the computed angle is ***expected***, based on dead-reckoning during this sampling interval.

We can now compute

$$\Delta\theta_A = \alpha_{act} - \alpha_{exp} \tag{12a}$$

and

$$\Delta\theta_B = \beta_{act} - \beta_{exp} \tag{12b}$$

where α_{act} and β_{act} are the ***actual*** angles between the compliant linkage and trucks A and B respectively, as measured by the two absolute rotary encoders located at points A and B (see

Fig. 2 and Fig. 6). Non-zero results for $\Delta\theta_A$ or $\Delta\theta_B$ do not only indicate the presence of a dead-reckoning error, but they are quantitatively accurate values for correcting these errors. Thus, computing

$$\theta'_A = \theta_A + \Delta\theta_A \tag{13a}$$

and

$$\theta'_B = \theta_B + \Delta\theta_B \tag{13b}$$

yields the *corrected* orientations for truck A and truck B.

4.2 Correction of translational errors

The IPEC method can detect only rotational errors, but not translational errors. However, rotational errors are much more severe than translational errors, because orientation errors cause ***unbounded*** growth of lateral position errors. This observation was illustrated in Table I, where the translational error resulting from traversing a bump of height 10 mm was ΔD = 2.63 mm. By comparison, the lateral error due to the rotational error $\Delta\theta$ was e_{lat} = 77 mm after only 10 m of travel.

We can further distinguish two kinds of translational errors: *pure* and *composite*. *Pure* translational errors occur when both wheels traverse bumps of similar height during the same sampling interval. These errors cannot be detected with the IPEC method, but they are rare in practice and they produce only small and finite position errors. *Composite* translational errors occur when only one wheel traverses a bump, thereby causing a translational ***and*** a rotational error. Since we can detect the rotational error, we can also correct for the translational part, as discussed next.

Since *composite* translational dead-reckoning errors are the result of a rotation (the magnitude of which is known from Eqs. (12)), it is possible to correct the translational error once we know the point around which the rotation took place. Banta [1988] helps solve this problem by explaining that a non-systematic orientation error is practically ***always*** caused by an encoder reporting a horizontal distance that is ***longer*** than the distance the wheel had actually traveled. This is true for all kinds of floor irregularities, whether they are bumps, cracks, or fluid spills. Because of this important insight we can safely assume that the dead-reckoning orientation error of $\Delta\theta_a = 0.44^\circ$ (in our example) is not caused by the left wheel that has progressed more than reported by the encoder — rather, it is the right wheel that has lagged behind in its horizontal progression although the (false) encoder readings make the robot believe both wheels had progressed the same horizontal distance. We can thus correct the internal position representation of truck A by applying the corrective rotation $\Delta\theta_A$ around the contact point of the left wheel, so that the position of the centerpoint A is corrected backward (see Fig. 7) by

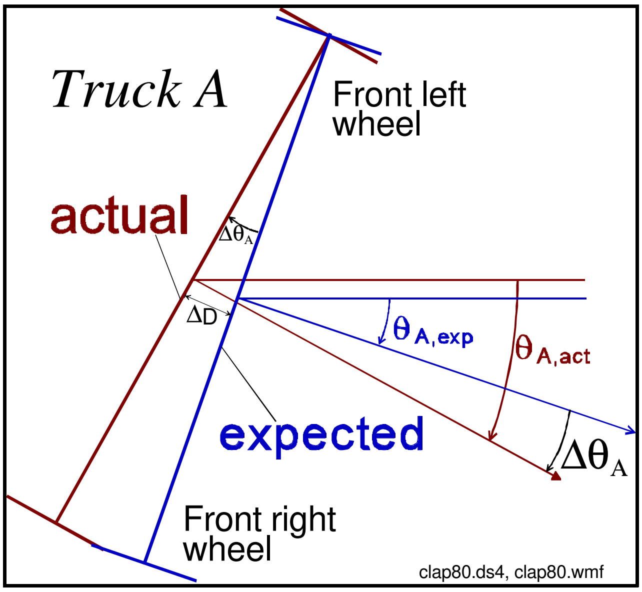


Figure 7: Correcting *composite* translational errors.

