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Calibration of Mobile Robot with Single Wheel Powered Caster

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Abstract

The accurate determination of kinematic parameters is crucial for mobile robots because an imprecise kinematic model can lead to significant uncertainties in their odometry and control systems. This is particularly critical for caster-type mobile robots, which have intricate kinematic models. Despite the importance of precise kinematic parameters for caster-type mobile robots, there has been limited research focused on calibrating their kinematic models. A previous study introduced a calibration method specifically designed for double-wheeled caster-type mobile robots, necessitating the direct measurement of the robot's center point and the distance between the casters. In contrast, this paper presents a novel calibration method based on a geometric approach. This method can be applied to single-wheeled caster-type mobile robots with two or more casters, eliminating the need for direct measurements. Furthermore, it effectively derives all the necessary kinematic parameters required for control and odometry. The proposed calibration method's validity and performance are confirmed through simulation and hardware experiments conducted in this study.

Keywords

Calibration
Mobile robot
Powered caster

1. Introduction

In the context of mobile robots, precise position estimation is crucial. Typically, odometry is employed for position estimation in mobile robots [1-3]. Odometry calculates the distance traveled in a unit of time using intrinsic information such as wheel encoders and the robot's kinematic parameters and accumulates this information to perform position estimation. This method has advantages such as cost-effectiveness and short-term precise position estimation, making it robust against changes in the surrounding environment. However, it has the drawback that errors in odometry increase as the traveled distance accumulates due to the cumulative nature of odometric properties [1,2]. Therefore, to achieve accurate position estimation, correction of odometric errors is necessary.

The sources of odometric errors can be broadly categorized into systematic errors and nonsystematic errors [1,3]. Systematic errors arise from geometric inaccuracies such as wheel position errors and diameter errors. Systematic errors are not influenced by changes in the driving environment, and they can be mitigated through pre-drive calibration.

Nonsystematic errors, on the other hand, are caused by the interaction between the robot and the driving environment, such as uneven terrain and slipping [1,4]. Nonsystematic errors do not consistently occur and are influenced by the driving environment. Research has been conducted to correct nonsystematic errors through probabilistic approaches [5], the use of additional sensors [6], and more recently, machine learning [7]. Typically, systematic errors are first corrected through kinematic calibration, followed by the correction of nonsystematic errors, reducing odometric errors [4]. This paper primarily focuses on correcting systematic errors through kinematic calibration.

Various methods have been proposed for kinematic calibration to correct systematic errors [8-13]. One method for calibrating differential drive robots called the UMBmark method [8] involves driving the differential drive robot in both clockwise and counterclockwise directions along a square path. It then analyzes the initial and final position errors to determine the wheel diameter difference and distance difference, which are used to correct systematic errors. However, this method assumes that wheel diameter and distance differences have independent effects on odometry, which is not accurate in practice, making it challenging to achieve precise systematic error correction [9]. Jung and Chung [9] improved the calibration performance by considering the combined effects of these two factors on position errors.

Calibration methods have also been proposed for wheeled robots [10]. Wheeled robots cannot perform in-place rotations like differential wheeled robots, and their structural differences from differential wheeled robots lead to different influences of systematic errors on the actual robot path and odometry path. Applying calibration methods for differential wheeled robots [8,9] to wheeled robots is challenging [10]. Lee and Yoo [10] proposed a calibration method suitable for wheeled robots due to these reasons. Therefore, considering the type of mobile robot, available movements, the impact of kinematic errors, and the parameters to be determined, different calibration methods are needed for each type of mobile robot.

Caster wheels are a type of omnidirectional wheel in the horizontal plane. Mechanum wheels, which exhibit omnidirectional characteristics, are special wheels with some limitations and vibrations in the operating environment, whereas caster wheels, which are regular wheels, have the advantage of being free from such problems [14,15]. Although calibration methods have been actively researched for various mobile robots such as differential wheeled robots [8,9,12], wheeled robots [10,13], and so on, caster-type mobile robots have been discussed in terms of the necessity for odometric error correction [14], but specific calibration methods have only been studied for a particular model, the active split offset caster (ASOC) [11].

Caster wheels used in caster-type mobile robots typically include the ASOC and single-wheel powered caster (SWPC) [15], as shown in **Figure 1**. ASOC controls two wheels in the same way as a differential wheeled robot, generating the desired motion at the steering axis. SWPC is a basic caster wheel that controls both the wheels and the steering axis with motors, allowing it to create the desired motion at the steering axis. This paper proposes a novel calibration method for SWPC-based mobile robots mentioned in previous research [14]. **Figure 2** depicts a SWPC module and the mobile robot that uses this module.

