Proceedings of the 10th IEEE International Symposium on Intelligent Control, August 27 - 29, 1995, pp. 571-576.

Experimental Evaluation of an Encoder Trailer for Dead-reckoning in Tracked Mobile Robots

Zhejun Fan* Johann Borenstein* David Wehe** Yoram Koren*

*Department of Mechanical Engineering and Applied Mechanics
**Department of Nuclear Engineering
The University of Michigan
Ann Arbor, MI 48109

Abstract

This paper describes a device developed for improved position and orientation estimation of tracked mobile robots. This device, called Encoder Trailer, consists of two incremental encoders, one absolute encoder, two "knife-edge" wheels, and a slip ring. It is a unique design in the sense that it can minimize the systematic errors and eliminate the most important nonsystematic errors such as uneven floors and unexpected obstacles. Both theoretical analyses and experimental results demonstrated that this encoder trailer improves platform dead reckoning when traveling over uneven floors and unexpected obstacles.

1. Introduction

We are interested in autonomous tracked vehicles that are capable of intelligent motion and action without requiring guide wires or teleoperator control. Currently, much research is concentrated on idealized mathematical models of military tanks to have a general understanding of the interrelationship between the terrain factors (such as soil type, soil shear strength, and compressibility) and the vehicle characteristics (weight, track length and width, location of center of gravity, etc.) during steering [Won.1]. Performance and mobility are the primary tasks here. In contrast, our Andros Mark V, made by REMOTEC, is primarily used in non-military hazardous environments, many of which are indoor. Kinematics is our primary task. To move the Andros along a specified trajectory, we need accurate knowledge of its position. For tracked vehicles, slippage is inevitable, so that regular shaft encoder used in wheeled robots are of little use. Dead reckoning with a shaft encoder accumulates errors with time such that the estimated position of the vehicle becomes useless [Fan.2]. To correct for those cumulative errors, we can use some kind of reference. Global Position System (GPS) is a good choice for outdoor vehicles. However, we can not use it for our tracked vehicle that will be used primarily indoors. Transmitters or bar codes should work, however, they require costly installation and maintenance. To overcome this problem, we have developed an encoder trailer for tracked mobile robots that can provide us accurate position information in spite of floor roughness and obstacles.

This paper is organized as follows: the University of Michigan's tracked vehicle is described in section 2. The Encoder Trailer is described in section 3. Error analysis is discussed in section 4. The robust property of the Encoder Trailer is proven in section 5. Experimental validation is described in section 6. Conclusions are given in section 7.

2. The University of Michigan's Tracked Vehicle

The Remotec Andros is a tracked vehicle for tele-operation on varied terrains (Figure 1). The platform consists of a main chassis with two main tracks, a front auxiliary track, and a rear auxiliary track. The vehicle is 711 mm wide, 1092 mm high and 764 mm long. The weight of the vehicle is 1557 N. The two auxiliary tracks can be raised or lowered individually to allow the vehicle to climb over large obstacles and move up and down stairs. It is intended to be operated under tele-operator control and the operator uses visual feedback to control the vehicle. Therefore the lack of dead-reckoning information is not a problem. However, this information is essential for the autonomous tracked vehicle.

In recent years there has been growing interest, especially in the DOE Robotics community, in converting tracked vehicles to fully autonomous operation [Fan.2]. In order to have accurate velocity control, two incremental encoders are mounted on the left and right main motors of the vehicle. For autonomous operation, the original onboard computer and motor controllers (used during tele-operation by a human operator) were replaced by a 486-66 MHz PC-compatible single board computer and our own controllers that are based on HCTL-1100 motor

0-7803-2722-5/95 $4.00

controller chips. The new controller communicates with the host computer through parallel communication via a DG96 digital I/O board [Fan.1].