$$\Delta D = b \sin(½\Delta\theta_A) \tag{14}$$

or

$$x'_A = x_A - b \sin(½\Delta\theta_A) \cos(\theta_A)$$
$$y'_A = y_A - b \sin(½\Delta\theta_A) \sin(\theta_A) \tag{15}$$

In actual experimentation we found that this correction of the translational error has only minimal effect on the overall accuracy of the system. By contrast, the position correction for truck B is of crucial importance, and it must be done in a different manner and for different reasons, as explained next.

It is clear at this time that the IPEC method does not eliminate dead-reckoning errors *completely*. Thus, after some travel time both trucks will have accumulated a certain position error. Yet, even the smallest position error of either truck will affect the computation of the orientation θ_L of the compliant linkage. Such an error in θ_L, in turn, would affect Eqs. (11), causing the system to "see" and correct non-existing dead-reckoning errors all the time. To avoid this problem, we have to correct the position of one truck relative to the other after every sampling interval. In our case, we correct the position of truck B according to

$$x'_B = x_A - l \cos\theta_L$$
$$y'_B = y_A - l \sin\theta_L \tag{16}$$

where x'_B, y'_B are the corrected coordinates of truck B, and l is the length of the compliant linkage, as measured by the linear encoder onboard the CLAPPER.

The effect of this correction is that the position of truck B is not at all computed by summing-up dead-reckoning increments. Rather, truck B's dead-reckoning is relevant only for the distance traveled during one sampling interval, while its accumulated position is always computed relative to truck A. This measure is perfectly legitimate because the position of truck B relative to truck A can always be computed from the three internal encoders. The single disadvantage is the need to measure the distance between the trucks (l) quite accurately, to avoid systematic errors during turning (as we will discuss in Section 5).

5. SYSTEMATIC DEAD-RECKONING ERRORS

In Section 4 we explained the IPEC method with regard to non-systematic errors. Another source of dead-reckoning errors is known as *systematic errors*. Systematic errors are usually caused by imperfections in the design and mechanical implementation of a mobile robot. In conventional, differential-drive mobile robots the two most notorious systematic errors are different wheel diameters and the uncertainty about the effective wheelbase [Borenstein and Koren, 1985, 1987; Banta 1988; Borenstein and Feng, 1995].

Systematic errors are particularly grave, because they accumulate constantly. On most smooth indoor surfaces systematic errors contribute much more to dead-reckoning errors than non-systematic errors. However, on rough surfaces with significant irregularities, non-systematic errors are dominant. One hard-to-defuse criticism of work aimed at reducing systematic dead-reckoning errors alone is the claim that any *unexpected* irregularity can introduce a huge error, no matter how effective the reduction of systematic errors was.

5.1 Correction of conventional systematic errors with the CLAPPER

The IPEC method corrects not only non-systematic errors, but it can also compensate for most systematic errors, provided the systematic error causes a dead-reckoning error in orientation. For example, consider a mobile robot programmed to move straight ahead. Unequal wheel-diameters will cause the mobile robot to follow a curved path, instead. Even though the resulting rate of rotation is very small, the CLAPPER will trigger a correction as soon as the accumulated orientation error exceeds the resolution of the absolute encoder (0.3° in the CLAPPER). In our experiments we found that the CLAPPER can easily accommodate and correct large systematic errors. Indeed, we have implemented a calibration procedure in which certain systematic errors (like unequal wheel-diameters) are automatically calibrated by monitoring the corrective actions of the CLAPPER while traveling on smooth surfaces. Similarly, the error resulting from the uncertainty about the effective wheelbase of the trucks can be corrected with the IPEC method.

