2002

Calibrating a 4-wheel mobile robot

Phillip J. McKerrow
University of Wollongong, phillip@uow.edu.au

D. Ratner
University of Wollongong, dannyr@uow.edu.au

Publication Details

This article was published as: McKerrow, P, Calibrating a 4-wheel mobile robot, Proceedings IEEE/RSJ International Conference on Intelligent Robots and Systems, 30 September-5 October 2002, 1, 859-864. Copyright IEEE 2002.

Calibrating a 4-wheel mobile robot

Abstract
When a mobile robot is constructed the odometry must be calibrated. Calibrating a 4-wheel robot requires the accurate measurement of steering angle as well as translation and rotation. Some measurements are made with a tape measure and some with ultrasonic sensors. The measurements are used to determine the parameters of the odometry calibration matrix and the steering kinematic model. A procedure for calibrating a 4-wheel robot is discussed.

Disciplines
Physical Sciences and Mathematics

Publication Details
This article was published as: McKerrow, P, Calibrating a 4-wheel mobile robot, Proceedings IEEE/RSJ International Conference on Intelligent Robots and Systems, 30 September-5 October 2002, 1, 859-864.

Proceedings of the 2002 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
EPFL, Lausanne, Switzerland • October 2002

Calibrating a 4-wheel mobile robot

[1]Phillip J. McKerrow, [2]Danny Ratner

[1]*University of Wollongong, Wollongong, Australia,* phillip@uow.edu.au
[2]*University of Wollongong, Wollongong, Australia,* dr19@uow.edu.au

Abstract

When a mobile robot is constructed the odometry must be calibrated. Calibrating a 4-wheel robot requires the accurate measurement of steering angle as well as translation and rotation. Some measurements are made with a tape measure and some with ultrasonic sensors. The measurements are used to determine the parameters of the odometry calibration matrix and the steering kinematic model. A procedure for calibrating a 4-wheel robot is discussed.

1. Introduction

When a mobile robot is doing landmark navigation, the navigator may command the robot to travel a certain distance between landmarks or follow a given curve from one leg to another [7]. As these motions are controlled using dead reckoning, accurate calibration of odometry and steering angle is required.

The Titan 4-wheel drive robot (Figure 1) is built from a 4-wheel drive wheel chair. It achieves Ackerman steering with differential velocity steering. It uses low-pressure pneumatic tyres and the front wheels act as castors when travelling forward. The wheel chair is controlled with joy-stick commands to control forward velocity and steering angle. Both are achieved by controlling the voltage on the motor armatures.

To convert it into a mobile robot for outdoor navigation research, we had to add sensors for position and steering angle. We used 2,500 pulses per revolution optical encoders. A machined disk was mounted on each of the rear drive axels. A second disk was attached to the axel of the encoder. A neoprene ring forms a friction coupling between the two disks. This system has been effective but the measurement is course (about 0.49 mm per pulse). The steering encoder was mounted on the steering axis of the left front wheel. As the front wheels castor, the steering axis is forward of the rotational axis of the wheel.

We model the motion kinematics of the robot with an odometry calibration matrix, which maps wheel rotation to robot motion. Calibration is the process of finding values for the parameters in the calibration matrix. The parameters compensate for the mechanical errors of the robot. They are calculated from measurements of the position of objects relative to the robot.

Determining the calibration matrix completes the calibration of a 2-wheel robot, but not the calibration of a 4-wheel robot. The kinematic model of the later includes a model of the steering. This model also includes parameters that have to be calibrated.