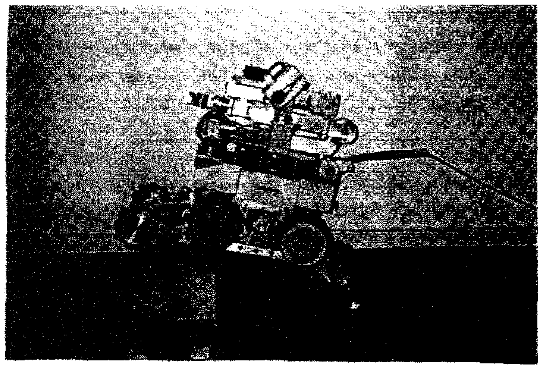

Figure 1 Remotec Andros

To assess the extent of dead-reckoning errors based on the two main track encoders, we performed University of Michigan Benchmark test (UMBmark) [Bor.2]. However, the nominal test-procedure had to be modified because of the dead-reckoning errors: the vehicle could not complete a square path. Typically, we encountered errors of 10 to 12 meters for a square path of nominally 16 meter total length, as shown in Figure 2. The orientation error was typically on the order of $120^{o} - 130^{o}$! Therefore, the dead-reckoning information based on the main track encoders is useless due to the significant slip. To have reliable position information, we developed a unique attachment for the tracked vehicle (or any robot with limited dead-reckoning ability), called the "Encoder Trailer" (ET).

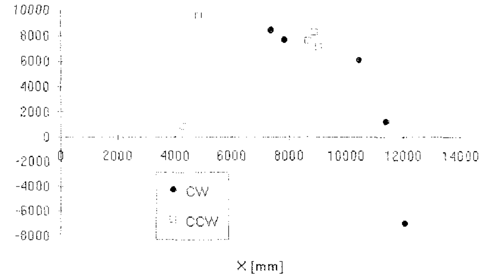

Figure 2 Return position errors for the Remotec Andros after attempting $4 \times 4\,\mathrm{m}$ bi-directional square path

3. The Encoder Trailer

The Encoder Trailer (ET) is a small two-wheel trailer that drags behind the main vehicle, as shown in Figure 3. Mounted on each wheel is an optical incremental encoder. A rotary joint allows the trailer to rotate horizontally around a fixed point behind the pulling vehicle. The trailer can rotate around this joint without limitation due to a slip ring that provides the electrical connections to the wheel encoders. When the Andros travels backward, the ET is designed to swivel and lead due to a hinge that connects the absolute encoder with the vehicle. The ET is also designed to be raised off the floor when the tracked vehicle drives over the obstacles, although this function is not yet implemented on our system.

The Encoder Trailer consists of two measurement wheels, two incremental encoders, one slip ring, one absolute encoder and connecting components as shown in Figure 3. The rim is made of aluminum, with an O-ring as a traction-providing tire, as shown in Figure 4. The incremental encoders have a resolution of 1200 pulses per revolution, and the absolute encoder has a resolution of 1024 pulses per revolution.

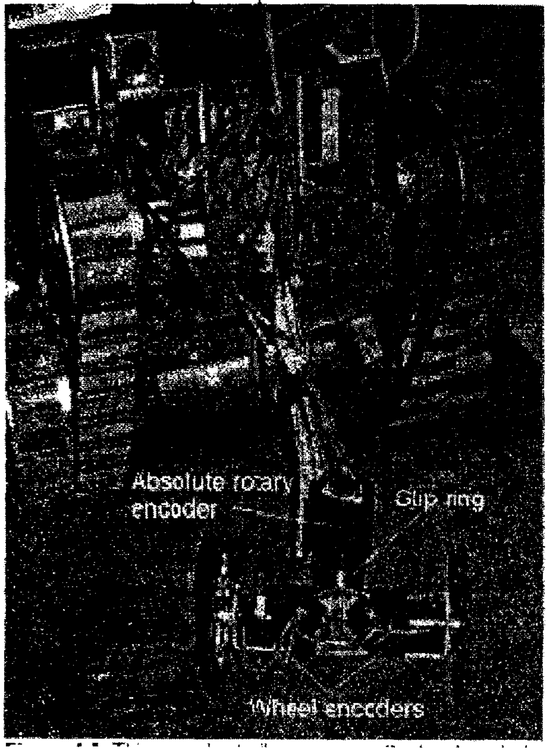

Figure 3 Remotec Andros with Encoder Trailer attached

Using the same dead-reckoning algorithm as is used for differential-drive robots, one can easily compute the position and orientation of the center-point of the trailer. Combining this information with the angle measured by the absolute encoder and with the joint length, the position and orientation of the main vehicle can be computed.