The characteristics of the proposed calibration method and the calibration methods mentioned earlier [8-11] are outlined in **Table 1**. The method proposed in this

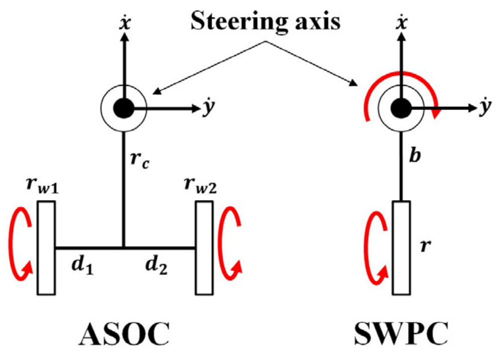

Figure 1. Active split offset caster (ASOC, left) and single-wheel powered caster (SWPC, right)

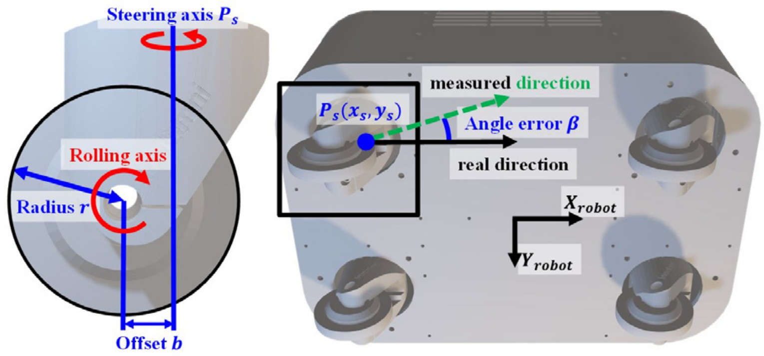

Figure 2. Single-wheel powered caster (SWPC) module (left) and bottom view of SWPC-based mobile robot (right)

Table 1. Comparison of calibration methods for mobile robots

Compared method	Drive type	External metrology system	Characteristic	Calibration method
Borenstein and Feng, 1995 [8]	Differential	O	Assuming kinematic errors are independent	• Using the relationship between odometric errors and kinematic parameter errors • Analyzing odometric errors after driving
Jung *et al.*, 2014 [9]	Differential	O	Considering the dependent relationship between kinematic errors	
Lee *et al.*, 2010 [10]	Wheeled	O	Assuming kinematic errors are independent	
Doebbler *et al.*, 2008 [11]	ASOC	X	Requiring direct-measuring	• Using geometric relationship • Analyzing self-rotating information
Proposed method	SWPC	O	Not requiring direct-measuring	

Abbreviation: ASOC, active split offset caster; SWPC, single-wheel powered caster.

paper is suitable for SWPC-based mobile robots and eliminates the need for direct measurements, unlike the previous method [11]. The previous methods [8-10] analyze post-drive errors based on the relationship between kinematic errors and driving errors, making them vulnerable to nonsystematic errors occurring during driving and requiring a large experimental area. In contrast, the proposed method is relatively robust against nonsystematic errors, as it analyzes in-place rotation information based on geometric relationships, even in a relatively small experimental area.

The structure of this paper is as follows. In Section 2, the calibration method for ASOC-based robots is analyzed, and in Section 3, the calibration method for SWPC-based robots is introduced. In Section 4, the proposed method is validated through simulations and real-world experiments. Additionally, driving experiments in real environments are conducted, and the calibration results are compared before and after calibration. This paper is concluded in Section 5.

2. Calibration of ASOC-based robots

Doebbler and Valasek [11] proposed a method for calibrating ASOC-based mobile robots without the need for external measuring equipment. In this method, two motors that are attached to one ASOC module wheel to prevent it from moving are fixed. The remaining modules, except for the fixed one, are aligned in a similar direction, and only small movements are allowed. By applying a current sufficient to create small movements, the robot rotates around the steering axis of the fixed module, as portrayed in **Figure 3**. This is repeated for each module, performing both clockwise and counterclockwise rotations once. As illustrated