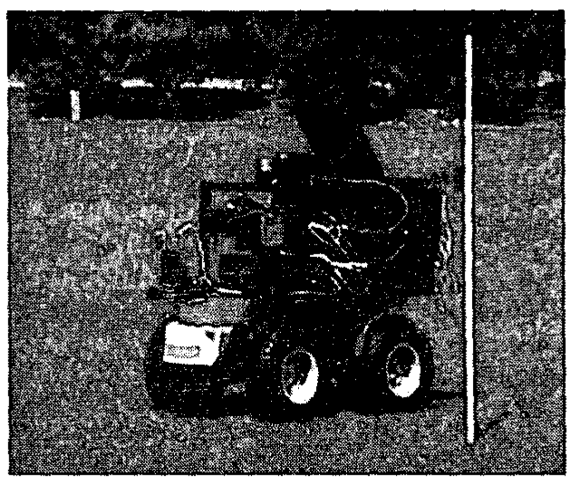

Figure 1: *Titan 4-wheel drive robot navigating across a field using poles as landmarks.*

2. Odometry errors

Dead reckoning is the process of calculating the location of a mobile robot from measurements of the angular rotation of odometer wheels. These wheels can be driven or freewheeling. Angular rotation is measured with rotary encoders attached to these wheels.

Errors in odometry arise from two sources: tolerances in the construction of the mobile robot and interaction with the environment. Construction errors persist over time and can be referred to as systematic errors. Errors due to changes in the environment, such as uneven terrain or wheel slippage, are short term and can be referred to as dynamic errors. The purpose of calibration is to minimise the effects of systematic errors.

In a 2-wheel robot the three most significant causes of systematic errors are: (1) uncertainty about wheel diameter, (2) unequal wheel diameters and (3) uncertainty about the effective wheelbase [1]. The first causes errors in translation measurement. All three cause errors in rotation measurement.

The UMBmark calibration technique for 2-wheel robots [1] corrects for the second and third causes of error. The robot is driven around a 4m*4m square, first in a clockwise direction and then in an anticlockwise direction. Chong and Kleeman [2] used this procedure to calibrate knife edge odometer wheels.

While a 4-wheel robot rotates about the centre of the axis between the two rear wheels (Figure 2), it cannot rotate on the spot like a 2-wheel robot. Hence, the calculation of location from odometry is the same, but the control of the radius of a turn is dependent on both the length of the robot and the angle of the front steering wheels. In the Titan robot the steering angle changes the kinematic length of the robot (Figure 4), because the front wheels act as castors. This introduces a forth source of error: uncertainty about the effective length of the robot.

3. Odometry equations

A wheel moves by rolling along the ground. A wheel with a solid tyre touches the ground at an instantaneous contact point. A wheel with a soft tyre contacts the ground over an area because the weight of the vehicle compresses the tyre. For rolling on a solid surface, we model both with a contact point, adjusting the radius to compensate for the compression of the soft tyre.

As a wheel turns the instantaneous contact point moves both on the wheel and on the ground. For perfect rolling, the velocity of the contact point equals the peripheral velocity of the wheel. When slippage occurs, the velocity of the contact point on the ground is different to its velocity on the wheel.

Wheel rotation is measured with rotary encoders. When a wheel rotates, the number of pulses is proportional to the angle rotated by the wheel. Ignoring wheel slip, the linear distance δd_l travelled by the periphery of the left wheel in time $\delta t = t(t) - t(t\text{-}1)$ is:

$$\delta d_l = k_l * \delta e_l = \frac{r_l * \delta e_l}{p_l} = r_l * \delta \phi_l \tag{1}$$

$$\delta d_r = k_r * \delta e_r \text{ in millimetres} \tag{2}$$

where r_l = the radius of the left wheel, ϕ_l = the angle of rotation of the left wheel, e_l = left encoder count, p_l = left encoder pulses per degree, ω_l = angular velocity of the left wheel, v_l = linear velocity of the left wheel contact point, and k_l and k_r are left and right wheel calibration parameters.

