Study and Implementation of a Robot Soccer System based on the CDIO approach

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***Abstract*—Soccer robots have been frequently used to validate models of multi-agent systems, involving collaboration among the agents. For this purpose, many researchers in robotics have been developing robotic soccer teams which compete in events such as RoboCup and FIRA. This study aims to explore a robot soccer system in which two prototypes of soccer robots are fabricated. A global vision system is implemented to collect real-time positions and orientations of the ball and robots. Then, their data is transferred to a host computer and processed. Finally, kinematic commands are sent to the robots to perform desired motions. The results of this study have successfully implemented the soccer robot system.**

***Index Terms*—soccer robots, visual localization**

I. Introduction

Autonomous robots have become an important branch of mechatronic research. There have been many studies on the implementation of the robot soccer system in competitions, showing that robot soccer game is a good motivation to study on designing and controlling a system of multiple robots in real-time. In 1993, Alan Mackworth proposed the idea of a robot soccer game, which promotes the full integration of the research into artificial intelligence and robotics. Then a series of robot soccer games and symposiums are held by two international associations: RoboCup and FIRA [1], [2].

Up to now, there are three soccer leagues of RoboCup: Small Size League, Middle Size League, Standard Platform League. A Small Size robot soccer game takes place between two teams of five robots each. The robot must fit within a 180 mm diameter circle and must be no higher than 150 mm. The robots play soccer on a green carpeted field that is 4.9 m long by 3.4 m wide with an orange golf ball [3]. The first international RoboCup match was held in 1997 as shown in Fig. 1.

Fig. 1. A Small Size League in 1997 [3]

The idea of soccer robots is very popular in the world. Many interesting algorithms have been studied to improve performance of soccer robots. Awang et al. have concentrated on developing position and obstacle avoidance algorithm for realizing soccer skills such as movement, shoot and goal keeping which were successfully implemented and tested by using Robot Soccer Simulator V1.5A [4]. Hamidreza et al. have utilized the sensor data fusion method in the control system parameters, self localization and world modeling in which a vision-based self-localization and the conventional odometry systems are used for robust self-localization of an omni-directional Middle size soccer robot [5]. Brodhead has focused on Fuzzy Petri nets in developing a robust kicking strategy and algorithm [6]. However, there are just a few projects about soccer robots in Vietnam, especially in the universities. With the evolution of technology, there are many components on the market that come with compact sizes, good specification, and reasonable price. Therefore, the motivation of this study is to develop a small size robot soccer system. This development is approached in the context of CDIO [7], which is to conceive, design, implement, and operate real-world systems and products, with the purpose of engaging more students in engineering, especially in mechatronics.

This paper presents an approach that found interested and fascinated by stake holders at the Department of Mechatronic Engineering. The content in this paper is organized into five parts. Section II highlights essential components of the system, conceiving their functionality. Section III presents the prototype development where the robots are designed and fabricated. This is followed by the vision-based sensor of the system in section IV. The controller implementation and experimental results will be addressed in in section V. Finally, the achievement is summarized in the conclusion.

II. Layout of the robot soccer system

For a very small size league, there are some main components as shown in Fig. 2. The soccer field has the size of $1.7\ m \times 1\ m$ and the camera is hung above the center of the field. The ball is a standard golf ball which is $42.67\ mm$ in diameter. The other components all play important role for the system performance as follows:

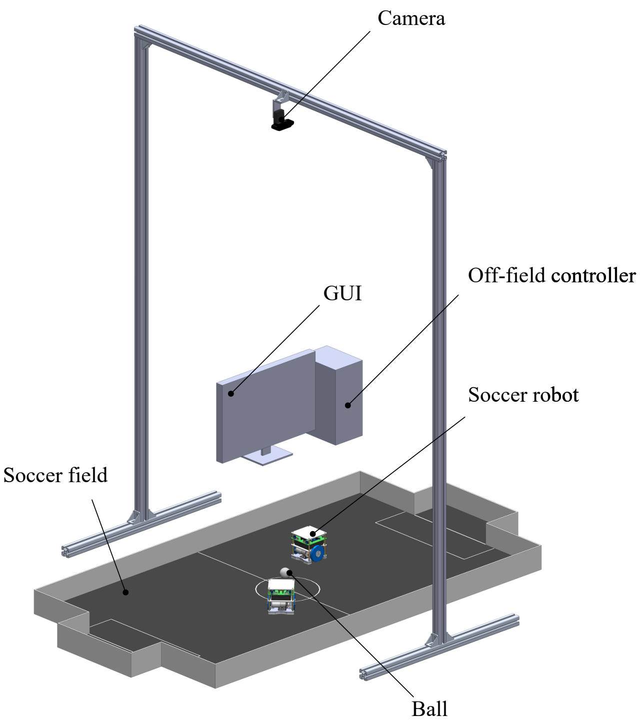

Fig. 2. Robot soccer system

- The camera is the eye of the system. It detects the objects and feeds the data back to the controller.
- The off-field computer is the controller of the system, it receives information from the camera. From that data, it determines the coordinates and motion of the objects. In addition, it provides communication for the robots via WiFi. Then, an algorithm is applied to drive the robot toward the ball from an arbitrary position.
- A graphical user interface (GUI) displays the information about the robot motion as well as the ball for the user.
- The soccer robots are the main players of the game. They receive the commands from the controller and execute to meet desired motion.

