Article

On-Board Correction of Systematic Odometry Errors in Differential Robots

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Abstract: An easier method for the calibration of differential drive robots is presented. Most of the calibration is done on-board and it is not necessary to expend too much time taking note of the robot's position. The calibration method does not need a big free space to perform the tests. The bigger space is just in a straight line, which is easy to find. Results with the proposed method are compared with those from UMB as a reference, and they show very little deviation while the proposed calibration is much simpler.

Keywords: differential drive robot; calibration; systematic error.

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1. Introduction

Odometry based on encoder information is the way used to get the relative position on most of the differential drive robots. In this paper, we describe our solution for the calibration of such robots in order to avoid systematic error.

1.1. Odometry calculations

As a summary, we include the odometry expresions for differential robots, in order to point out the dependency of those calculations on the parameters we need to calibrate. Iteratively, the position of the robot is obtained by approximation. For a given iteration, P_R and P_L represents the pulses of the right and left encoder respectively.

The factor that converts the pulses into mm of linear displacement is C_m, given by

$$C_m = \frac{\pi D}{C_e}$$

where D is the wheel diameter and C_e is the number of pulses per revolution of our encoder. So, in each iteration i, the distance travelled by the right and left wheels $\Delta U_{R/L,i}$ is

$$\Delta U_{R/L,i} = C_m P_{R/L,i}$$

The distance travelled by the centre of the wheel axis and the change in the orientation in each iteration are given by

$$\Delta U_i = \frac{1}{2}(\Delta U_{R,i} + \Delta U_{L,i})$$

$$\Delta \theta_i = \frac{1}{b}(\Delta U_{R,i} - \Delta U_{L,i})$$

where b is the wheelbase: the distance from the contact point of both wheels with the floor. The global orientation is

$$\theta_i = \theta_{i-1} + \Delta \theta_i$$

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And finally, the estimated position of the robot for iteration i is

$$X_i = X_{i-1} + \Delta U_i cos(\theta_i)$$

$$Y_i = Y_{i-1} + \Delta U_i sin(\theta_i)$$

As can be seen from these equations, they depend on D and b, where D will be D_R and D_L because of the two wheels.

1.2. Related work

Deviations in these parameters produce systematic errors, and a calibration process is necessary for differential drive robots due to construction errors. Non-systematic errors will appear due to a slippery or unregular floor, but these are not our objective in this paper.

[1] and [2] are the main references for systematic odometry error correction. In [1] a 4 m side square is travelled clockwise and counterclockwise in order to correct the relation of the wheel diameters and the distance between the wheels.

There are 3 sources of error. First, in the average wheel diameter D_{avg}, we consider a scaling factor E_s from the nominal value.

$$D_{avg} = E_s D_{nom}$$

Second, the fact that the wheel diameters are unequal. Depending on the construction of the wheel, this error can be larger or smaller. If we take the diameter D_R of the right wheel as a reference, the left diameter D_L is given by the factor E_d:

$$D_L = E_d D_R$$

The last error source to adjust is the wheelbase, b, so the relation between the actual wheelbase, b_{act} and the nominal is

$$b_{act} = E_b b_{nom}$$

Some papers have proposed correcting E_d and E_b [1] and [3]. For example, in [4], the 3 parameters are adjusted.

In [4], two experiments are proposed. A movement forward with a rotation of π and then coming back, one with a clockwise rotation and one counterclokwise. Simulation results are shown, but it does not indicate the number of iterations of the experiments. In [1], travelling over a 4 m side square both counterclockwise and clockwise is proposed, 5 times each. One of the problems is that you need a freee space of 4 m $\times$ 4 m plus the dimensions of the robot with a regular non-slippery floor. They also assumed $E_s = 1$, so you need to calibrate D_{avg} before starting the experiments. The robot must be placed carefully in the same position and orientation for the 10 trials. In [5], the expresions from [1] are corrected. They also analyse the effect of the square path size: 1 m $\times$ 1 m was not successful, because is was too small. Their expressions show in simulation better convergence if the experiment is iterated and better results for 2 m $\times$ 2 m. In [3] a bidirectional circular path test is proposed to estimate the correction factors. They said: 'the low noise procedure allows to obtain good results without the need to repeat the experimets.' They point out that a circular path of 5 m in diameter, that it is even worse than the 4 m square recommended in [1].