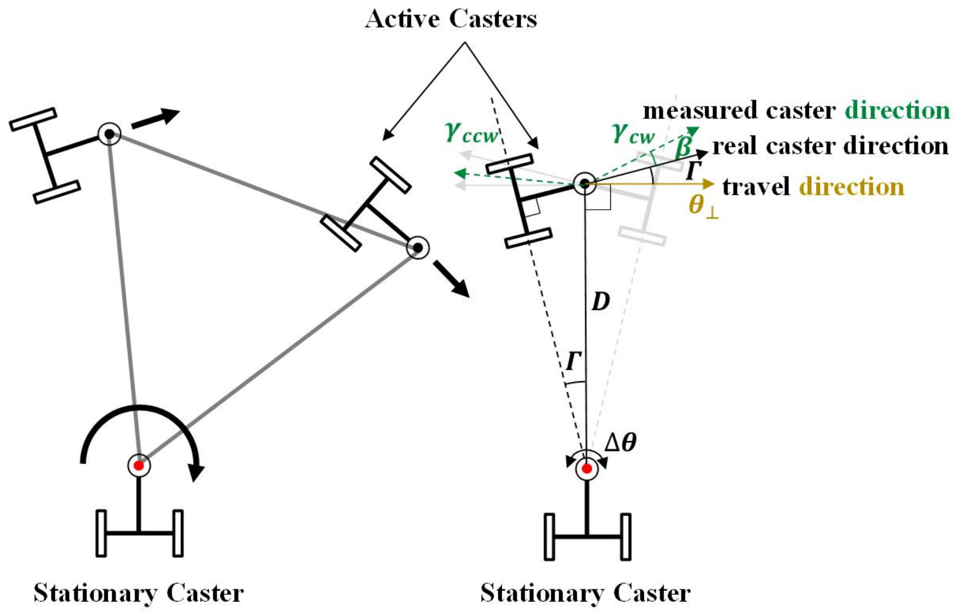

Figure3. Rotation of ASOC-based mobile robot with regards to a steering point of a stationary caster (left) and its geometric relationship when rotating (right)

in **Figure 3**, angle errors , wheel radii , offsets , and distances from the offset axis to each wheel for each modules are calculated using the geometrical relationships that occur when the robot rotates around the steering axis of the fixed module, encoder information during rotation, and the directly measured distance between modules.

The previous method [11] conducted calibration without external measuring equipment by directly measuring the distance *D* between modules and using the midpoint between modules as the robot's origin for ease of linear motion control. The robot used in the previous method [11] had an exposed steering axis between the modules, which made it easy to measure the distance between the modules and the midpoint. However, for robots where the steering axis is not exposed, disassembling the robot may be necessary for measurement, and if there are other components in the straight-line distance between steering axes, direct measurement may become challenging.

The previous method [11] is not applicable when the caster module has only one wheel. When two wheels of the ASOC module are fixed, rotation and linear motion do not occur at the wheel part where there is a two-point contact, and the robot only rotates around the steering axis of the fixed module. Consequently, rotation information can be acquired from the encoder information of the steering axis. However, in the case of the SWPC module with only one wheel, releasing the fixation of the steering axis motor and fixing only the wheel axis motor to rotate the robot results in unintended rotation at the wheel part where there is a one-point contact, as illustrated in **Figure 4**. In other words, it becomes challenging for the robot to execute precise rotational motion around the steering axis of the fixed module. Fixing both the steering axis and wheel axis motors of the fixed module to rotate the robot around the fixed module's wheel axis results in the robot rotating around the wheel of the fixed module, but it becomes impossible to determine the robot's rotational information solely from internal information. Additionally, in the equation for calculating the parameters of the moving module used in the previous method, information from the fixed module mixes in, making it difficult to calculate accurate parameters. The next section proposes a calibration method to address

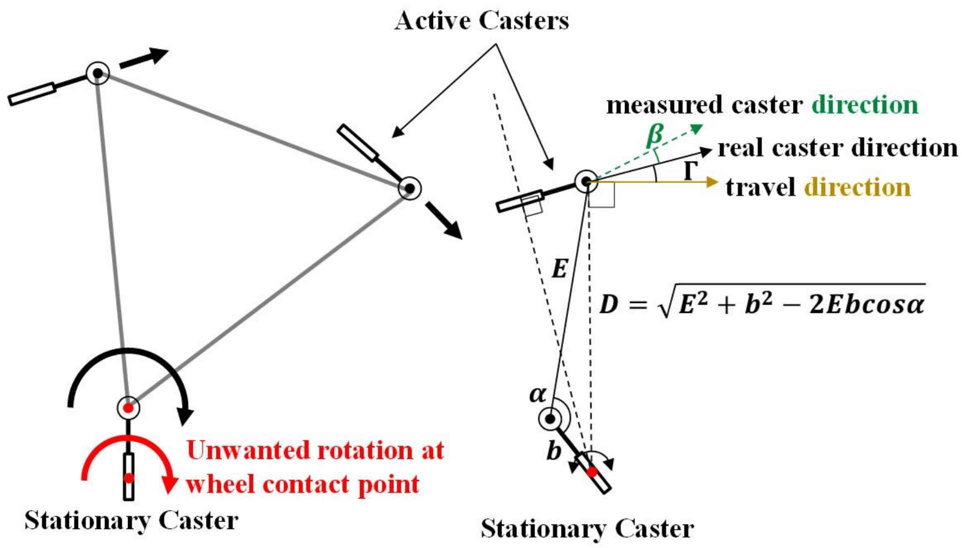

Figure 4. Unwanted rotation occurring at the wheel contact point which disturbs the robot from generating pure rotation centered at the steering point (left) and kinematic parameters of the stationary caster being included when calculating parameters of the active caster (right)

Table 2. Kinematic parameters of each caster module

$P_s(x_s, y_s)$	Position of steering axis with regards to the robot base
β	Angle error between the assumed and real position of the homing sensor of the steering axis
b	Distance between steering axis and wheel axis (offset)
r	Wheel radius

the aforementioned issues.

