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Forward and Inverse Kinematic on Wheeled Soccer Robot

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Abstrak

In this research rotary encoder sensor and gyroscope sensor are used as main sensor for moving wheeled soccer robot. Rotary encoder is used to measure the speed and distance of each robot wheel and the gyroscope is used to measure the orientation of the robot, then both of them expressed in cartesian diagrams (x, y, θ). A rotary encoder type magnetic incremental encoder is used in this research and it mounted on each wheel. Inverse kinematic and forward kinematic are used to control the movement of the robot when positioning in the field or making decision when kicking the ball towards the opponent's side and the other decision. From the test results, robot can move to any direction from the starting position to the end position with a different robot orientation and robot can measure the coordinates of the robot with average error of x = 5.37%, y = 5.2%, and Theta = 0.26%. The robot is also able to move in the direction of the coordinates given with a traveling time of 3-4 seconds.

Keywords: *Forward Kinematic, Inverse Kinematic, Rotary Encoder, Soccer Robot.*

1. Introduction

Robot is one of the technologies that created to help the human work, in the broadest sense the robot is a tool that at certain limits can work automatically or manually according to the instructions of the design. Robotics in Indonesian develops every year, this development can be seen from the robot contest that frequently hold by the Directorate General of Higher Education (DIKTI) or several institutions, which is the participant are both at the student level (elementary / middle / high school / equivalent), and college student.

One of the new Indonesian robot contests in 2017 is the Indonesian Soccer Robot Contest. The Indonesian Soccer Robot Contest refers to the rules of the International Soccer Robot Contest, RoboCup. RoboCup is a world-class official soccer robot competition under the RoboCup organization (http.//www.robocup.org). Like a FIFA organization in the world championship for human football. In this robot contest like the soccer race in humans, the soccer Robot Contest also requires the speed and accuracy of the robot movement so that it can maximize the oppurtunity of making score. Because of that, the movement control system is very important, one of the control systems is the navigation or path planning (inverse kinematic). In the robot application, there is relative position and absolute position. Relative position is a set of data used through calculations to determine a robot's position (forward kinematic), while a relative position is only an estimate. Position accuracy will make a great influences in decision making of robot movements. Where the determination of the movement can be influenced by the input data of several sensors in the robot. The design of the robot movement control system is very important in determining this movement. One of a kind is the three omnidirectional kiwi drive control system which combined with the PID controller as the main controller.

The forward kinematics specifies which direction the robot will drive in (linear velocities $\dot{x}$ and $\dot{y}$) and what its rotational velocity $\dot{\theta}$ is based on the given individual wheel velocities. The inverse kinematics is a matrix formula that specifies the required individual wheel speeds for given desired linear and angular velocity ($\dot{x}$, $\dot{y}$, $\dot{\theta}$) and can be derived by inverting the matrix of the forward kinematics [1].

The purpose of this research is to design and implement a control system on wheeled soccer robots, then the Robot can determine the position in the field by using forward kinematic, and the robot is able to move automatically using inverse kinematic.

2. Literature Review
2.1 Robot Kinematics

In physics, kinematics is a branch of mathematics that discusses the motion of objects and system objects without questioning the force that causes the movement. The word kinematics is invented by the French physicist A.M. Ampere, cinematique is taken from the ancient Greek words, kinema (motion) is derived from kinein. The study of kinematics is also known as motion geometry [2] [3] [4].

In robotics study, kinematics is very important for controlling the movement of robots, whether it's a robot with construction of manipulators, humanoids, animalia, or wheeled robots. The important thing in robot kinematics is the understanding of the mechanical motion system of the robot itself before making software or program design from the robot itself.

In the wheeled robot, forward kinematic means how to get the position coordinates (x, y, theta) if the speed of the wheel in each robot is known, while inverse kinematic means how to get the speed on each wheel if the position coordinates (x, y, theta) of the robot is known.