A description of self-calibration is presented in [6]. It is based on a laser range finder that allows high accuracy measurement. Similar papers using laser range finders can be found in the literature, but those are not related with the present paper.

We are looking for a method for occasional calibration that will require little time. Calibration is important to increase accuracy and to reduce the number of corrections needed using absolute position estimation: these can be reduced if the relative position is accurate. In the present paper, a calibration method to reduce systematic relative position error for a differential drive mobile robot is presented. The proposed method needs just enough space for the robot to turn and to perform a

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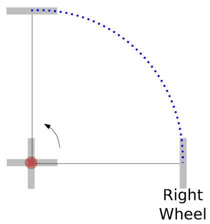

Figure 1. Robot scheme while turning with left wheel stopped.

3 m long straight movement. It is also important to note that most of the data for the calibration are obtained and calculated on-board. It is not necessary to be careful with the initial position of the robot. Both features allow calibrating the robot very quickly.

Our research group has been working on developing many different technical aids under the solidarity program "Padrino Tecnológico" ($http://padrinotecnologico.org/$), from walkers to electric wheelchairs. This is an approach to use robots for assistive tasks. Orientation for people with cognitive disorder is being stressed, and helping to increase their autonomy is the first goal of this project, although many other functionalities can be included using the same hardware. This is the second platform we have worked on. The previous one was too small to get into disabled attention centres.

2. Calibration method

2.1. Estimation of E_d

The proposed calibration method aims at reducing the time required to perform a calibration. We are searching for the actual D_R, D_L and b. The first experiment looks for the relation $E_d = D_R/D_L$: the robot will describe a circular path with the left wheel stopped for N rounds. Then, this is repeated with the right wheel stopped for another N rounds. Fig. 1 represents the robot while turning with a stopped left wheel. The distance travelled, s, in each round, can be expressed in different ways depending on the **effective** wheelbase, and the number of pulses in each round P_{1_R} and P_{1_L}:

$$s = 2\pi b = \frac{P_{1_R}\pi D_R}{c_e} = \frac{P_{1_L}\pi D_L}{c_e} \tag{1}$$

where c_e pulses/rev is a constant to translate wheel turns to pulses.

Using Equation (1) yields

$$E_d = \frac{D_L}{D_R} = \frac{P_{1_R}}{P_{1_L}}$$

The movements involved in this test suffer from one problem: stopped wheels need low friction to perform the circular movement of the robot but enough friction to get the wheel at the same point. When the test is done on a slippery floor, a small piece (see Fig. 2) has been designed to achieve this goal, so now the wheel pivots on that piece over an axial bearing. Fig. 3 illustrate the situation of the wheel during the test: the wheel, the piece, and the axial bearing are visible.

In our case, this modification of the robot structure introduces a little distortion in the mechanism system, increasing the height of the stopped wheels by 6 mm, that is, approximately 0.6° for the wheel axis. We used the piece on a polished stone floor and we removed it for the lab floor.

If a distance or orientation sensor is available, the N rounds can be monitored in order to extract the relation E_d. In our case, an ultrasound sensor (HC-2R04) has been used to get the distances to the obstacles while turning. Fig. 6 and the zoomed Fig. 7 show the distances from the sensor as a function of the pulses of the encoder of the moving wheel.

The autocorrelation of the sequence of the distances has been obtained and the period $P_{1_{R/L}}$ can be easily extracted onboard if the robot has sufficient capabilities. Fig. 8 shows the autocorrelation for

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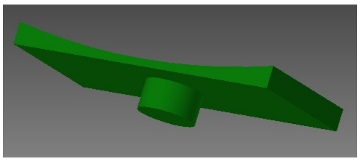

Figure 2. Bearing Base.

Figure 3. Wheel Detail.

the distances read from the ultrasound sensor. It must be take into account that these do not necesarily have to be accurate distances and the scenario must not be 'periodic', i.e. an irregular one is better in order to obtain the number of pulses per turn.