Figure 5 defines the position and orientation of the encoder trailer x_k, y_k, and θ_k at time t_k. X_k, Y_k, and β_k are the position and orientation of the center of gravity of the tracked vehicle. ϕ_k is the orientation of the tracked vehicle with respect to the encoder trailer measured by the absolute shaft encoder. ΔS_k is the distance traveled by the encoder trailer during the kth step. $\Delta\theta_k$ is the change of orientation of the encoder trailer during the kth step. From Figure 5, we derive:

$$x_k = x_{k-1} + \Delta S_k \cos(\theta_{k-1} + \Delta\theta_k / 2) \qquad (1)$$

$$y_k = y_{k-1} + \Delta S_k \sin(\theta_{k-1} + \Delta\theta_k / 2) \qquad (2)$$

$$\theta_k = \theta_{k-1} + \Delta\theta_k \qquad (3)$$

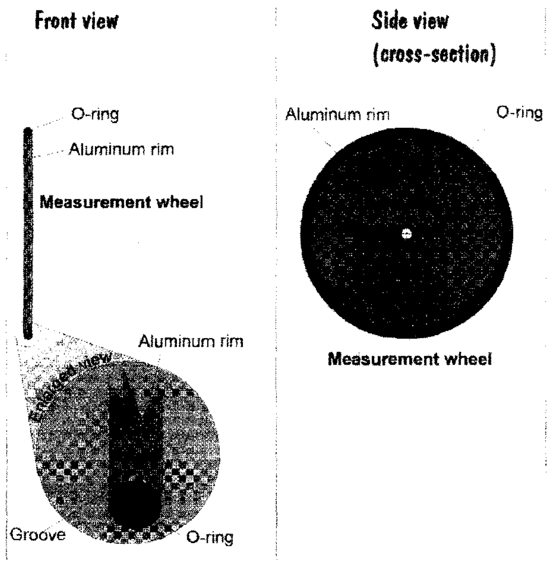

Figure 4 Measurement wheel design

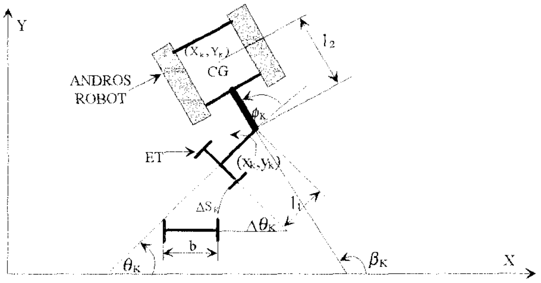

Figure 5 Location and velocity from Encoder Trailer

$$\Delta S_k \approx \frac{N_R D_R + N_L D_L}{2} \qquad (4)$$

$$\Delta\theta_k \approx \frac{N_R D_R - N_L D_L}{b} \qquad (5)$$

where N_R, and N_L are the right and left encoder reading respectively. D_R, and D_L are the right and left wheel diameter, and b is the wheel base.

The velocity of the encoder trailer can be expressed as

$$\dot{x}_k = \frac{v_L + v_R}{2} \cos\theta_K \qquad (6)$$

$$\dot{y}_k = \frac{v_L + v_R}{2} \sin\theta_K \qquad (7)$$

$$\dot{\theta}_K = \frac{v_R - v_L}{b} \qquad (8)$$

where v_R and v_L are the speed of the right and left measurement wheel at time t_k.