Slippage of either wheel results in dynamic errors in odometry. When calibrating a robot the measurement setup must be designed to ensure that no slippage occurs. The translation (D_R) and rotation (θ_R) of the robot are calculated from the linear distances moved by the peripheries of the drive wheels.

$$D_R = \frac{d_r + d_l}{2} = v_R * t \text{ and } \delta d = \frac{\delta d_l + \delta d_r}{2} \tag{3}$$

where v_R is the linear velocity of the robot, $d_l = d_l(t\text{-}1) + \delta d_l$ is the translation of the left wheel, and, $d_r = d_r(t\text{-}1) + \delta d_r$

$$\theta_R = \frac{d_r - d_l}{W_R} = k_\theta\,(k_r e_r - k_l e_l) \text{ in radians} \tag{4}$$

where $W_R = 2*r_R$ is the wheel base, and k_θ is the rotation calibration parameter.

When the wheel velocities are equal and opposite, the robot spins around its centre. Four-wheel, car like robots (Figure 5) cannot spin around an axis. However, the motion of the robot around an arc can be decomposed into rotation and translation components, which are modelled by Equations 3 and 4.

To model the kinematics of a mobile robot, we locate a robot frame (x,y,θ) midway between the rear wheels. Also, sensors and wheels are represented by coordinate frames which are fixed relative to the robot frame. When the robot is turning a rotation frame is located at the centre of rotation (c_{rot} in Figure 2).

We control mobile robots by controlling the angular velocity of the drive motors. Consequently, their kinematics is often modelled with velocity equations. The ratio of the angular velocity of the motors ω_{lm} to the angular velocity of the wheels ω_l is determined by the drive train. With belt drives and gearboxes it is modelled with the gear ratio n.

$$\omega_l = n * \omega_{lm} \tag{5}$$

The linear velocity of the periphery of the left wheel, (left side of a robot), when there is no slippage, is:

$$v_l = r_l * \omega_l = \frac{\delta d_l}{\delta t} \tag{6}$$

The general motion of a mobile robot can be decomposed into a translation component and a rotation component. A robot moves with combined translation (linear velocity v_R) and rotation (angular velocity ω_R) when the angular velocities of the wheels are different.

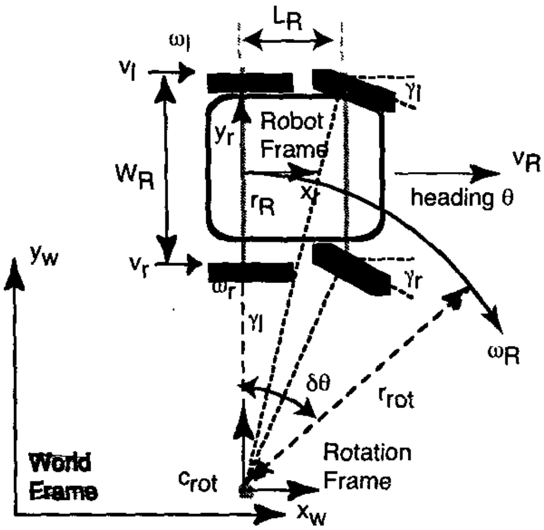

Figure 2: Kinematics of a 4-wheeled robot

$$v_R = r_{rot}\omega_R = \frac{v_r + v_l}{2} \tag{7}$$

and $$\omega_R = \left(\frac{v_r - v_l}{W_R}\right) \tag{8}$$

The location of the robot in cartesian coordinates is calculated each time step by integrating the distance moved, assuming that δt is small and so $\delta\theta_R$ is small.

$$\delta x = d * \cos\theta_R \tag{9}$$

$$\delta y = d * \sin\theta_R \tag{10}$$

$$x = x(t-1) + \delta x \tag{11}$$

$$y = y(t-1) + \delta y \tag{12}$$

4. Odometry calibration matrix

These kinematic equations make assumptions about the robot's mechanical design and construction. Wheels are assumed to be aligned because the axes of the wheels are assumed to be collinear with the wheels orthogonal to these axes. When a robot is precisely manufactured, the left and right dimensions are the same and the above equations calculate the location correctly.