5.2 Unconventional systematic errors in the CLAPPER

While the CLAPPER corrects most systematic errors of *conventional* mobile robots, the vehicle introduces new *unconventional* systematic errors that are specific to the CLAPPER. These *unconventional* systematic errors are related to (a) biased measurements of the absolute rotary encoders, and (b) biased measurements of the link-length l. Consider, for example, the situation in which the CLAPPER is programmed to move straight ahead. The onboard controller will comply with this task by controlling both trucks such that both absolute encoders don't deviate from $\alpha = \beta = 0^{\circ}$. Now suppose that because of inaccurate assembly of the vehicle encoder A reads 0° while truck A is actually rotated, say, $+1^{\circ}$ relative to the compliant linkage. Suppose further encoder B showed 0° while truck B was actually rotated -1° relative to the compliant linkage. The resultant path would be curved to the left instead of straight. This condition cannot be detected by the IPEC method and its effect is similar to that of unequal wheel-diameters in conventional mobile robots.

Another unconventional systematic error is related to the biased measurement of the linear encoder. Even though the resolution of this encoder in our prototype vehicle is 0.1 mm, we suspect that our prototype vehicle has a constant bias on the order of 2 mm and, in addition, a problem with eccentricity, which changes the bias when the two trucks rotate relative to the compliant linkage. This link-length bias will cause a slight inaccuracy in the correction of the rear-truck position, because Eqs. (16) depend on the link length l. During straight line travel the link-length bias has no effect on the overall accuracy of the system. However, during turning movements any small inaccuracy in the position of the rear truck will cause a small error in computing the orientation of the compliant linkage, θ_L, because of Eq. (10). Such an error will be interpreted by the CLAPPER as a dead-reckoning error during the next sampling interval, because of Eqs. (11). Consequently the CLAPPER will "correct" this perceived dead-reckoning error. In informal experiments we found that a constant bias of 1 mm in the measurement of the link-length l causes an orientation error of roughly 1° for every full 360° turn of the CLAPPER. In either case, however, the vehicle can be calibrated to the extend that these errors become negligible, as the experimental results with a well calibrated vehicle will show in Section 6, below.

5.3 Conventional versus unconventional systematic errors

So far we have seen that the CLAPPER corrects most *conventional* systematic errors, while introducing some new, *unconventional* systematic errors of its own. However, we argue that these *unconventional* errors are less of a problem, for the following reasons:

a. The most severe conventional systematic errors depend to a large degree on circumstances that can not be controlled by the robot's manufacturer. For example, unequal wheel-diameters are often the result of different loading characteristics of the vehicle. By contrast, the unconventional systematic errors of the CLAPPER depend on fixed manufacturing characteristics of the vehicle. Being aware of the importance of reducing measurement bias, the manufacturer of a CLAPPER-type vehicle can design and build the vehicle with tight tolerances for the assembly of the encoders.

b. The measurement bias of the absolute encoders in the CLAPPER can be detected and corrected by means of simple calibration procedures. Once these procedures have been performed, the resulting calibration parameters remain basically valid under all operating conditions, independent of floor or load characteristics.

6. EXPERIMENTAL RESULTS

In order to evaluate the performance of the CLAPPER's IPEC method we conducted several sets of representative experiments. In this section we report results from repeatable, basic experiments inside the lab. Results from other experiments, including runs on a bumpy lawn, are documented in [Borenstein, 1995V].

All indoor experiments were conducted on fairly smooth concrete floors. We produced controlled irregularities by repeatedly placing a piece of 10 mm diameter cable under one side of the vehicle. We will refer to this irregularity as a "bump." All experiments started and ended near an L-shaped reference corner. Three ultrasonic sensors were mounted on the CLAPPER, two sensors were facing the long side of the L-shaped corner, the third sensor faced the short side. The ultrasonic sensor system allowed measurement of the absolute position of the vehicle to within ±2 millimeters in the x and y directions, and to about $\pm 0.25^\circ$ in orientation.

At the beginning of each run a sonar measurement was taken to determine the starting position of the vehicle. The CLAPPER then traveled through the programmed path and returned to the L-shaped corner, where the *perceived* position (i.e., the position the vehicle "thought" it had, based on dead-reckoning) was recorded. Then, a sonar measurement was taken to determine the *absolute* position. The difference between the absolute position and the perceived position is called the *return position error*. The average speed in all runs was slightly below 0.5 m/sec.