Correspondingly, we can express the position and orientation of the tracked vehicles as follows:

$$X_k = x_k + l_1 \cos\theta_k + l_2 \cos\beta_k \qquad (9)$$

$$Y_k = y_k + l_1 \sin\theta_k + l_2 \sin\beta_k \qquad (10)$$

$$\beta_k = \theta_k + \phi_k \qquad (11)$$

Differentiating the above equations yields the velocity of the tracked vehicle:

$$\dot{X}_k = \dot{x}_k - l_1 \dot{\theta}_k \sin\theta_k - l_2 \dot{\beta}_k \sin\beta_k \qquad (12)$$

$$\dot{Y}_k = \dot{y}_k + l_1 \dot{\theta}_k \cos\theta_k + l_2 \dot{\beta}_k \cos\beta_k \qquad (13)$$

$$\dot{\beta}_k = \dot{\theta}_k + \dot{\phi}_k \qquad (14)$$

Therefore, the robot's position is uniquely determined from the reading of the left and right incremental encoders, and of the absolute encoder. The rationale for using a device like the ET, despite its obvious disadvantage, is that many indoor applications might require a tracked vehicle because of occasional obstacles, but would offer relatively smooth concrete floors during most of the robot's travel. For autonomous operation, continuous absolute position updates are required. With conventional techniques, this would require the costly installation and maintenance of beacon systems in which several of the beacons must be seen at all times. We believe that the installation cost for such a system could be dramatically lower, if dead-reckoning information was available most of the time. The encoder trailer is economical, effective, and computationally cheap. In addition, it can provide fast position updates without modification of the environment. We will show in the following section that the encoder trailer can minimize the systematic errors due to unequal wheel diameters and uncertainty about the effective wheelbase.

4. Error Analysis

According to Eqs. (1)-(5), the position and orientation of the center of the trailer can be easily computed based on the two incremental encoders, which are mounted on the trailer wheels. This computation is called dead-reckoning. However, dead-reckoning is based on the assumption that wheel revolutions can be translated into linear displacement relative to the floor. This assumption is only of limited validity. For example, a wheel might rotate without any linear displacement, a condition known as total slippage. In this case, the wheel encoder will register wheel revolutions and calculate the predicted linear displacement even though there is no actual linear displacement at all. Under normal conditions, dead-reckoning errors may fit into one of two categories: (1) systematic errors and (2) non-systematic errors [Bor.2].

1. Systematic errors
   a. Two wheel diameters are different
   b. Wheelbase is uncertain
   c. Wheels are misaligned
   d. The average of two wheel diameters is different from the nominal value
   e. Encoder resolution is finite
   f. Encoder sampling rate is finite

2. Non-systematic errors
   a. Travel over uneven floors
   b. Travel over unexpected objects on the floor
   c. Slip due to
      - slippery floors
      - over-acceleration
      - fast turning (skidding)
      - non-point wheel contact with the floor

4.1 Systematic Dead-reckoning Errors

Systematic errors are usually caused by imperfections in the design and mechanical implementation of a mobile robot. The two most significant systematic error sources are *unequal wheel diameters* and the *uncertainty about the effective wheelbase* [Bor.2].

a) *Unequal wheel diameters*: Most mobile robots use rubber tires to improve traction. These tires are difficult to manufacture to exactly the same diameter. Furthermore, rubber tires compress differently under asymmetric load distribution. Either one of these effects can cause substantial dead-reckoning errors.

b) *Uncertainty about the wheelbase*: The wheelbase is defined as the distance between the contact points of the two drive wheels of a differential-drive robot and the floor. The wheelbase must be known in order to compute the amount of rotation of the vehicle. Uncertainty in the effective wheelbase is caused by the fact that rubber tires contact the floor not in one point, but rather in a contact area. The resulting uncertainty about the wheelbase can be on the order of 1% in some commercially available robots.

Systematic dead-reckoning errors can be reduced by adaptive calibration [Fan.1] or UMBark [Bor.2]. In this chapter, the large systematic errors of the tracked vehicle are reduced by the special design of Encoder Trailer. The wheels of the encoder trailer are "knife-edge" thin and not compressible because they are made of aluminum with a thin layer of rubber as a tire. The two wheels are carefully manufactured to nearly the same diameter. Also, since the measurement wheels carry only a small well-balanced load, asymmetric load distribution on the robot has no effect on measurement accuracy. Therefore, the problem of unequal wheel diameters is minimized. Furthermore, since O-ring "tire" contacts the floor only at one point, the uncertainty about the effective wheelbase is minimized. In addition, misalignment of wheels is also minimized by careful design and assembly of the trailer. Therefore, all important systematic errors sources are minimized except minor sources such as limited incremental encoder resolution, which is 1200 pulse/revolution, and limited encoder sampling rate, which is 16 ms/sample in our low level controller. Both of these values are good enough in typical applications.