3. Calibration of SWPC-based robots

In this section, we introduce a calibration method for SWPC-based robots using geometric relationships. As mentioned earlier, SWPC-based robots can rotate the robot by completely fixing one module and using the wheel of the fixed module as a reference. Nonetheless, it is not possible to obtain the robot's rotation information solely from motor encoders. Thus, the method proposed in this paper uses external measuring equipment to obtain the robot's rotation information. By using external measuring equipment, it becomes possible to measure the rotation information of SWPC-based robots that were not measurable with internal information, making calibration possible without directly measuring the distance between modules.

The kinematic parameters of SWPC-based robots obtained in this paper are summarized in **Table 2** and depicted in **Figure 2**.

To perform the calibration for obtaining these parameters, the process of acquiring rotation information through external measuring equipment is required. Initially, one caster module's steering axis and wheel axis motor are both secured (stationary caster) whilst the remaining modules (dynamic casters) are aligned to face the same direction, allowing them to rotate around the static module as a reference. Subsequently, a constant torque is applied to the wheel axis motor of the dynamic casters, while the steering axis motor is left free to rotate, allowing the robot to rotate naturally while aligning itself, as shown in **Figure 5**. During the rotation of the robot, the robot's center of rotation P_1 in the robot's coordinate system is obtained using the measured robot's origin and direction information. By changing the steering angle

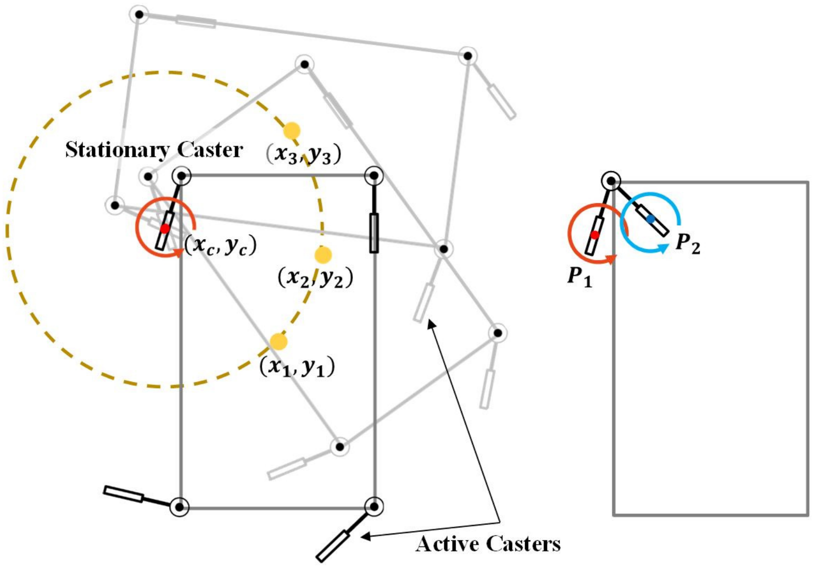

Figure 5. Rotation of single wheel powered caster mobile robot where the rotation center is located at a wheel contact point of a stationary caster (left) and another rotation center point (P_2) after changing the steering angle of a stationary caster (right)

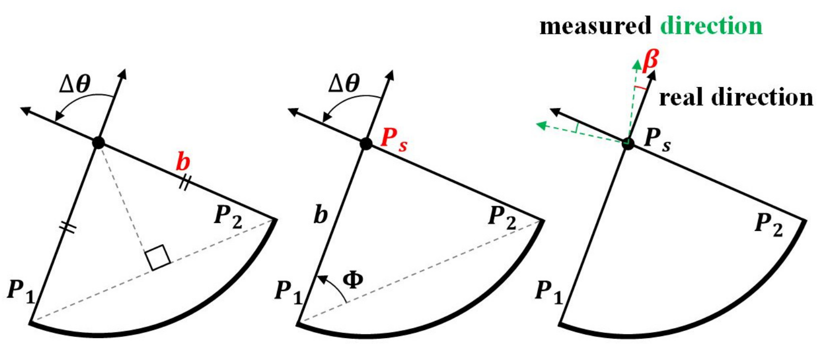

Figure 6. Geometric relations: b (left), P_s (center), and β (right)

of the static module and repeating the process, the rotation center P_2 in the robot's coordinate system at different positions, as shown in **Figure 5**, is obtained.

When the wheels are at the positions P_1 and P_2, $\Delta\theta$ is calculated using the measured steering angles $\hat{\theta}_1$ and $\hat{\theta}_2$. Here, while $\hat{\theta}_1$ and $\hat{\theta}_2$ contain information about the angle error β, β is a constant value generated by the diference between the expected position of the zero point sensor and the actual position, and its influence is nullified when calculating the difference between the two measured values.