6.1 The *Straight Line Experiment*

In this experiment the CLAPPER traveled straight forward for 18 m, stopped, and returned straight-backward for 18 m, to the starting position. We performed three runs for each one of the following four conditions:

a. Without IPEC, without bumps
b. Without IPEC, with ***ten*** bumps
c. With IPEC, without bumps
d. With IPEC, with ***twenty*** bumps

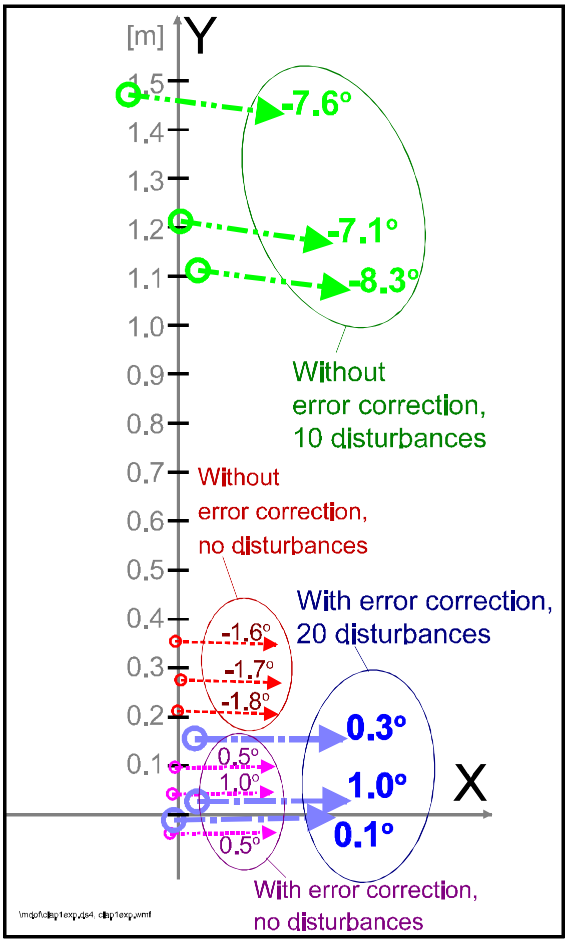


Figure 8: Return position errors after completing the *Straight Path Experiment*.

In the runs "without bumps" one can assume disturbance-free motion because our lab has a fairly smooth concrete floor. In the runs "with bumps" we used bumps only on the return leg of the 2×18 m round-trip and only under the right side-wheels of the vehicle (to avoid mutual cancellation of errors). In the runs with error correction we used 20 bumps approximately evenly spaced along the 18 m return-path. Some bumps affected both the front and rear truck, some affected only one of the two trucks. In the runs without error correction we used only 10 bumps, because our cluttered lab could otherwise not accommodate the large path deviations. Without error correction, each bump caused an orientation error of approximately $\epsilon_\theta = 0.6^o$.

Figure 8 summarizes the results from the straight-line experiment. Shown are the return position errors and the return orientation errors of the vehicle after completing the 36 m journey back and forth along the x-axis. Note that without bumps, the return position errors with IPEC are only slightly smaller than those without IPEC. We contribute the almost uniform orientation error of approx. -1.7 ^{o} in the run without IPEC to conventional systematic errors. The run with IPEC shows how the conventional systematic errors are overcome. The more important results are those from runs with bumps. Here the non-IPEC runs average a return orientation error of $\epsilon_{\theta,avrg} =$ -7.7^o, out of which -1.7^o are likely to be the result of systematic errors. The remaining error average of $\epsilon_\theta = -6^o$ can be interpreted as the result of the 10 identical bumps, each of which contributed 0.6 ^{o}.

We performed many more straight line experiments than the ones documented here. In all runs the return orientation error ϵ_θ with IPEC was less than ±1.0 ^{o} for the 36 m straight line path.

