Correction of Systematic Errors in Odometry Model for Position Determination of Mobile Tracked Robot

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Abstract – **This paper presents the application of odometry model for position determination of mobile robot with differential drive with tracks. Sources of systematic errors for this type of robot drive are identified, analyzed and corrected. For practical analysis Lego Mindstorms robot was used. Presented experimental results show tenfold improvement of odometry localization accuracy.**

Keywords – **Odometry, Mobile robot, Correction of systematic errors.**

I. Introduction

The fundamental issue in mobile robotics is possession of knowledge of robot's position in space [1]. Position of mobile robot can be determined using various methods [2]. Odometry is a simple method which determines position of mobile robot based on distance traveled by its drive wheels [2]. Authors of paper [3] improved odometry model so it can be used with robots with track drive. Tracked drive is a special type of robot's differential drive which provides better traction on rough types of terrains compared to wheeled drive. Track slippage which occurs during turning, influences on the accuracy of odometry positioning. Authors of papers [4-11] presented methods for correction of systematic errors for mobile robots with wheels, but these methods haven't been applied for robots with tracks. Our paper applies method for correction of systematic errors [4] for tracked robots, where they haven't been applied yet. In this paper method based on odometry model is used for determining the position of Lego Mindstorms robot with differential tracked drive, after which correction of systematic errors is performed.

II. Odometry Model and Identification of Error Sources

Robot position in three-dimensional space is defined by coordinated of its position (x, y, z) and orientation angles (θ, ψ, φ) between the robot and coordinate axes (z, x and y). The most common type of movement is planar movement in $0xy$ plane, where robot has three degrees of freedom, position (x, y) and orientation θ between the robot's vertical axis and z coordinate axis. Robot's current position p is determined based on previous position (x, y, θ) and increments of position parameters (Δx, Δy, $\Delta\theta$) determined from distance traveled by left and right wheel according to Eq. (1) [12].

$$p=\begin{bmatrix}x\\y\\\theta\end{bmatrix}+\begin{bmatrix}\Delta x\\\Delta y\\\Delta\theta\end{bmatrix}=\begin{bmatrix}x\\y\\\theta\end{bmatrix}+\begin{bmatrix}\frac{\Delta s_r+\Delta s_l}{2}\cdot\cos\left(\theta+\frac{\Delta s_r-\Delta s_l}{2b}\right)\\\frac{\Delta s_r+\Delta s_l}{2}\cdot\sin\left(\theta+\frac{\Delta s_r-\Delta s_l}{2b}\right)\\\frac{\Delta s_r-\Delta s_l}{b}\end{bmatrix}, \quad (1)$$

where: Δs_r - distance traveled by right wheel, Δs_l - distance traveled by left wheel, b - distance between drive wheels.

Odometry model determines the accurate position for robot with two very narrow drive wheels, each making contact with the ground at one point and assuming there is no slippage between drive wheels and ground. These points are defined as Instantaneous Centers of Rotation, ICR_l and ICR_r, for left and right wheel respectively. The robot will rotate around ICR_l point, when left wheel is stationary and right one is moving. The distance between these two ICR points of rotation is matching the distance between the narrow wheels as shown for robot on Fig. 1*a*.

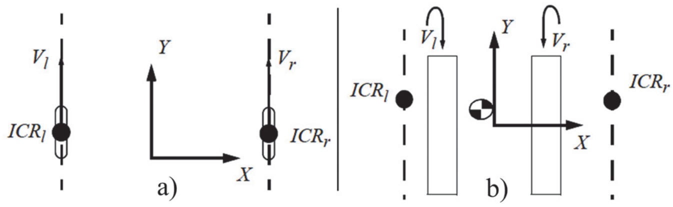

Fig. 1. Position of point of rotation ICR_l and ICR_r for wheeled robot (a) and for tracked robot (b) [3]

Robots with tracks make contact with the ground on the much larger surface, so when turning slippage will occur because not all points on track travel the same distance. The position of ICR_l and ICR_r points of rotation will be variable and they will be always placed on an outer side of tracks [13, 14] as shown in Figure 1(b). In odometry model for robot with tracked drive, the central distance between robot's tracks b cannot be used, so the distance between ICR_l and ICR_r points of rotation b_{ICR} is used instead.