2.2. *Estimation of D_R*

The movement of the robot while trying to travel in a straight line is ilustrated in Fig. 4. The actual distance from A to B is not the output of the encoder corrected by the conversion factor c_m. However, if the robot's orientation is kept below a given threshold, the maximum deviation of that measurement can be controlled. For example, if the orientation remains below 1°, then the maximum deviation remains less than 0.02%, and for 2°, less than 0.06%. Those deviations can be accepted for our experiments and we will analyse the robot's orientation to reject those measurements where the maximum deviation of orientation has been greater than a given threshold.

The right wheel is taken as a reference, and D_L is corrected by the factor E_d. In the second experiment, a straight motion for 3 m is performed by the robot, and the number of pulses of the right wheel, P_{2_R}, with the actual distance traveled d_{3m} gives the conversion factor from pulses to mm as

$$c_m = \frac{d_{3m}}{P_{2_R}}$$

The actual D_R is given by

$$D_R = \frac{c_m c_e}{\pi} \tag{2}$$

in our case, $c_e = 152.7$ pulses/rev.

Coming back to Equation (1), the actual b is given by

$$b_{act} = \frac{P_{1_R} D_R}{2c_e}$$

and E_s is obtained as the mean of D_R and D_L:

$$Es = \frac{D_R}{D_{nom}} \frac{1 + E_d}{2} \tag{3}$$

We found a problem with the effective wheelbase (b_{eff}). It is larger when the speed–wheel relation is close to unity, and is smaller when one of the wheels is stopped. Most of the movements during

Figure 4. Movement diagram.

Figure 5. Robotic platform.

the robot's operation are performed with the two wheels having similar speeds, but the proposed calibration method uses part of the experiments with one wheel stopped.

In order to get b_{eff}, we performed a movement turning over one stopped wheel and then turning with both wheels at the same speed, taking into account the number of pulses to complete a turn with the stopped wheel $P_{0_{R_b}}$ and the number of pulses when turning with the two wheels at the same speed $P_{0_{R_{b/2}}}$. Then, the factor to obtain b_{eff} is

$$K = \frac{2 * P_{0_{R_{b/2}}}}{P_{0_{R_b}}}$$

3. Experiments

Our robot software has 3 parameters to adjust. They are set before starting each calibration method:

$$c_m = \frac{\pi D_{nom}}{c_e} = \frac{\pi 190}{157.2} = 3.80 \quad mm/pulse$$

$$E_d = 1$$

and

$$b = 590 \quad mm$$

3.1. UAH Calibration 1

The first experiment was carried out with the robot platform shown in Fig. 5. First, we obtained the effective wheelbase factor for movements with a stopped wheel, so the robot performed movements as was explained previously. We get $P_{0_{R_b}} = 951$ pulses and $P_{0_{R_{b/2}}} = 478$ pulses, so

$$K = 1.0053.$$

Then, with the left wheel stopped, the robot performed a given number of rounds and the experiment was then repeated for a stopped right wheel.

Fig. 6 shows the output of the ultrasound sensor for 7 turns and in Fig. 7 just 2 periods are plotted. It is important to be sure that the scenario is not symmetrical in order to get the proper period. In our case, because of the limited sensor range, the scenario must not be very large. Fig. 8 shows the

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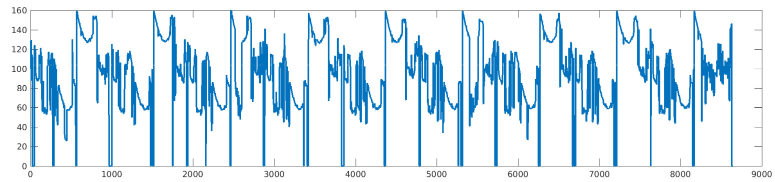

Figure 6. Sensor Output rotating over the left wheel.