As precise manufacture is very expensive, all robots require calibration. The kinematic equations include three calibration parameters. The first (k_l) is the millimetres of translation (d_l) per encoder count of the left wheel (e_l). This parameter compensates for variations in wheel radius, tyre inflation and gear ratio from designed values. It is measured by driving the robot along a straight path and measuring both the distance traveled and the encoder count for the left wheel. From equation 1,

$$k_l = \frac{\delta d_l}{\delta e_l} \tag{13}$$

The second parameter (k_r) is the millimetres of translation (d_r) per encoder count of the right wheel (e_r). Differences between the radii of the wheels show up in the odometry as the robot following a curved path (Figure 3).

The third parameter (k_θ) is the degrees the robot turns around its centre per encoder count. This parameter compensates for variation in the wheelbase of the robot from the design value. From Equation 4:

$$k_\theta = \frac{\theta_R}{k_r e_r - k_l e_l} \tag{14}$$

These equations can be written in matrix form to obtain a calibration matrix. Now calibration of odometry is the process of finding the parameters of the matrix.

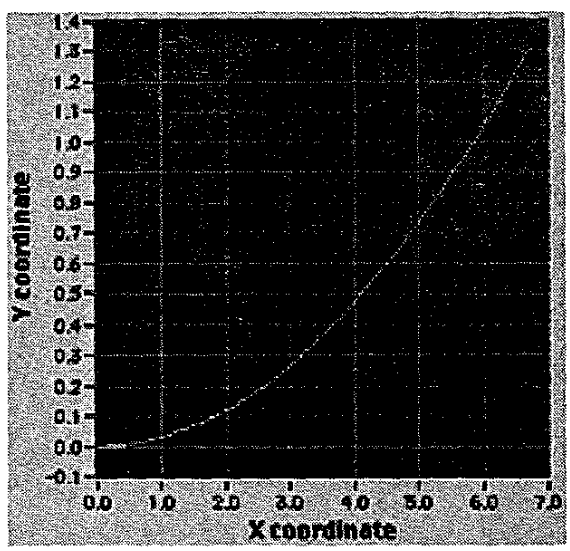

Figure 3. *Differences between left and right sides of Titan robot causing odometry to veer to the left while travelling in a straight line – dimensions in meters.*

$$\begin{bmatrix} D_R \\ \theta_R \end{bmatrix} = \begin{bmatrix} \frac{k_r}{2} & \frac{k_l}{2} \\ k_\theta k_r & -k_\theta k_l \end{bmatrix} * \begin{bmatrix} e_r \\ e_l \end{bmatrix} \tag{15}$$

5. Steering model

As shown in Figure 2, when the robot moves with combined translation and rotation it steers around an arc. We locate a rotation frame at the centre of curvature and define the arc by the radius of rotation (r_{rot}). The radius of the arc is determined by the length of the robot and the steering angle (k_s is a calibration factor for uncertainty in the length of the robot).

$$r_{rot} = \frac{V_R}{\omega_R} = \frac{\delta D_R}{\delta \theta_R} \tag{16}$$

$$\tan \gamma_l = \frac{k_s L_R}{r_{rot} - W_R} \text{ for a right turn} \tag{17}$$

However, when we investigate the steering we find that one result of the castor design of the front wheels effect of the front wheels is that the length of the robot changes with steering angle (Figure 4).

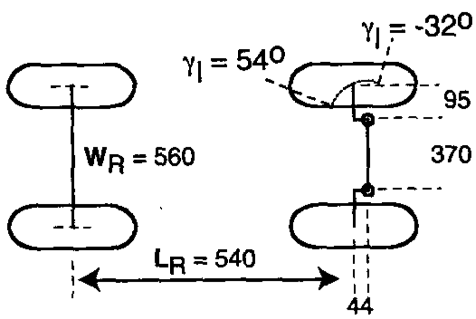

Figure 4. Steering kinematics, showing castor arrangement of front wheels

A second result of the castor arrangement is that the steering angle of the left and right wheels is different (Figure 5). The different angles are required to achieve Ackerman steering. Also, the relationship between the wheel angles is non-linear, results in the steering being close to Ackerman over a large range of angles.