The distance between ICR points of rotation b_{ICR} can be determined by measuring turning efficiency. Turning efficiency χ is defined as the ratio between the central distance between robot's tracks b and distance between ICR points of rotation b_{ICR} [3]. Turning efficiency of the ideal differential drive with narrow wheels without slippage is one. For the deferential drive with wide wheels turning efficiency is around 0.9, while for tracked drive is around 0.6 [3].

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$$\chi = \frac{b}{x_{ICR_r} - x_{ICR_l}} = \frac{b}{b_{ICR}} \quad 0 \le \chi \le 1 . \tag{2}$$

Turning efficiency χ is calculated as ratio between measured turning angle θ_m and expected turning angle θ_0, when robot is rotated around its vertical axis. Distance which tracks need to travel with same speed, but in the opposite directions in order to make expected turn angle θ_0 is calculated based on the central distance between robot's tracks b. Due track slippage, measured turning angle θ_m will be smaller than expected turning angle θ_0. When calculated turning efficiency is replaced it Eq. (2), the distance between ICR points of rotation of tracked drive is been calculated [3].

Due approximations in odometry model for determining robot's position and other influences such as: unequal circumference of drive tracks, uncertainty of effective distance between ICR points of rotation, directionless of tracks, finite encoder resolution and finite sampling time systematic errors can occur [15]. Systematic errors are the dominant type of errors on smooth surfaces and their influence is constant and accumulates over time and can be determined and corrected in odometry model. Influence due unequal circumference of drive tracks on odometry error is represented by E_d parameter:

$$E_d = \frac{O_r}{O_l}, \tag{3}$$

where: O_r – circumference of right track, O_l – circumference of left track.

Uncertainty of effective distance between ICR points of rotation is caused due large track's contact surface with ground and is represented by E_b ratio:

$$E_b = \frac{b^*_{ICR}}{b_{ICR}}, \tag{4}$$

where: b^*_{ICR} – corrected distance between ICR points of rotation of tracks, b_{ICR} – distance between ICR points of rotation of tracks before correction.

Nonsystematic errors are caused when the robot moves on the rough and uneven ground, where slippage or contact with other objects can occur. It is not possible to correct the influence of such errors since their occurrence is unpredictable and in that case, the robot will always reach difference final position for the repeated movement. Influence of nonsystematic errors on odometry model can be expressed statistically as the uncertainty of the determined position of the mobile robot.

Systematic odometry errors can be measured using bidirectional test [16] in which robot moves on the quadratic path with the length of segment of L. In one set of experiments, robot moves on the quadratic path in clockwise (CW) direction, and in other set in counterclockwise (CCW) direction (Fig. 2). Influence of E_d parameter is dominant in straight parts of the paths, while the influence of E_b parameter becomes dominant at path turns. Using bidirectional test, the influence of E_d and E_b parameters can be separated from each other, because when robot moves on path in one direction

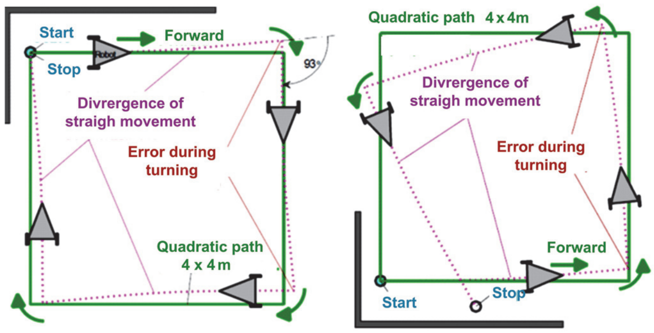

Fig. 2. Robot movement in bidirectional test on quadratic path

influence of these parameters adds up, while for other direction their influence cancel each other. The robot starts movement in one direction from the Start point (x_0, y_0 and θ_0). The robot is programmed to move on four line segments of length L, and at end of the each segment, the robot stops and turns for 90º. Such movement would in ideal case return robot in starting point Start, but due the influence of systematic and nonsystematic errors robot will finish its movement in some other point marked Stop with position (x_1, y_1 and θ_1). Difference between start and final position represents odometry error as shown by Eq. (5):