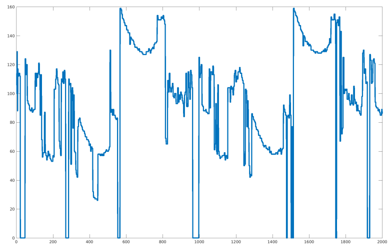

Figure 7. Zoom Sensor Output over the left wheel.

Table 1. Results from the second experiments

Iteration	P_{2_R} (Pulses)	distance (mm)	$max(\theta)$ (degrees)	c_m (mm/pulse)
1	795	3078	0.75	3.87
2	795	3068	0.93	3.86
3	795	3068	0.75	3.86
4	795	3070	0.76	3.86

98 autocorrelation sequence of the sensor output and from this data the period, i.e. the number of pulses
99 per turn, can be easily obtained.

The number of pulses when the left wheel is stopped per turn (period) P_{1_R} is

$$P_{1_R} = \{951.1, 952.0, 951.0\} \quad pulses$$

for three iterations, as can be seen the variance for different iterations is low. When the right wheel is stopped, P_{1_L} is

$$P_{1_L} = \{944.0, 943.0, 943.0\} \quad pulses$$

also for three iterations of the experiment. So, taking the mean value

$$Ed = \frac{D_L}{D_R} = \frac{P_{1_R}}{P_{1_L}} = 1.007$$

100 Now, in order to perform the second experiment, the E_d factor must be included in the robot's
101 odometry, so we set up the new E_d in the robot software or automatically update it if the calculation is
102 done on-board.

103 Then a 3m long motion is performed and the number of pulses in several iterations are illustrated
104 in Table 1, where the number of pulses for the distance actually travelled gives the factor c_m. The
105 maximum deviation in orientation is also considered in order to discard those results with deviations
106 bigger than 1°.

107 From the results in Table 1 we get $c_m = 3.86$ mm/pulse.

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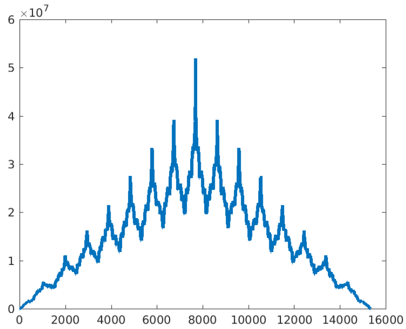

Figure 8. Sensor output autocorrelation sequence.

The wheelbase distance b can be obtained from

$$2\pi b = P_{1_R} \cdot c_m$$

but P_{1_R} was obtained from a movement with stopped left wheel, so it must be corrected with K:

$$2\pi \frac{b}{K} = P_{1_R} \cdot c_m$$

so, $b = \frac{951.3 \cdot 3.86 \cdot 1.0053}{2\pi} = 586.5$ mm, from Equation (2) $D_R = 187.61$ mm and from Equation (3) $E_s = 0.9924$ where the used nominal diameter was $D_{nom} = 190$ mm and the new avarage of the diameters is $D_{avg} = 188.55$ mm. We do not use D_{avg} but it will be necessary to perform a calibration from [1] for comparison.

3.2. UMB Calibration

The D_{avg} from UAH calibration 1 is used to perform the UBM calibration [1]. The setup parameters are

$$c_m = \frac{\pi D_{nom}}{c_e} = \frac{\pi 188.55}{152.7} = 3.88$$

$$E_d = 1$$

and

$$b = 590.$$

The UMB method [1] was carried out for a square of $L = 2$ m (as was suggested in [5]) for 5 rounds clockwise and 5 counterclockwise, writing the final point deviations of each movement. Our robot platform is almost 1 m long and a larger free scenario was not viable.