To determine the position of the robot, global references (XG, YG) and local references centered on the robot (XR, YR) are needed. The robot's position is obtained from this formula.

$$\xi_I = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} \quad (1)$$

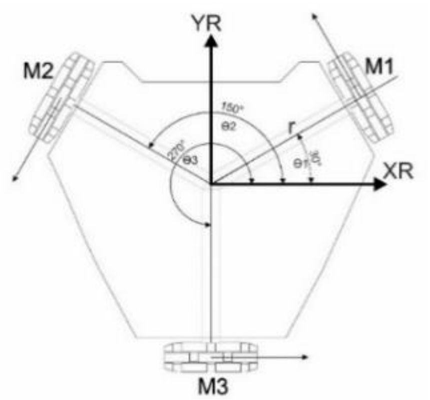

Figure 1 Reference of position vector in three wheeled robot

The movements mapping between local and global references only with matrix rotation (considering that these local references are fixed and not rotating against the robot), where θ is the angle of rotation in an anticlockwise direction *[1]*.

$$R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \quad (2)$$

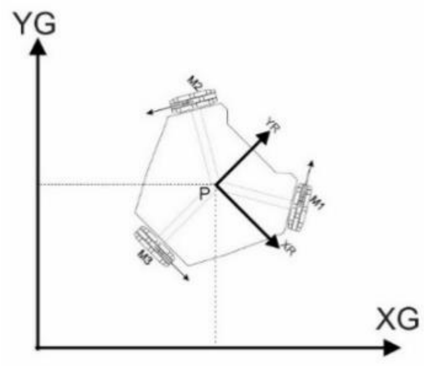

Figure 2 Reference for 3 wheel robot rotation vector

The matrix equation above can be used for global references map (XG, YG) to move according to local references (XR, YR). This equation is stated in $(\theta)\xi_I$ because the calculation of the equation depends on the value θ.

$$\dot{\xi}_R = R(\tfrac{\pi}{2})\dot{\xi}_I \tag{3}$$

To determine the velocity vector of the robot, it's obtained from the position vector derivative. Speed kinematics can be known by observing the function of movement direction in each wheel, the axis of the robot, the angular rotation velocity and the geometry of the robot itself.

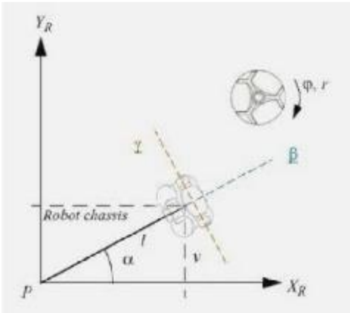

Figure 3 Kinematic omni wheels reference

For the forward kinematic equation of robot are as follows.

$$\begin{pmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{pmatrix} = R\begin{bmatrix}-\frac{2s\theta}{3} & \frac{c\theta}{\sqrt{3}}+\frac{s\theta}{3} & \frac{c\theta}{\sqrt{3}}+\frac{s\theta}{3}\\ -\frac{2c\theta}{3} & \frac{c\theta}{3}+\frac{s\theta}{\sqrt{3}} & \frac{c\theta}{3}-\frac{s\theta}{\sqrt{3}}\\ \frac{1}{3L} & \frac{1}{3L} & \frac{1}{3L}\end{bmatrix}\begin{bmatrix}v1\\ v2\\ v3\end{bmatrix} \tag{4}$$

For the inverse kinematic equation of robot are as follows.

$$\begin{pmatrix}v1\\ v2\\ v3\end{pmatrix} = \begin{bmatrix}-C(60+\theta) & S(60+\theta) & 1/3\\ -C(60-\theta) & -S(60-\theta) & 1/3\\ C(\theta) & -S(\theta) & 1/3\end{bmatrix}\begin{bmatrix}x\\ y\\ \theta\end{bmatrix} \tag{5}$$

2.2 Rotary Encoder

Rotary Encoder is a transducer used to measure angular position and rotating shaft speed. Rotary encoders are commonly used to monitor and control industrial processes and robotics engineering [5].

2.3 Gyroscope Sensor

Gyroscope sensor is a motion sensor that can detect and measure the angular motion of an object. A gyroscope basically consists of a rotating mass that rotates around its axis. In particular, when the mass rotates on its axis, it tends to remain parallel to itself and opposes attempts to change its orientation. This mechanism was discovered in 1852 by physicist Léon Foucault during his study of the rotation of the earth. If a gyroscope is mounted on a gimbal that allows the mass to navigate freely in three directions of space, the spinning axis will remain oriented in the same direction, even if it changes direction [6].