$$\varepsilon x = x_0 - x_1; \qquad \varepsilon y = y_0 - y_1 . \tag{5}$$

Due influence of systematic errors, end points in which robots finishes its movements will be grouped into sets centered around points CW($x_{cg(cw)}$, $y_{cg(cw)}$) and CCW($x_{cg(ccw)}$, $y_{cg(ccw)}$). Coordinates of these center points will be used in order to correct the influence of systematic errors in odometry model. When turning, robot will make turning error for angle α, due uncertainty of effective distance between ICR points of rotation. When moving in the straight line robot will diverge in one direction for angle β, because of unequal circumference of drive tracks. The value of these two angles α and β is calculated using Eq. (6) and Eq. (7) [16]:

$$\alpha = \frac{x_{cg(cw)} + x_{cg(ccw)}}{-4L} \frac{180^\circ}{\pi}, \tag{6}$$

$$\beta = \frac{x_{cg(cw)} - x_{cg(ccw)}}{-4L} \frac{180^\circ}{\pi}. \tag{7}$$

The ratio of the unequal circumference of drive tracks, represented by E_d parameter is acquired by Eq. (8):

$$E_d = \frac{O_R}{O_L} = \frac{L + b_{ICR} \sin(\beta/2)}{L - b_{ICR} \sin(\beta/2)}. \tag{8}$$

The uncertainty of effective distance between ICR points of rotation can be corrected using E_b ratio calculated by Eq. (9):

$$E_b = \frac{b^*_{ICR}}{b_{ICR}} = \frac{90^\circ}{90^\circ - \alpha} \Rightarrow b^*_{ICR} = \frac{90^\circ}{90^\circ - \alpha} b_{ICR} . \tag{9}$$

III. Experimental Results

Lego Mindstorms EV3 Home Edition [17] is set of components which are used for assembly of various types of mobile robots. EV3RSTORM is one of these robot models, which has differential track drive. The maximum speed of movement is around 300 mm/s with movement resolution of 0.3 mm per degree of rotation of drive motors. Track width is 20 mm while length of track in contact with the ground is 110 mm with the central distance between tracks of 128 mm.

In order to make full turn of 360° around its vertical axis, robot tracks need to travel 402 mm in opposite directions, based on distance between center of tracks (b=128 mm) Measurement results presented in Table I show that measured turning angle is much smaller than expected turning angle due track slippage with average value is 239.9º. Based on the measured angle of rotation we determined turning efficiency of $\chi = 0.667$ which is further used to calculate the effective distance between ICR points of rotation of 192 mm later used in odometry model.

Table I
Measured Turning Angles of Mobile Robot

No Meas.	Measured turning angle θ_m [°]
1	240
2	238
3	247
4	239
5	235
6	241
7	237
8	243
9	240
10	239
Average	239.9

Robot is programmed to move on the quadratic path and ten bidirectional tests are conducted for both directions and results of odometry errors are presented in Table II and Fig. 3.

Table II
Odometry Errors in Bidirectional Test Prior Correction

No. Meas.	CCW		CW	
	εx_{ccw}(mm)	εy_{ccw}(mm)	εx_{cw}(mm)	εy_{cw}(mm)
1	-148	41	-268	-274
2	-300	120	-266	-205
3	-300	134	-128	-84
4	-280	180	-268	-342
5	-249	108	-122	-58
6	-242	118	-115	-156
7	-105	55	-112	-96
8	-122	65	-218	-274
9	-108	26	-105	-109
10	-100	40	-234	-237
Average	-195.4	88.7	-183.6	-183.5