6.2 The *Rectangular Path Experiment*

In this experiment the CLAPPER was programmed to pass-by the corners of a 7×4 m rectangular path with smooth 90 ^{o} turns at the corners and a total travel length of approximately 24 m (see Fig. 9). To provide fluid, uninterrupted motion, the programmed path did not require the vehicle to stop at the intermediate points — passing-by at a distance of less than 0.2 m was sufficient. In order to measure the position errors after completing the path, the vehicle began and ended each run in the L-shaped "home" corner, as shown in Fig. 9.

When testing dead-reckoning errors in closed-path experiments, it is imperative to run the experiment in both clockwise (cw) and counter-clockwise (ccw) directions. If tests are run in only one direction (for example, to calibrate parameters that determine the effective wheel-base or compensate for different wheel-diameters), then systematic dead-reckoning errors can mutually compensate for each other. This way, an experimenter might carefully calibrate two parameters to yield excellent accuracy for a particular test-path, yet the calibrated parameters are quite wrong. If, however, the test is performed in both cw and ccw direction, then mutual compensation in one direction increases the resulting error when run in the other direction. Thus, if a mobile robot performs a closed test path accurately in both directions, one can be assured that the vehicle is well calibrated.

Figure 10 shows the return position errors for the *Rectangular Path Experiment* under different test conditions. The CLAPPER ran through the path for 10 runs in cw, and 10 runs in ccw direction. In each of these runs the CLAPPER had to traverse 10 bumps. In one half of the runs bumps were located under the right-side wheels of both trucks, and in the other half of the runs under the left-side. The return position errors of these runs are marked by small squares (see *Legend* in Fig. 10). None of the 20 runs produced a position error of more than 5 cm. Also shown in Fig. 10 are the results of five cw and five ccw runs with IPEC but