6. Calibrating the steering

The first step in calibration is to set the tyre pressures to be equal. For Titan, the tyre pressure is 25 Kpa (9% of the pressure of a car tyre), requiring a sensitive electronic gauge. Next, we have to measure the offset (zero error) and scale of the steering encoder. As the encoder is directly coupled to the steering axis, the scale can be calculated (SCALE = 0.288° per pulse).

A manual calibration of the zero steering position is made by holding a straight edge against the left steering wheel and turning it until the straight edge touches the left rear wheel. Best alignment is achieved when the straight edge touches both tyres at two points, but, the knobbles on the tyres limit the precision.

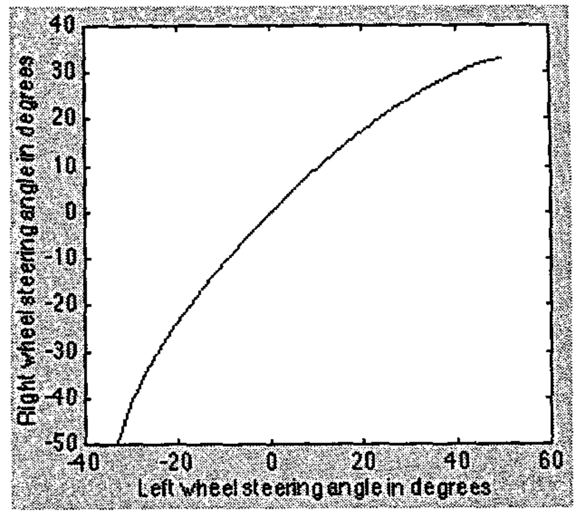

Figure 5. Steering angle non-linearity

A better approach is to place the robot beside a straight surface, formed by stretching a cord between two poles (Figure 6). The steering control is set to zero steering angle. As the robot is driven along a path roughly parallel to the cord, the range to the cord is measured with the ultrasonic sensor.

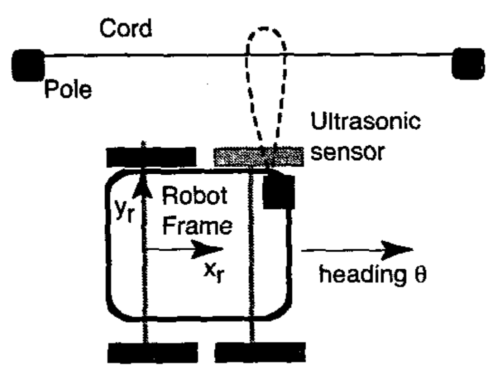

Figure 6. Environment for measuring calibration parameters

The range to the cord is plotted against distance in Figure 7. As the cord is straight, any error in the zero position of the steering will show up as a curve in the graph. When the steering is correctly calibrated, the graph will be straight.

Equation 17 relates the steering angle and the radius of rotation. Figure 4 shows that the castoring of the front wheels causes the length of the robot to change with steering angle.

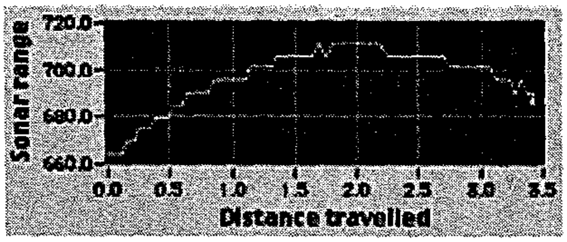

Figure 7. Calibrating steering zero position – range (mm) versus distance travelled (m).

The uncertainty in the wheelbase and the uncertainty in the length of the robot both effect the calculation of steering angle to achieve a certain radius of rotation. Calibrating the wheelbase is discussed in Section 8, and must be done first.