Systematic errors are particularly serious because they accumulate. On most smooth indoor floors, systematic errors are dominant. However, on rough floors with significant irregularities, non-systematic errors are dominant [Bor.1]. One particularly serious problem with non-systematic errors is that they may appear unexpectedly (for example, when the robot traverses unexpected objects such as cables), and they cause an orientation error, which, in turn, can cause unbounded position errors. Such disturbances can decrease the accuracy of the vehicle's trajectory controller.

4.2 Non-systematic Dead-reckoning Errors

Non-systematic dead-reckoning errors are those errors that are caused by the interaction of the robot with unpredictable features of the environment. For example, irregularities on the floor surface, such as bumps, cracks, or debris, will cause a wheel to rotate more than predicted, because the affected wheel travels up or down the irregularity, in addition to the expected horizontal amount of travel. Non-systematic errors are a great problem for actual applications, because it is impossible to predict an upper bound for the dead-reckoning error [Bor.1].

The typical dead-reckoning is very sensitive to normal floor irregularities such as cracks or bumps, because such disturbances cause orientation errors that induce unbounded lateral errors. To overcome this problem, we have introduced a method called internal position error correction (IPEC) [Bor.1]. With this approach two mobile robots mutually correct their dead-reckoning errors. However, it requires that both robots can measure their relative distance and bearing continuously and accurately. Such redundancy may only have limited application in practical applications. To overcome this problem, we introduced the ET, which is accurate and robust with respect to the typical floor irregularities.

In mobile robot motion control, the orientation errors are the dominant errors since they cause unbounded growth of the contour errors. The tracking errors are usually of less concern [Fan.1, Fen.1].

As shown in the next section, an essential property of the Encoder Trailer is that it is robust with respect to the typical irregularities and unexpected obstacles. Due to this property, the vehicle orientation based on ET does not change after ET travels over bumps.

5. The Robust Property of the Encoder Trailer

Due to the design of the Encoder Trailer, it is shown to be robust with respect to typical floor irregularities and unexpected obstacles in the following postulates:

Postulate 1. The robot's orientation based on encoder trailer remains the same if one wheel of the encoder trailer travels over a bump.

Proof. To prove Postulate 1, it is sufficient to show that the robot's orientation remains the same while one wheel of the encoder trailer travels over a bump during the straight line motion. For straight line motion, the angular velocities are approximately the same for the left and right wheels of the encoder trailer while one wheel travels over a bump. Therefore, the total distance traveled by two wheels are approximately the same. However, the horizontal distance traveled by the left wheel (traveling over a bump) is ΔL less than that of the right wheel. This difference causes an orientation change of γ (positive in this example). As shown in Figure 6, the initial heading of the robot is 90 degrees or $\beta = 90^{o}$. As $AB \perp ED$ and $CD \perp AC$, ϕ equals γ in magnitude. As γ is defined to be positive if the rotation from AB to AC is counter-clockwise and ϕ is defined to be positive if the rotation from CD to DE is counter-clockwise, we can conclude:

$$\phi = -\gamma \tag{15}$$

From Figure 6, we can see that:

$$\theta = 90^{o} + \gamma \tag{16}$$

$$\beta = \theta + \phi \tag{17}$$

Substitute Eqs. (15) and (16) into Eq. (17) to get:

$$\beta = 90^{o} + \gamma - \gamma = 90^{o} \tag{18}$$

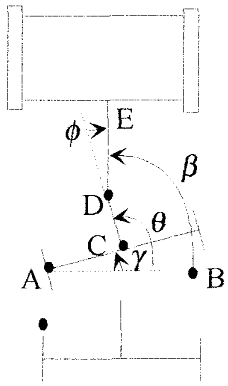

Figure 6 The change of orientation due to traversing a bump

Hence Postulate 1 is proven.