The results for the error centres of gravity for clockwise ($X_{cg,cw}$, $Y_{cg,cw}$) and counterclockwise ($X_{cg,ccw}$, $Y_{cg,ccw}$) are

$$X_{cg,cv/ccw} = \frac{1}{5} \sum_{i=1}^{5} \epsilon x_{i,cv/ccw}$$

$$Y_{cg,ccw} = \frac{1}{5} \sum_{i=1}^{5} \epsilon y_{i,cv/ccw}$$

where the error is the difference between the actual absolute position of the robot and the calculated one.

$$\epsilon_x = x_{abs} - x_{calc}$$

$$\epsilon_y = y_{abs} - y_{calc}$$

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Table 2. Validation Results 3m

Method	ϵ_x (mm)
Before cal.	80
Before cal.	80
Before cal.	83
UAH	16
UAH	23
UAH	7
UMB	-4
UMB	-8
UMB	-5

116
$$X_{cg,ccw} = 24.0 \qquad Y_{cg,ccw} = -34.6$$
$$X_{cg,cw} = -65.6 \qquad Y_{cg,cw} = 53.0$$

Using the equations from [1]:

$$\alpha = \frac{X_{cg,cw} + X_{cg,ccw}}{-4L} \frac{180^\circ}{\pi}$$

in degrees, the previous results give $\alpha = 0.298$ and

$$\beta = \frac{X_{cg,cw} - X_{cg,ccw}}{-4L} \frac{180^\circ}{\pi}$$

in degrees, $\beta = 0.642$, so: $b_{actual} = 591.96$ mm and $E_d = 1.003$.

If the correction from [5] is included, a slight change is obtained: $b_{actual} = 591.98$ mm.

4. Validation

In [1], the same experiment used for calibration is repeated after calibration in order to test the method. The distances from zero error to the centres of gravity are used to compare the results. This validation process needs a large space to perform the test. In [4] and [3], only simulation results are presented to compare the methods.

Table 2 shows the error in the first 3 m of the experiment, and Table 3 the error after the whole journey.

To validate the results of calibration, travelling along a 3 m long path, followed by a turn through an angle of π and then coming back again 3 m, was carried out. Table 2 and 3 show the error ($\epsilon_x = x_{abs} - x_{calc}$ and $\epsilon_y = y_{abs} - y_{calc}$) in mm in the X and Y coordinates before calibration for the calibration method UAH and for UMBmark. Table 2 after the first 3 m of travel and Table 3 after coming back.

The tests were been performed 3 times for each calibration in order to avoid non-systematic error. Note that the error in Table 2 comes bassically from the error in the wheel diameters and the error in Table 3 is affected by the wheel diameters and b.

Fig. 9 shows the error before calibration, with the UMB method calibration and the proposed one. As can be seen, the results for both calibrations are very similar, although sligthly better for the UMB method. But the simplicity of our method leads us to use it instead of the UMB. It must be taken into account that most of the measurements in the proposed method are done on-board and in most of the movements, the initial point is not important.

Table 3. Validation Results 3m-π-3m

Method	ϵ_x (mm)	ϵ_y (mm)
Before cal.	109	223
Before cal.	98	273
Before cal.	95	248
UAH 1	71	36
UAH 1	78	-17
UAH 1	71	-24
UMB	72	-4
UMB	71	21
UMB	76	17

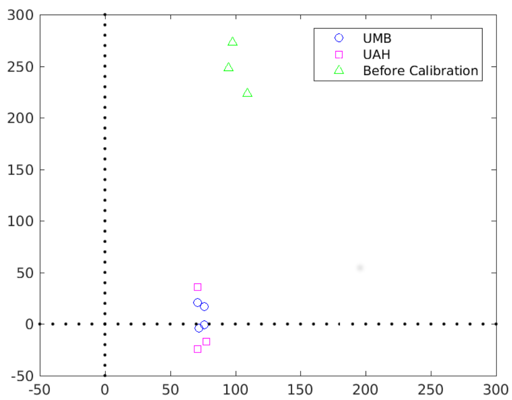

Figure 9. Error from different calibrations.

5. Conclusions

A new method for differential drive robot calibration has been presented. One of the main contributions is that free space needed to perform the calibration in our method is very small. Another feature to point out is that the number of manual measurements is just one with our method, which can be repeated in order to check the correctness, but checking the maximum orientation makes it easy to discard wrong measurements. The most complicated part of the calibration method can be done on-board. If a calibrated distance sensor is available, the whole method can be implemented on-board.

The results are very close to those obtained with the UMB method, so we use our method instead because of its simplicity in performing the calibration.

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