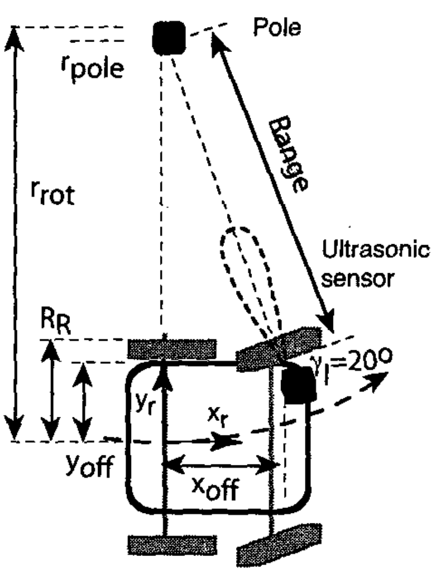

Figure 8. Set up for measuring the uncertainties in the length of the robot.

To calibrate the length of the robot, we set the steering control to drive the robot in a circle with a pole placed close to the centre. The ultrasonic sensor is angled toward the pole, so that range is measured as the robot travels around the circle (Figure 8). The data can be plotted for visual inspection. Also, the average and standard deviation of the range during the traversal of a circle is calculated. The turning radius of the robot is:

$$r_{rot} = \left(range_{avg} + radius_{pole}\right)\cos\gamma_l + y_{off} \qquad (18)$$

These values are substituted into Equation 20 to calibrate the length calibration factor. Comparing the standard deviation of the range between successive circles will show whether the robot is crabbing or not.

7. Odometry calibration issues

The UBMark procedure requires the robot to be driven around a 4 meter square. For a 2-wheel robot, the trajectory is 8 decoupled motions: 4 pairs of 4m translation followed by a 90° rotation. However, the trajectory for a 4-wheel robot is not decoupled. As a 4-wheel robot cannot rotate, it must turn around an arc, so the length of the translation must be reduced by the radius of the arc.

However, moving from a straight segment to an arc requires a transition curve, such as a clothoid or a quintic polynomial [3]. This implies that trajectory planning and trajectory following algorithms, as well as distance and steering control, have been implemented. But, tuning these algorithms requires a calibrated robot. So, to progress the development of the robot, we had to find simple ways to calibrate it.

Coupling between measurement and control can also create problems. It is not always obvious whether an error that you are observing is in the control or the calibration. For example, when translating a robot a given distance, three distances are involved: the commanded distance, the measured distance, and the actual distance.

An error in the control system can result in the actual distance being different to the commanded distance. An error in the calibration can result in the actual distance being different to the measured distance. When these differences are equal and opposite, the control can appear to be translating the robot by the correct distance. A significant practical problem when designing a calibration process for a robot is decoupling these three distances.

8. Odometry calibration procedure

The odometry calibration procedure consists of finding a set of motions that decouple the measurement of the three calibration parameters. These measurements are done with ultrasonic sensors and represent ground truth to which the odometry calculations are compared [6].

First, the robot is commanded to translate a given distance, toward a flat surface with the ultrasonic sensor pointing forward. The previous calibration of steering ensures that the robot travels in a straight line. The distance the robot moves is measured with a tape measure and with the ultrasonic sensor.

From the encoder values for both wheels, an initial value is calculated for both the left (Equation 1) and right (Equation 2) wheel calibration parameters. To confirm that these values are correct, the robot is commanded to drive along the straight cord again (as for the steering zero angle calibration).

The x and y coordinates calculated by the odometry are plotted (as in Figure 3), and the range versus distance moved (as in Figure 7). The cord is straight, and we previously calibrated the zero steering angle, so both graphs should be straight. If they are not, then the right wheel calibration factor is adjusted until they are.

The final parameter to calibrate is the wheelbase (Equation 4). To calibrate this parameter we drive the robot along the cord, turn left around the pole at the right end, and drive the robot along the other side of the cord (in the opposite direction) (Figure 9).