Postulate 2. The robot's orientation based on encoder trailer remains the same if both wheels of the encoder trailer travel over the same bumps.

Proof. Postulate 2 is obvious.

Postulate 3. The robot's orientation based on encoder trailer remains the same if both wheels of the encoder trailer travel over two different bumps.

Proof. To prove Postulate 3, it is sufficient to show that robot's orientation remains the same during the straight line motion. If the bump traversed by left trailer wheel is larger than that of right wheel, the horizontal distance traveled by the left wheel is less than that of right wheel. This difference causes an orientation change of γ (positive in this case). Similarly, if the bump traversed by left trailer wheel is smaller than that of right wheel, there is a negative orientation change of γ. Postulate 3 can be proven similarly as in the proof of Postulate 1.

According to those postulates, the dead-reckoning accuracy based on the ET is not affected by the uneven floors or unexpected objects on the floor. Therefore, all non-systematic errors are compensated except wheel-slippage that has minor effect for the typical application, as shown in the experiments.

If the floor has irregularities or expected obstacles, which is the case in reality, the trailer's accuracy is not affected. However, the regular dead-reckoning encoder is much worse (orders of magnitude worse, as reported in [Bor.1]). This robustness with respect the typical irregularity is the essential feature of the Encoder Trailer.

6. Experimental Validation

Experiments are conducted to assess the dead-reckoning accuracy of the ET. The vehicle is driven by a joystick to follow the 4×4 m path and we compared its computed (i.e., using dead-reckoning) position with the vehicle's actually measured stopping position. The actual starting and stopping position is measured by 3 sonars installed on the vehicle and a corner bracket. The initial position of the ET is calculated based on the measured starting position of the vehicle by 3 sonars. The experiments consist of the nominal 4×4 m bi-directional square path.

Each bump may cause an orientation error of 0.6 degree for the dead-reckoning of the typical mobile robot [Bor.1], resulting in a 6 degree total orientation error for 10 bumps. However, according to Table 1, the average orientation error for the Encoder Trailer is approximately the same whether there are 10 bumps or not. This robust property with respect to the typical uneven floors and expected objects is the most essential feature of the ET.

Ave. Errors	Without Bumps	10 Bumps
CW	-0.32 deg.	0.57 deg.
CCW	0.076 deg.	-0.71

Table 1 The Average Orientation Errors for the ET

7. Conclusion

A basic encoder trailer is developed and discussed in detail in this paper. Its unique design minimized the systematic errors and compensated for the most important nonsystematic errors. Experiments verified that this encoder trailer can give excellent results in both clockwise direction and counterclockwise directions, while the main track encoders fail to provide any useful information on the vehicle's position and orientation due to slippage. Three postulates prove ET's robustness with respect to unexpected obstacles. To verify those postulates, experiments are conducted with bumps and without bumps. The experimental results confirm those postulates.

References

[Bor.1] Borenstein, J., "Internal Correction of Dead-reckoning Errors With the Compliant Linkage Vehicle," accepted for publication in the Journal of Robotic Systems, to appear in the April 1995 issue.

[Bor.2] Borenstein, J., and Feng L., "A Method for Measuring, Comparing, and Correcting Dead-reckoning Errors in Mobile Robots," Technical Report prepared for United States Department of Energy's Robotics Technology Development Program, December 1994.

[Fan.1] Fan, Zhejun, Koren, Y., and Wehe, D., "Tracked Mobile Robot Control: Hybrid Approach," Control Engineering Practice, Vol. 3, No. 3, 1995, pp. 329-336.

[Fan.2] Fan, Z., Borenstein, J., Wehe, D., Koren, Y., "Experimental Evaluation of an Encoder Trailer Dead-reckoning in Tracked Mobile Robots," The University of Michigan Technical Report, UM-MEAM-94-24, 1994.

[Fen.1] Feng, L, Koren, Y., and Borenstein, J., "Cross-Coupling Motion Controller for Mobile Robots," IEEE Journal of Control Systems, December 1993, pp. 35-43.

[Won.1] Wong, J. Y., *Theory of Ground Vehicles*, Wiley-Interscience Publication, 1993.