3. Methodology

3.1 Mechanical Design

Mechanical robots are designed using a 4 square aluminum base material with ½ inch of thickness, and some robot parts use solid aluminum with a thickness of 3mm. The robot in this study was designed to refers with the RoboCup 2018 line, from the determination of the maximum size of the robot and the placement of several drives such as the ball dribble that has been determined in the rules. In the robot, there are 3 rotary encoder sensors on each motors with the distance between the wheels is 120º to simplify the placement of the rotary and the main motor of the robot. In this study the rotary encoder uses a rotary encoder that is already on the main motor so that rotary encoder placement is the same as the motor placement, which is the angle in each rotary is 120º. Figure 4 is the basic design of the robot.

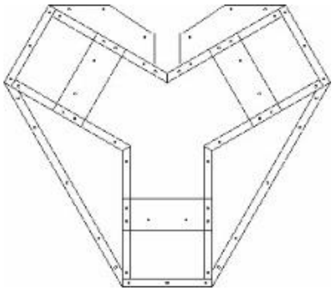

Figure 4 Basic mechanics design of robot

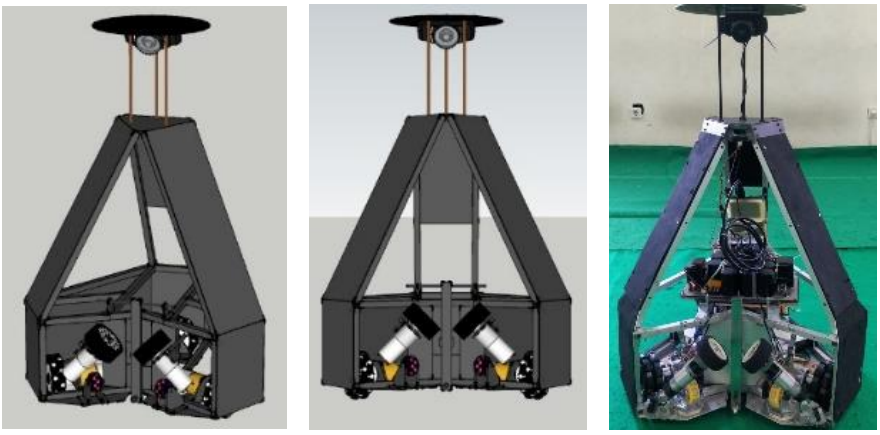

Figure 5 3D design and the final design of a soccer robot

3.2 Electronic Design

Robot electronics consists of a voltage source, sensors, a control circuit and motor drivers. The electronic diagram of the robot in this study show in Figure 6.

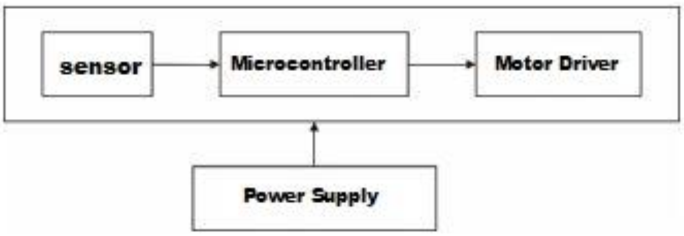

Figure 6 The block diagram of electronics robot

The sensors used in robots are Rotary encoder sensors and gyroscope sensor. The encoder sensor uses a magnetic encoder sensor, while the gyroscope sensor is the MPU6050 module sensor, while the controller circuit or microcontroller system is the Arduino Mega2560 microcontroller module, and the motor driver is the BTS7960 motor driver module.

3.3 Source Code Design

Source Code design in this study includes designing a base-station programs with the form of desktop applications and designing a robot microcontroller program. The base-station program is used to monitoring and control the position of the robot via a PC. The program that use to design the base-station program is Visual Studio with Visual Basic as its programming language. While the microcontroller uses the Arduino IDE programming application and the Arduino standard language as its programming language.

4. Result and Analysis

4.1 Gyroscope

This experiment was carried out by measuring the orientation of the robot with a reference that using the arc and reading the gyroscope sensor data.