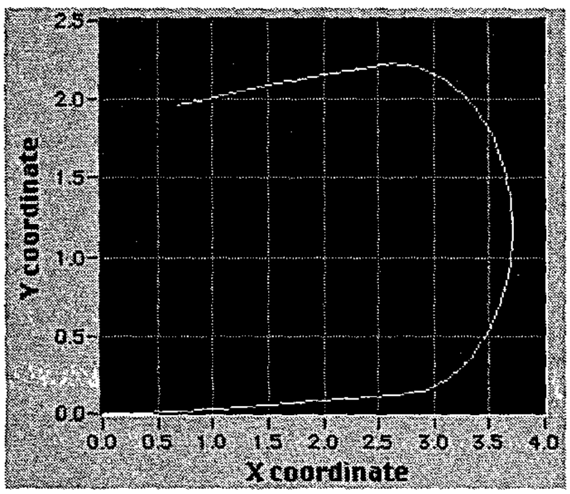

Figure 9. *Path traversed by robot during wheelbase calibration*

From the range readings, the orientation of the robot as it travels along the cord can be determined using the outline segment algorithm [4] and fusing the segments into lines [5]. The difference between the two orientations is the angle turned by the robot. This angle, together with the rear encoder counts is used to calculate the wheelbase calibration parameter using Equation 4. Finally, we go back and calculate the length calibration parameter.

9. Accuracy

The accuracy of the calibration procedure is limited by the quality of the calibration environment and the resolution of the sensors. Factors which effect the quality of the environment include the flatness of the floor, and the resolution of the sensors.

As ultrasonic sensors are used as the external sensors, it is important to calibrate their range readings. One way is to measure the range to an object placed at a known distance. The resolution of ultrasonic sensors is dependent upon the signal processing. While, ultrasonic sensors can achieve 0.1mm resolution [2], those on the Labmate [1] have 1mm resolution.

The CTFM sensor on Titan has 5.27mm resolution (at 20° C) when set to the a maximum range of 2.5 metres (100msec sweep time), due to the use of an FFT to determine the frequency of the echo. When measuring slope using 2 range readings taken 1 meter apart, the slope resolution is 0.18°.

While the surface to the left is straight, the floor may not be flat. When a robot traverses an uneven floor the inclination of the robot changes and the heading of the robot can change. Both result in variations in sensor readings.

10. Conclusion

When a robot is assembled, its odometry and steering has to be calibrated. In this paper, we derived a calibration matrix and steering kinematics for a 4-wheel robot. We presented a simple process for measuring the calibration parameters. This procedure uses ultrasonic sensors to measure the motion of the robot relative to a flat surface to the side.

11. References

[1] J. Borenstein and L. Feng, "Measurement and Correction of Systematic Odometry Errors in Mobile Robots", IEEE Transactions on Robotics and Automation, vol 12, no 6, pp 869-880, December 1996.

[2] K.S. Chong. and L.Kleeman, "Accurate Odometry and Error Modelling for a Mobile Robot", Proceedings IEEE International Conference on Robotics and Automation. pp 2783-2788, April, 1997.

[3] W. Nelson, "Continuous-Curvature Paths for Autonomous Vehicles", Proc IEEE Conference on Robotics and Automation, pp 1260-1264. 1989.

[4] P.J. McKerrow, 'Echolocation - From Range to Outline Segments', Robotics and Autonomous Systems, Elsevier, Vol 11, No 4, pp 205-211, 1993.

[5] P.J. McKerrow, "Robot Perception with Ultrasonic Sensors using Data Fusion", Proceedings IEEE Systems, Man and Cybernetics Conference, Vancouver, pp 1380-1385, October, 1995.

[6] P.J. McKerrow and S.J. Volk, "Correcting Mismatch in a Data Fusion System for Ultrasonic Mapping with a Mobile Robot", Proceedings MFI '96, IEEE, Washington, DC, pp749-756, December, 1996.

[7] P.J. McKerrow, and D. Ratner "Navigating an outdoor robot with simple discontinouus landmarks', Proceedings EUROBOT'2001. Lund, Sweden, pp 33-39, September, 2001.