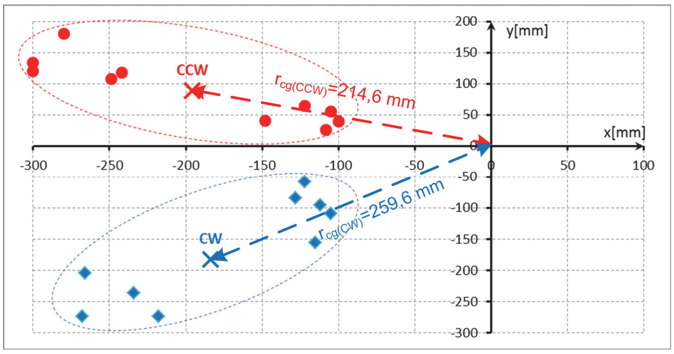

Fig. 3. Odometry errors in bidirectional test prior correction

Results of experiments carried both in CW and CCW directions represent odometry errors grouped around centers of gravity for each test direction. Absolute odometry error represents the furthest distance of center of gravity of CW or CCW cluster and is equal to 259.6 mm prior correction.

$$e_{\max(sys)} = \max(r_{cg(cw)}, r_{cg(cw)}) = 259.6 \text{ mm}. \quad (10)$$

Based on coordinates for the centers of CW and CCW cluster, correction angles α and β are determined which are used to correct the influence of systematic errors in odometry model.

$$\alpha = \frac{x_{cg(cw)} + x_{cg(ccw)}}{-4L} \frac{180^\circ}{\pi} = 5.42^\circ, \quad (11)$$

$$\beta = \frac{x_{cg(cw)} - x_{cg(ccw)}}{-4L} \frac{180^\circ}{\pi} = -0.17^\circ. \quad (12)$$

Based on determined values of α and β angles, values of correction parameters E_d and E_b are also determined:

$$E_d = \frac{O_R}{O_L} = \frac{L + b\sin(\beta/2)}{L - b\sin(\beta/2)} = 0.9988, \quad (13)$$

$$E_b = \frac{90^\circ}{90^\circ - \alpha} = 1.064 \Rightarrow b_e = \frac{90^\circ}{90^\circ - \alpha} b = 204.3 \text{ mm}. \quad (14)$$

The value of E_d parameter is very close to one and influence could be ignored. Using E_b parameter effective distance between ICR points of rotation is corrected to 204.3 mm. Bidirectional test was repeated with corrected parameters and results are presented in Table III and Fig. 4.

Absolute odometry error after correction of 25.3 mm represents the substantial increase of odometry position accuracy, which justifies the usage of this method for systematic error correction in practice.

$$e_{\max(sys)} = \max(r_{cg(cw)}, r_{cg(cw)}) = 25.3 \text{ mm}. \quad (15)$$

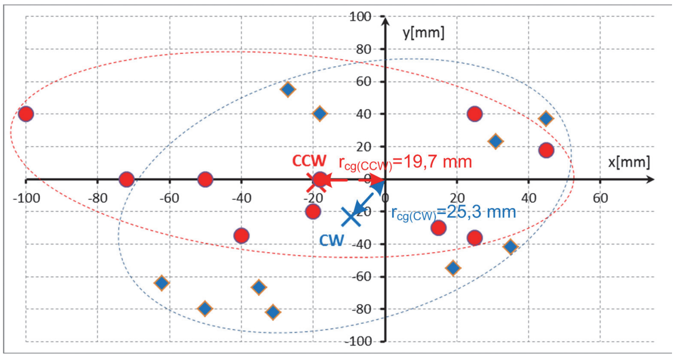

Fig. 4. Odometry errors in bidirectional test after correction

TABLE III
ODOMETRY ERRORS IN BIDIRECTIONAL TEST AFTER CORRECTION

No. Meas.	CCW		CW	
	εx_{ccw}(mm)	εy_{ccw}(mm)	εx_{cw}(mm)	εy_{cw}(mm)
1	-50	0	-62	-64
2	-18	0	-50	-80
3	-100	40	-31	-82
4	-72	0	-35	-67
5	25	40	-18	40
6	15	-30	-27	55
7	-40	-35	31	23
8	-20	-20	45	37
9	45	18	35	-42
10	25	-36	19	-55
Average	-19	-2.3	-9.3	-23.5