Both points P_1 and P_2 are on the circumference of a circle with an offset b from the steering axis of the static module, so the angle $\Delta\theta$ between the two points can be determined since they lie on the circumference of the circle. Therefore, using the relationship in Equation (1), the radius b of the circle can be calculate.

$$\overline{P_1P_2} = 2b\sin\frac{|\Delta\theta|}{2} \tag{1}$$

Subsequently, φ is calculated using Equation (2), and then, as shown in Equation (3), P_1 is rotated by φ in the direction of the center of the circle, moving a distance of b to obtain the center point $P_s(x_s, y_s)$ of the circle. In this case, rot is the matrix that rotates around the z-axis (a perpendicular axis in **Figure 6**).

$$\phi = sign(\Delta\theta) \times \frac{\pi - |\Delta\theta|}{2} \tag{2}$$

$$P_s = P_1 + b\,rot(\phi) \times \frac{\overrightarrow{P_1P_2}}{|P_1P_2|} \tag{3}$$

The angle $\hat{\theta}_1$ of the vector $\overrightarrow{P_1P_2}$ in the robot's coordinate system represents the actual steering angle when the wheel is in position P_1. The angle error β for the actual steering angle $\hat{\theta}_1$ measured when the wheel of the static module is at position P_1 is calculated. **Figure 6** illustrates the process described above. By repeating this process for each module, the geometric parameters $P_s(x_s, y_s)$, β, and b for each module can be obtained.

Subsequently, as shown in **Figure 7**, the wheel radius r is determined using the obtained rotation information and geometric parameters. Since the wheel of the dynamic module rotates relative to the wheel of the static module, $\overline{P_1P_w}$ and $\overline{P_wP_s}$ are perpendicular to each other. Using this relationship, the distance D between the wheels of the dynamic and static modules can be calculated. Since the distance covered by the dynamic module wheel's position while the robot rotates by $\Delta\theta_{robot}$ equals the distance covered by the corresponding dynamic module wheel while it rotates by $\Delta\theta_{wheel}$ in the same time, equation (4) can be used to obtain the wheel's radius r. It is necessary to measure $\Delta\theta_{robot}$ using an external measurement device and $\Delta\theta_{wheel}$ by measuring the motor encoder at the same time. Since each static module has two fixed points, the information for the radius r of one module can be obtained twice. For a robot with a total of N modules, information for the radius r for one module can be obtained $2(N-1)$ times, and this can be used to calculate a robust average r that is free from any measurement errors.

$$r\Delta\theta_{wheel} = D\Delta\theta_{robot} \tag{4}$$

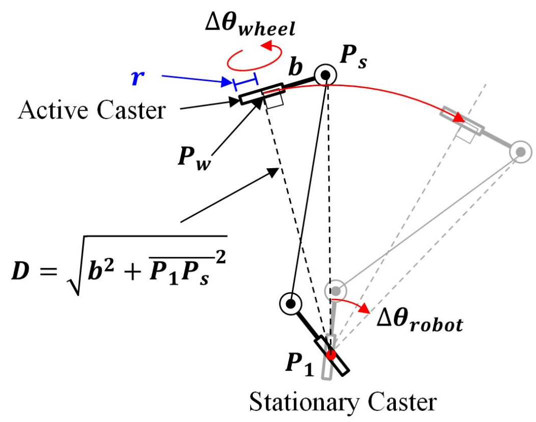

Figure 7. The geometry of the robot while the robot rotates around P_1 for computation of r

Through the above process, all parameters of SWPC-based robots can be obtained. The proposed method addresses the issue of having to directly measure the robot's origin and distance between modules, which was a problem with the previous method [11], and enables calibration of SWPC-based robots. Furthermore, the proposed method can be implemented for calibration with a minimum of two caster modules, and the calibration method can be applied in the same manner regardless of the number of casters.

4. Experiments

As mentioned in the introduction, the calibration method depends on the type of mobile robot. Calibration methods for differentially driven mobile robots and vehicle-type mobile robots [8-10] use the relationship between kinematic and driving errors. SWPC-based robots have an offset parameter, which is the distance between the steering axis and the wheel axis, that differential-wheeled and wheeled robots do not have, and they have different overall structures and driving methods. Therefore, the relationship between the kinematic error and the driving error of SWPC-based robots is different from that of differential-wheeled and wheeled robots. The existing method for caster-based robots [11] is for ASOC-based mobile robots and can only be applied when the caster module is in two-point contact with the ground. The SWPC module is in one-point contact with the ground and rotation occurs at the contact point, so the required motion cannot be performed. In other words, the calibration method depends on the type of mobile robot, because the parameters to be calibrated and the movements that can be realized are different due to the different kinematics of each type of robot. For this reason, it is difficult to apply existing calibration methods [8-11] to SWPC-based robots.

In this section, we verify the proposed calibration method through simulation and perform calibration in a real environment. As mentioned above, other calibration methods cannot be applied to SWPC-based mobile robots, so we compare the results of driving experiments with two different kinematic parameters before and after applying the proposed calibration method in a real environment. The mobile robot used uses four SWPC modules as shown in **Figure 2**.