Table 1 Gyroscope Sensor Testing Results

No	Degree		Error
	Real	Gyro	
1	0	0	0.00
2	10	10.34	3.40
3	30	29.83	0.57
4	50	51.52	3.04
5	70	71.4	2.00
6	90	91.41	1.57
7	110	111.42	1.29
8	130	131.41	1.08
9	150	151.4	0.93
10	170	172.2	1.29
11	190	189.58	0.22
12	210	210.42	0.20
13	230	231.42	0.62
14	250	250.52	0.21
15	270	271.42	0.53
16	290	291.42	0.49
17	310	311.22	0.39
18	330	331.54	0.47
19	350	359.1	2.60
20	360	359.7	0.08
Error rata-rata			1.05

From the results of the tests that carried out by giving or directing the robot at several degrees, from 0 to 360 degrees, the result is that the gyro sensor has been able to read the orientation of the robot in the form of degrees with a range from 0 to 360. At each reading there is a very small error value that no more than 2 degrees. And the average error value is 1.24%. The error value is obtained by comparing the results of the reduction in the reading instrument value with the sensor reading value and divided by the value of the measuring instrument then multiplied by 100.

4.2 Rotary Encoders (Rotation Speed)

In this experiment carried out by measuring the speed of each wheel in the robot by using a rotary encoder as the speed-reading sensor then compared with a rotation speed measuring instrument (tachometer). In this test, RPM of the wheel is measured using a rotary encoder by applying the RPM equation = pulse encoder * 600 / the amount of pulses per rotation, where pulses per rotation is 270 pulses. In this test, the PWM value (Pulse Width Modulation) is given to the motor driver and then measuring the speed of each motor. It’s necessary to pay attention to the supply voltage for the motor driver so that in each experiment the motor speed measurement (RPM) has the same value, where the voltage that used in this experiment is 24v from using two 3 cells batteries that arranged in series.

Table 2 Results of Left Motor Rotation Speed Testing

No	PWM	Real Speed (RPM)	Encoder Speed(RPM)	Error (%)
1	0	0	0	0.00
2	10	20.8	21.4	2.80
3	20	50.4	50	0.80
4	30	70.7	70.1	0.86
5	40	90.3	89.8	0.56
6	50	110.5	111.4	0.81
7	60	136.9	140.1	2.28
8	70	158.3	160.1	1.12
9	80	175.9	180.2	2.39
10	90	198.4	201.1	1.34
11	100	219.7	220.4	0.32
12	110	238.6	240.1	0.62
13	120	259.3	260.5	0.46
14	130	274.9	276.2	0.47
15	140	298.4	299.5	0.37
16	150	318.2	319.4	0.38
17	160	336.9	337.6	0.21
18	170	359.5	360.6	0.31
19	180	379.6	380.1	0.13
20	190	399.2	400.5	0.32
21	200	418.6	419.4	0.19
22	210	438.5	439.5	0.23
23	220	459.3	460.2	0.20
24	230	478.6	479.1	0.10
25	240	499.2	500.2	0.20
26	250	519.4	520.5	0.21
27	255	528.8	530.1	0.25
Average error				0.66

From the experiment, the rotation speed is directly proportional to the provision of PWM (Pulse Width Modulation). PWM runoff starts from a minimum PWM that is 0 to maximum PWM which is 255. Also the other result is that from the tachometer measuring instrument, the maximum speed of the left motor is 528.8 RPM (Rotation per Minute) and the maximum speed of rotary encoder sensor is 530.1 RPM. From the test results, the rotary encoder sensor has been able to read the speed on the left motor with a small error value with an average presentation error value of 0.66%. The error value is obtained by comparing the results of the reduction in the reading instrument value with the sensor reading value and divided by the value of the measuring instrument then multiplied by 100.

Table 3 Results of Right Motor Rotation Speed Testing

No	PWM	Real Speed (RPM)	Encoder Speed(RPM)	Error (%)
1	0	0	0	0.00
2	10	20.2	21.5	6.05
3	20	50.2	50.3	0.20
4	30	70.4	70.2	0.28
5	40	90.3	89.5	0.89
6	50	110.4	111.6	1.08
7	60	136.7	140.4	2.64
8	70	158.5	160.8	1.43
9	80	175.8	180.3	2.50
10	90	198.3	201.9	1.78
11	100	219.6	220.5	0.41
12	110	238.5	240.4	0.79
13	120	259.2	260.6	0.54
14	130	274.5	276.8	0.83
15	140	298.6	299.9	0.43
16	150	318.7	319.5	0.25
17	160	340	337.7	0.68
18	170	359.8	360.9	0.30
19	180	379.9	380.2	0.08
20	190	399.6	400.5	0.22
21	200	418.6	419.6	0.24
22	210	438.7	439.7	0.23
23	220	459.8	460.3	0.11
24	230	478.9	479.5	0.13
25	240	499.4	500.6	0.24
26	250	519.6	520.7	0.21
27	255	530.3	530.9	0.11
Average error				0.84