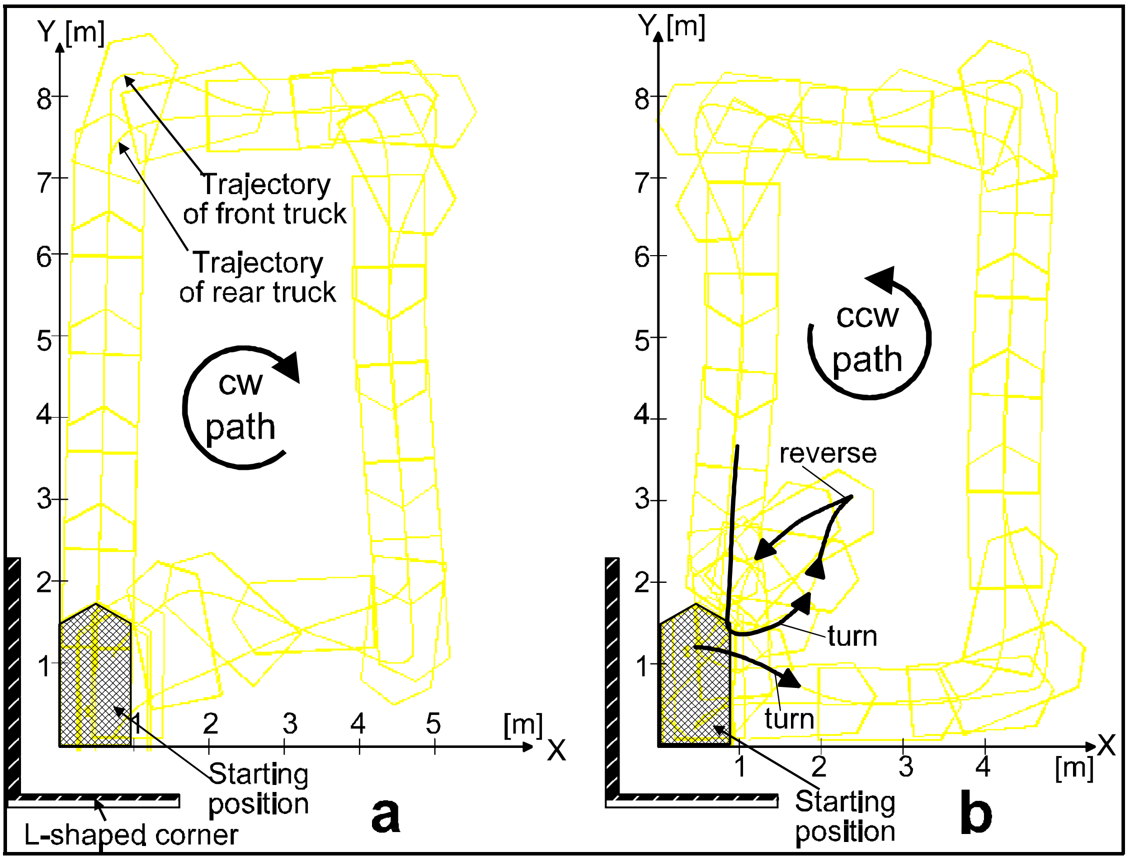


Figure 9: The *Rectangular Path Experiment* was performed in clockwise (cw) and counter-clockwise (ccw) direction. Some sideways and backward maneuvering was necessary to return to the home position.

without bumps (marked by small circles). Note that the results with bumps are almost indistinguishable from the results without bumps. In a further experiment the vehicle ran through the path with bumps, while the IPEC function was *disabled* (i.e., using normal dead-reckoning like conventional mobile robots). The results of these runs are marked by stars in Fig. 10. Also noted in the inset table in Fig. 10 are the resulting *average absolute orientation errors* of these runs, defined as

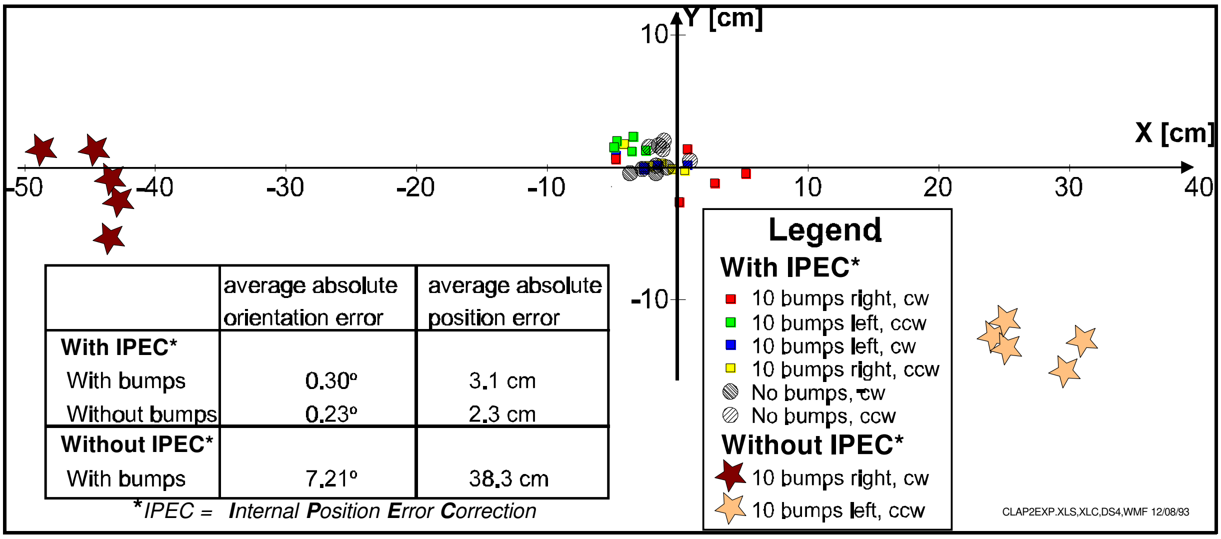
$$\epsilon_{\theta,|avrg|} = \frac{1}{n}\sum_{i=1}^{n} |\epsilon_{\theta,i}| \qquad (17)$$

One might recall that for longer distances the orientation errors cause the lateral position errors to grow without bound. The results in Fig. 10 show that the IPEC method resulted in a more than 20-fold reduction in orientation errors. Indeed, in longer paths with more disturbances one should expect even better improvements, because the average absolute orientation error of $\epsilon_{\theta,avrg} = 0.3^{\circ}$ is just about equal to the accuracy with which we are able to measure the actual position of the CLAPPER with the three onboard ultrasonic sensors.