4.1. Calibration of the simulation environment

The simulation experiment consists of collecting the rotation information and motor encoder information of the SWPC-based robot based on the kinematic parameters with arbitrary errors and estimating the kinematic parameters by the proposed method.

First, the steering angles of the static module are fixed at 45.0° and 165.0° to create a situation where the robot rotates counterclockwise with respect to the wheels of the static module. The rotation information with the static module wheel as the origin is collected as shown in **Figure 8**. Using the collected information, the proposed calibration method is performed to calculate the kinematic parameters and compare them with the set parameters.

A total of 10,000 simulation trials were performed. For the parameters required for the simulation, $P_s(x_s, y_s)$ was set within ±30.0% of the design value, and β was set to random values within the range of ±30.0°. The mean absolute error (MAE) between the kinematic parameters obtained through simulation experiments and the set parameters is summarised in **Table 3**, showing that the proposed calibration method accurately estimates various arbitrarily assigned errors. This demonstrates that the proposed calibration method can accurately determine the parameters of SWPC-based robots.

4.2. Real environment calibration

Real environment experiments were conducted in a manner similar to simulation experiments, with the steering angle of the static module fixed at 45.0° and 165.0° to create a situation where the robot rotates counterclockwise with the wheel of the static module as the reference. A motion capture system was used with 29 Vicon T-160 cameras and Vicon NEXUS software, collecting information from three points above the robot, as shown in **Figure 9**, at 100 Hz to determine the robot's origin and direction.

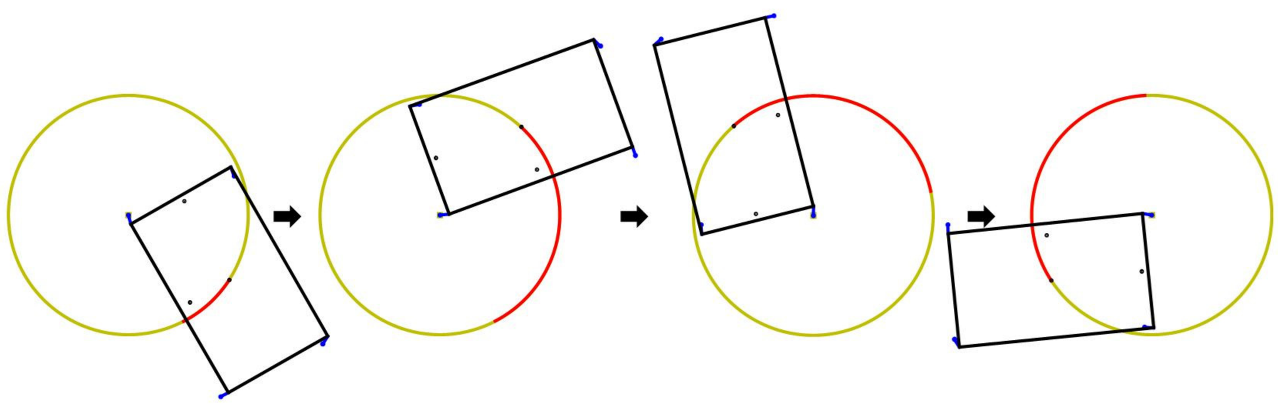

Figure 8. Rotation data generating process in simulation. The yellow circle is the trajectory of the robot's center point when the robot rotates around its stationary caster wheel.

Table 3. MAE of given and calculated parameters in the simulation

	Mean absolute error (MAE)
P_s (mm)	6.7818e-15
β (°)	2.7289e-16
b (mm)	7.1324e-15
r (mm)	1.0411e-13

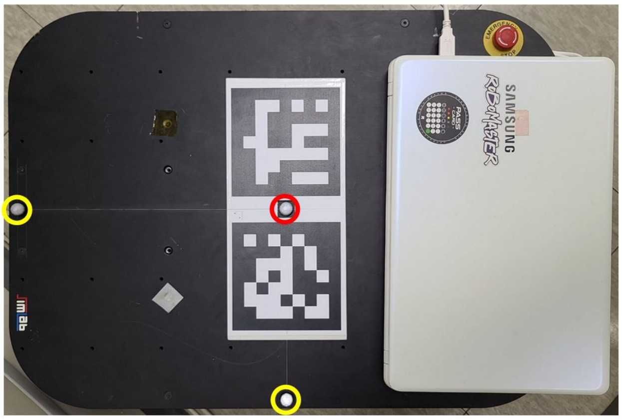

Figure 9. Three motion capture points for measuring the position and orientation of the robot

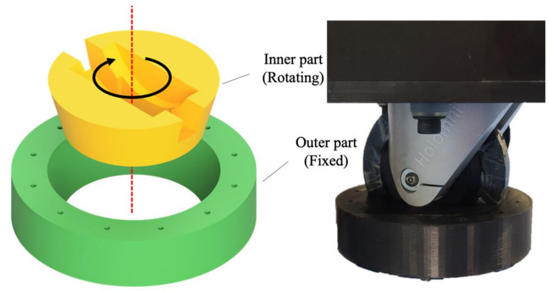

Figure 10. Fixing tool for slip prevention. The inner part is connected to the stationary caster wheel and the outer part is connected to the ground.