CONCLUSION

This paper presents the realization of odometry model for tracked robots, which makes it easy to determine the current position of the robot in space. Developed odometry model is implemented in the form of a program block for Lego Mindstorms EV3 mobile robot. Correction of systematic errors in odometry model has been performed, based on the carried experiments. Systematic errors are primarily caused due to the uncertainty of the effective distance between the ICR points of rotation, which is corrected to the value of 204.3 mm. Adjusted odometry model showed the significant increase in the accuracy of determining the position of a mobile robot in space. Realized movement model can be successfully used for autonomous navigation of robots in a familiar or an unfamiliar environment, such as: precision agriculture, search and rescue missions in emergency situations and manipulation in hazardous industrial areas.

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REFERENCES

[1] J.C. Latombe, *Robot Motion Planning*. Norwood, MA, Kluwer Academic Publishers, 1991.

[2] J. Borenstein, H. R. Everett, L. Feng, and D. Wehe, „Mobile Robot Positioning: Sensors and Techniques“, *Journal of Robotic Systems*, vol. 14, no. 4, pp. 231-249, 1997.

[3] J.L. Martínez, A. Mandow, J. Morales, S. Pedraza, and A. García-Cerezo, „Approximating Kinematics for Tracked Mobile Robots“, *The International Journal of Robotics Research*, vol. 24, no. 10, October 2005, pp. 867-878.

[4] 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, December 1996, pp. 869-880.

[5] J. Borenstein, and L. Feng, „Correction of Systematic Odometry Errors in Mobile Robots“, *1995 International Conference on Intelligent Robots and Systems (IROS '95)*, Pittsburgh, Pennsylvania, August 5-9, pp. 569-574.

[6] I. Bostan, I. Lita, E. Franti, M. Dascalu, C. Moldovan, and S. Goschin, “Systematic Odometry Errors Compensation for Mobile Robot Positioning”, *CADSM'2003*, February 18-22,2003, Lviv-Slasko, Ukraine.

[7] A. Bostani, A. Vakili, and T. Denidni, “A Novel Method to Measure and Correct the Odometry Errors in Mobile Robots”, *CCECE/CCGEI*, May 5-7 2008 Niagara Falls, Canada.

[8] C. Jung, and W. Chung, “Design of Test Tracks for Odometry Calibration of Wheeled Mobile Robots”, *International Journal of Advanced Robotic Systems*, vol. 8, no. 4, pp. 1-9, 2011.

[9] S. Krivić, A. Mrzić, J. Velagić, and N. Osmić, “Optimization Based Algorithm for Correction of Systematic Odometry Errors of Mobile Robot”, *9th Asian Control Conference (ASCC)*, Istambul, Turkey, 2013.

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

[11] T. Ravikumar, R. Saravanan, and N. Nirmal, “Modeling and Optimization of Odometry Error in a Two Wheeled Differential Drive Robot”, *International Journal of Scientific and Research Publications*, vol. 3, no. 12, December 2013.

[12] M. Petrović, N. Lukić, N. Vuković, and Z. Miljković, „Mobilni robot u unutrašnjem transportu materijala inteligentog tehnološkog sistema – edukacija i razvoj“, *36. Jupiter konferencija*, Beograd, 2010.

[13] J.E. Shigley, and J.J. Uicker, *Theory of Machines and Mechanisms*, McGraw Hill, NewYork, 1980.

[14] J.Y.Wong, *Theory of Ground Vehicles*, John Willey, 2001

[15] J. Borenstein “Experimental Results from Internal Odometry Error Correction with the OmniMate Mobile Robot”, *IEEE Transactions on Robotics and Automation*, vol. 14, no. 6, December 1998, p. 963.

[16] J. Borenstein, L. Feng, „UMBmark —A Method for Measuring, Comparing, and Correcting Dead-reckoning Errors in Mobile Robots”, Technical Report UM-MEAM-94-22, University of Michigan.

[17] D. Benedetelli, „LEGO Mindstorms EV3 Laboratory“, No Starch Press, Inc, 2014.