From the experiment, the rotation speed is directly proportional to the provision of PWM (Pulse Width Modulation). PWM runoff starts from a minimum PWM that is 0 to maximum PWM which is 255. Also the other result is that from the tachometer measuring instrument, the maximum speed of the right motor is 530.3 RPM (Rotation per Minute) and the maximum speed of rotary encoder sensor is 530.9 RPM. From the test results, the rotary encoder sensor has been able to read the speed on the right motor with a small error value with an average presentation error value of 0.84%. The error value is obtained by comparing the results of the reduction in the reading instrument value with the sensor reading value and divided by the value of the measuring instrument then multiplied by 100.

Table 4 Results of Back Motor Rotation Speed Testing

No	PWM	Real Speed (RPM)	Encoder Speed(RPM)	Error (%)
1	0	0	0	0.00
2	10	20.1	21	4.29
3	20	50.2	49.9	0.60
4	30	70.4	69.8	0.86
5	40	90.9	89.5	1.56
6	50	111	111.1	0.09
7	60	139	140.3	0.93
8	70	159.4	160.3	0.56
9	80	179	180.1	0.61
10	90	198.9	201.3	1.19
11	100	219.5	220.1	0.27
12	110	238.8	240.2	0.58
13	120	259.2	260.3	0.42
14	130	274.5	276.4	0.69
15	140	298.8	299.2	0.13
16	150	318.8	319.3	0.16
17	160	336.5	337.4	0.27
18	170	359.9	360.5	0.17
19	180	379.7	380	0.08
20	190	399.4	400.1	0.17
21	200	418.7	419.2	0.12
22	210	438.9	439.3	0.09
23	220	459.5	460.1	0.13
24	230	478.8	479.2	0.08
25	240	499.3	500	0.14
26	250	520.4	520.1	0.06
27	255	530.1	530.9	0.15
Average Error				0.53

From the experiment, the rotation speed is directly proportional to the provision of PWM (Pulse Width Modulation). PWM runoff starts from a minimum PWM that is 0 to maximum PWM which is 255. Also the other result is that from the tachometer measuring instrument, the maximum speed of the back motor is 530.1 RPM (Rotation per Minute) and the maximum speed of rotary encoder sensor is 530.9 RPM. From the test results, the rotary encoder sensor has been able to read the speed on the back motor with a small error value with an average presentation error value of 0.53%. The error value is obtained by comparing the results of the reduction in the reading instrument value with the sensor reading value and divided by the value of the measuring instrument then multiplied by 100.

4.3 Wheel Mileage

This experiment is done by moving the robot manually so that the wheel turns clockwise and anticlockwise from each wheel. The test results of the mileage on each wheel can be seen in the table 5.

Table 5 Wheel mileage test results

No	Real Distance (cm)	Wheels Mileage (cm)		
		Right	Left	Back
1	10	10.01	10.01	10.01
2	20	20.02	20.02	20.02
3	30	30.03	29.94	30.03
4	40	39.93	39.93	40.04
5	50	49.82	50.05	50.05
6	60	60.06	60.06	60.06
7	70	69.96	70.07	70.07
8	80	80.08	80.08	80.08
9	90	89.98	89.98	89.98
10	100	99.99	100.02	99.99
Average error		0.11289	0.09446	0.03715

From this experiment, the system can measure the mileage of each wheel with an average error reading distance is very small that is for the left wheel is 0.11308 cm, the right wheel is 0.09450 cm, and the rear wheel is 0.03712 cm. To measure the mileage on each wheel, several parameters are needed such as the wheel diameter and the number of pulses in one wheel rotation in order to calculate the circumference of the wheel and the distance per pulse of the wheel. With that reference, the wheel distance can be calculated by multiplying the distance per pulse with rotary pulses.