To prevent slippage during robot rotation, a device like **Figure 10** was created. The internal components rotate with the wheel of the static module while the external components are fixed to the floor, preventing slippage and allowing the robot to rotate in place. The results of the rotation are shown in **Figure 11**. The two circles represent the rotation information of the robot's origin when the robot rotates with reference to different positions of the static module's wheels (P_1, P_2). The connecting part of the two circles represents the motion information obtained during the transition of the fixed points of the static module from P_1 to P_2. During the robot's rotation, motor encoder and motion capture information were collected, and calibration was performed. The kinematic parameters for each module before and after calibration are summarized in **Table 4**.

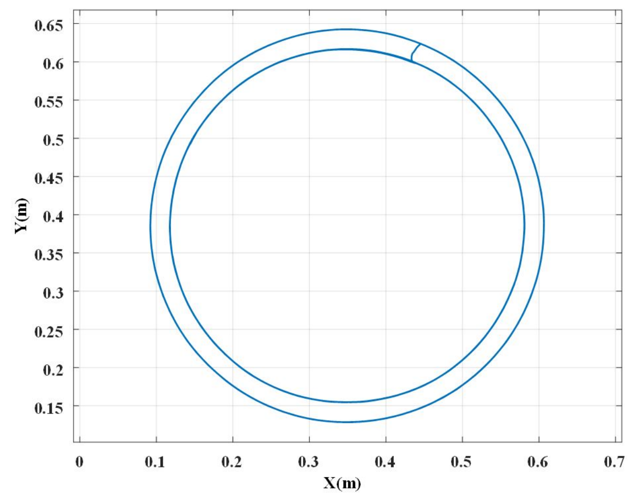

Figure 11. Trajectory of robot center point measured by motion capture system

Table 4. Kinematic parameters of each SWPC module

	Caster module	Without calibration	With calibration
$P_s(x_s,y_s)$ (mm)	1	(215, 125)	(216.16, 126.96)
	2	(215, -125)	(216.52, -124.74)
	3	(-215, -125)	(-216.22, -125.26)
	4	(-215, 125)	(-216.67, 126.47)
β (°)	1	0.0	0.6349
	2	0.0	1.5247
	3	0.0	0.9764
	4	0.0	1.2154
b (mm)	1	20.0	20.3907
	2	20.0	20.2223
	3	20.0	20.3055
	4	20.0	20.2897
r (mm)	1	55.0	54.3960
	2	55.0	54.7413
	3	55.0	55.9731
	4	55.0	55.6682

4.3. Real environment experiments

To evaluate the proposed calibration method, navigation experiments were conducted in the environment shown in **Figure 12**, where the robot traveled along a square path. To compare the impact of changes in kinematic parameters on odometry with various previous studies [1,3,4,8,9,11,12,14], experiments were conducted to compare the position errors at the start and end of the robot's path while it traveled along a square path. Although SWPC-based robots are capable of omnidirectional motion, i.e. can travel a square path without turning at each corner, in this experiment it was configured to make a 90° turn at each corner so that both the steering axis and the wheel axis motors could be used in different ways. Two rounds of driving on a square path of 2.5 m × 2.5 m were performed in clockwise (CW) and counter-clockwise (CCW) directions with the parameters before and after calibration respectively. When a mobile robot drives, it is affected by non-systematic errors caused by the interaction between the robot and the driving environment, such as uneven road surface and slippage. To reduce the effect of these non-systematic errors, the driving experiments were performed four times each and the average results were compared. The torque control method for caster-based robots proposed by Holmberg [15] was used, and the robot was driven at a low speed of about 0.2 m/s to reduce the effect of non-systematic errors.

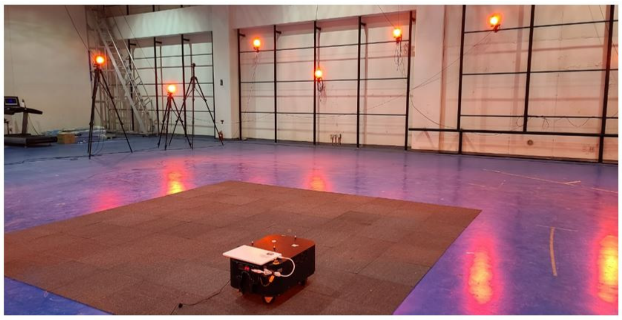

Figure 12. Tracking test environment with motion capture system for measuring robot pose

The motion information measured by motion capture is shown in **Figure 13**. It can be seen that the path after calibration follows the actual square path better than the previous path. The position and orientation information at the end of the path is shown in **Figure 14** and the MAE of position and orientation is summarised in **Table 5**. Before calibration, the robot had an average position error of 0.4674 m and an average orientation error of 9.6721° when driving. After the proposed kinematic calibration, the robot had an average position error of 0.1655 m and an orientation error of 1.9200°. The proposed method reduces the position error by 64.60% and the orientation error by 80.15%, and the odometry accuracy is improved. Through the square path driving experiment, it is shown that the calibration method proposed in this paper can obtain accurate kinematic parameters of the actual robot and improve the odometry precision.