These experimental results compare well with experimental results obtained by the author in earlier work [Borenstein, 1994a] with the same MDOF vehicle but without IPEC. In those experiments the average translational error in 10 runs along a 4×4 m rectangular path was $\epsilon_{max} = 5.6$ cm and the average absolute orientation error was approximately 0.7 °. These earlier experiments, of course, were conducted on smooth floors with a well calibrated vehicle. The improvement evident in the results of Fig. 10 over the earlier, non-IPEC results on smooth floors can be accredited to the ability of the IPEC method to correct not only non-systematic dead-reckoning errors but also conventional systematic errors. These results further indicate that careful calibration of the non-conventional system parameters in the CLAPPER is more effective than the equally careful calibration of conventional system parameters in conventional vehicles.

7. CONCLUSIONS, APPLICATIONS, AND FUTURE WORK

A new method for *Internal Position Error Correction* (IPEC) for mobile robots has been developed. The IPEC method has been implemented and tested on the University of Michigan's Multi-Degree-of-Freedom (MDOF) vehicle called CLAPPER. The main strength of the new method is the immediate correction of both systematic and non-systematic dead-reckoning errors without external references and during motion. Experimental results with the



	average absolute orientation error	average absolute position error
With IPEC*		
With bumps	0.30°	3.1 cm
Without bumps	0.23°	2.3 cm
Without IPEC*		
With bumps	7.21°	38.3 cm

**IPEC = Internal Position Error Correction*

Figure 10: Return position errors after completing the *Rectangular Path Experiment.* Total travel distance in each run: 21m.

CLAPPER show one to two orders of magnitude more accurate dead-reckoning than conventional (2-DOF) mobile robots. Thus, the CLAPPER not only eliminates the excessive wheel slippage found in other MDOF vehicles, but it corrects dead-reckoning accuracy even further, for a total improvement of two to three orders of magnitude over other MDOF vehicles.

The CLAPPER is especially suitable for industrial applications where its unique dead-reckoning accuracy will allow it to operate without the guide-wires typically found in conventional AGV applications. The IPEC method is also useful in applications where substantial floor irregularities or the mere possibility for unexpected floor irregularities render conventional dead-reckoning unfeasible. Construction and agricultural applications, where dead-reckoning has been impossible in the past because of the large amount of slippage on soft soil, might benefit directly from the IPEC method. Other relevant applications are map-building and exploratory tasks, where conventional absolute position sensors are unfeasible.

We have just begun to investigate the applicability of the IPEC design to other vehicle configurations. One promising approach is the attachment of an unpowered *encoder trailer* to existing, conventional mobile robots. Linking this *encoder trailer* with one rotary joint to the main vehicle would produce a configuration similar to the CLAPPER's, except for the fact that the *encoder trailer*, acting as truck B, would be passively towed instead of being motorized. Simulations results with such an encoder trailer were encouraging [Borenstein, 1994c] and we have recently begun building the actual device. Results are expected in early 1995.

We are also considering the possibility of using the IPEC method on two collaborating but physically unconnected mobile robots. Both robots would have to be equipped with positioning sensors capable of accurately measuring the relative position and bearing between the two units. This approach may be useful for tracked vehicles in military, agricultural, or construction applications.

Acknowledgements:

This research was funded by NSF grant # DDM-9114394 and in part by Department of Energy Grant DE-FG02-86NE37969.

Special thanks to Dr. Liquiang Feng who provided comments and suggestions in the review of this manuscript and to Mr. Dilip Dubey who conducted some of the experiments.

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