4.4 Kinematics

In this experiment consists of testing the robot mileage readings to test the forward kinematic and the other test by giving the coordinate for robot destination to test the inverse kinematic. First, the forward kinematic test is done by moving the robot to any direction with the position of cartesian coordinates (x, y, and theta) with units of centimeters (cm). The forward kinematic test results can be seen in the table 6.

Table 6 forward kinematic test result

No	Real Distance (cm)			Measured Distance(cm)		
	x	y	θ	x	y	θ
1	0	10	0	0	10.5	0.52
2	10	10	0	10.11	9.99	0.46
3	10	20	90	11.9	21.09	91.6
4	20	20	90	22.04	21.3	89.9
5	20	30	180	22.1	32.2	180.1
6	30	30	180	32.01	32.5	179.9
7	30	40	270	32.11	43.02	270.2
8	40	40	270	42.06	43.03	271.01
9	40	50	360	42.03	54.19	358.99
10	50	50	360	53.19	54.53	359.33
11	50	60	360	52.99	63.32	359.28
12	60	60	360	61.06	63.45	359.34
13	60	70	270	61.23	73.5	271.45
14	70	70	270	72.6	73.6	271.54
15	70	80	180	72.9	82.99	181.35
16	80	80	180	82.4	83.52	180.34
17	80	90	90	82.6	93.23	91.35
18	90	90	90	92.66	94.12	89.32
19	90	100	0	93.45	102.56	1.25
20	100	100	0	105.6	103.63	1.46t
Average error				5.371552	5.200101	0.265778

From the results of the tests that the system can measure the distance of the robot in coordinates (x, y, θ). At the mileage of the robot in the beginning has a little error value but after the robot moving more than 10cm, the error value has increased more than 1cm. The value of this error will increase as long as the mileage of the robot. It's because the wheel get some skid so it affect the value of robot mileage. This error value is also because when conducting the experiment is using only a manual push without a specific accurate route.

The inverse kinematic test to represent the speed measuring test in each motor is done by giving a coordinate point through the PC then observing how accurate and fast the response of the robot when moving to that point. Figure 13 shows the display of the simulation program from the application that was created.

Figure 7 Soccer Robot Simulation

The results of the tests carried out by providing some of the intended coordinates can be seen in the table 7.

Table 7 inverse kinematic test result

No	Start			End			Time (s)
	x	y	θ	x	y	Θ	
1	0	0	0	0	450	0	4.2
2	0	450	0	0	0	0	4
3	0	0	0	300	0	0	4.8
4	300	0	0	0	0	0	3.1
5	0	0	0	0	450	90	4.3
6	0	450	90	0	0	0	4.2
7	0	0	0	300	0	90	3.8
8	300	0	90	0	0	0	3.4
9	0	0	0	0	450	180	4.3
10	0	450	180	0	0	0	4.2
11	0	0	0	300	0	180	3.5
12	300	0	180	0	0	0	3.2
13	0	0	0	0	450	270	4.2
14	0	450	270	0	0	0	4.1
15	0	0	0	300	0	270	3.8
16	300	0	270	0	0	0	3.7

From the experiments, the system was able to carry out inverse kinematic execution from the robot so that the robot was able to move towards the given coordinate point with the time recorded as in the inverse kinematic test results table. In the experiment by testing the destination point in the form of x-axis movement from 0 cm to 450 cm and the y axis 0 cm to 300 cm in several directions, namely 0^o, 90^o, 180^o, and 270^o which is then carried out the reversed route is from 450 cm to 0 cm for the x axis, and 300 cm for 0 cm for the y axis. From these experiments it can be observed that the movement towards the end point of 0 cm tends to be slower than the movement towards the x point of 300 cm and towards the y of 450 cm. This is because there are several movements such as a rotation robot in the beginning or when it starts to move. From the test results, after several movements the robot is not able to be at the intended point but still has a few errors, this is due to the skid of the wheel that affects the rotary encoder reading on each wheel and the robot's reading mileage has some errors.

5. Conclusion

Forward kinematic robot can provide robot position information in cartesian coordinates in this case is the robot point on the soccer robot contest is a soccer field but still has a slight error when it has moved with the skid on the wheel and affects the rotary encoder reading with average error x coordinate =5.37%, y coordinate =5.20% and theta=0.26%.

Inverse kinematic robot can provide a response in performing movements in the field of soccer robot contests by providing a robot's destination point.

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