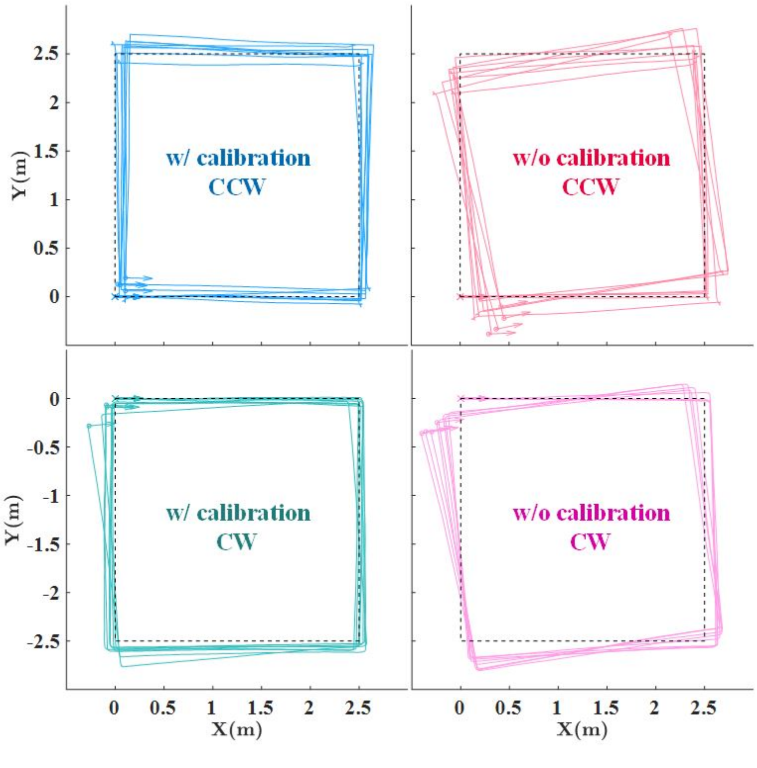

Figure 13. Robot trajectory: counterclockwise (CCW) path with calibration (top left) and without calibration (top right); clockwise (CW) path with calibration (bottom left) and without calibration (bottom right)

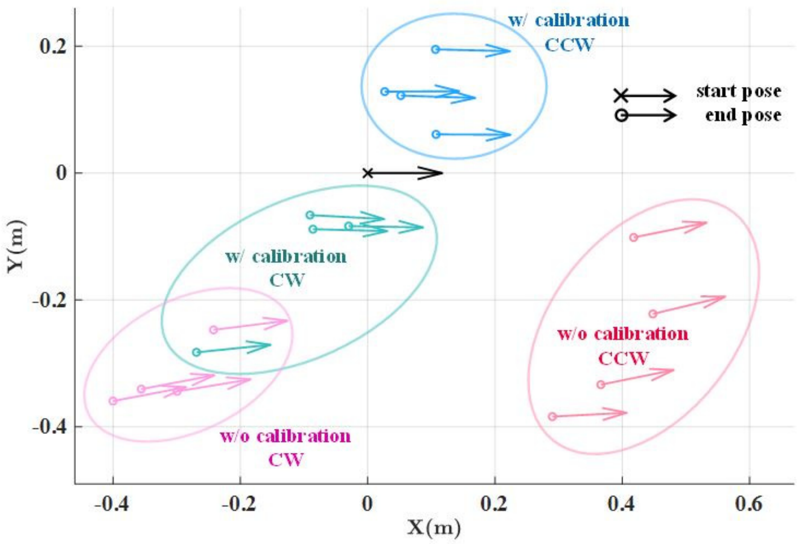

Figure 14. Results of tracking test: end position and heading

Table 5. Mean absolute error (MAE) of position and heading

	Without calibration	With calibration
Position (m)	0.4674	0.1655
Heading (°)	9.6721	1.9200

5. Conclusion

This paper presents a calibration method for SWPC-based mobile robots through a geometric approach. We calibrate the position of each module's steering axis from the robot origin, its angular error, the offset between the steering and wheel axes, and the wheel radius. This is achieved by using the robot's rotation around the wheels of the fixed modules and encoder data. The simulation confirmed the validity of the proposed method, while the square path driving experiment in a real environment demonstrated its ability to accurately determine kinematic parameters and improve odometry precision.

Disclosure statement

The authors declare no conflict of interest.

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