III. Prototype development

A. Conceptual design

The robot is required to fit into a $100 \times 100 \times 100\ (mm)$ space, driven by two wheels and the robot's structure must be modular. The robot is designed to meet the specification as listed in Table I.

TABLE I
Robot specification

Mass of the robot	M	$1\ kg$
Wheel radius	r	$0.0325\ m$
Maximum speed	v_{max}	$1.5\ m/s$
Maximum acceleration	a_{max}	$1\ m/s^2$

In this study, the soccer robot is a differential drive mobile platform. This struture consists of two driving wheels mounted on a common axis, and each wheel can independently be driven either forward or backward. The center wheel axle is a good design choice, as shown in Fig. 3, the robot rotates around its center, which supports robot detection later in vision. The subsequence calculation of the robot components are listed as follows:

- For the design requirement of the soccer robot, the wheels diameter is chosen as $65\ mm$.
- The spur gear drive is used with the gear ratio 2:3 (the driven gear has 40 teeth, driving gear has 60 teeth).
- From the robot requirements, motor torque should be high enough, so the brushed DC motor GA25 V1 is selected.
- A Node MCU ESP32 board is used as the controller and a TB6612FNG is chosen as the motor driver.

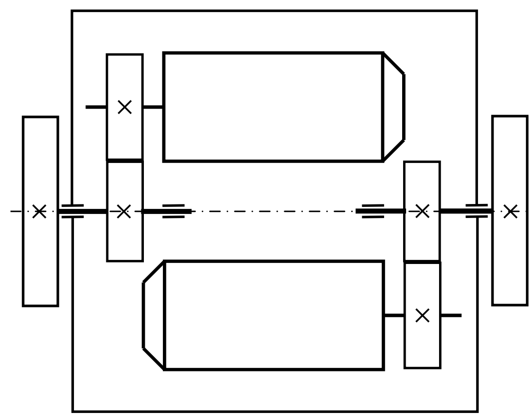

Fig. 3. Symmetric transmission layout

After the components are chosen, they are arranged neatly in the limited space separating in four layers as highlighted in Fig. 4.

- Detection layer contains the marking to detect the robot position and orientation.
- Electronic layer is a printed circuit board containing the micro-controller as well as the motor driver.
- Battery layer contains the power source with 4 Li-Po batteries. The robot is estimated to operate up to 2 hours with a full charge.
- Drivetrain layer contains the motors, gears and auxiliary elements to maintain the balance when moving.

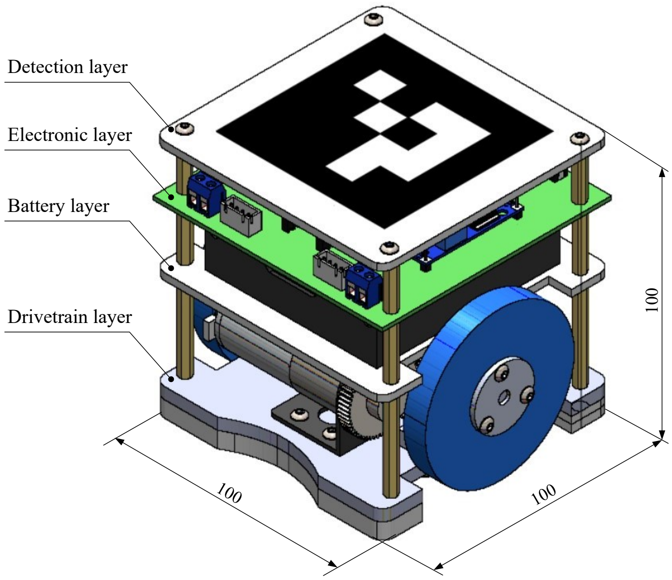

Fig. 4. Final design of soccer robot

B. Kinematic model of the robot.

The soccer robots are differentially driven by two wheels, which are nonholonomic systems. The kinematic model of the robot is shown in Fig. 5, where v_L, v_R are linear velocity of left and right wheel. The combination of v_L and v_R creates the 2-dimensional motion of robot on the OXY plane with v is the linear velocity and $\omega = \dot{\theta}$ is the angular velocity.

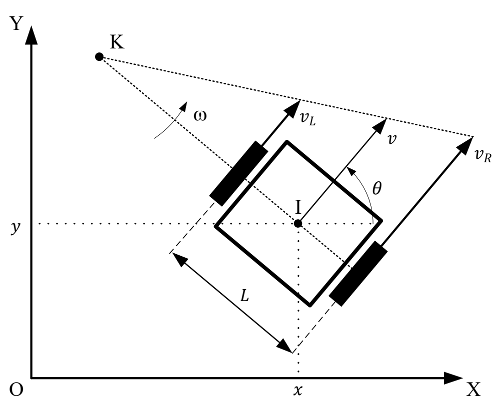

Fig. 5. Differential drive robot kinematics

With the assumption of no sliding at the wheels, the kinematic model of the robot is summarized in (1). The equation shows that the differential drive robot is a multiple-input multiple-output (MIMO) system that has 2 inputs (ω_R, ω_L) and 3 outputs $(\dot{x}, \dot{y}, \dot{\theta})$. The motion of robot can be seen as a rotation around an instantaneous center of curvature (ICC) K, which leads to three cases as follows:

- $v_L = v_R = v$, the robot translates forward and backward, the ICC is at infinity and $\omega = 0$.
- $v_L = -v_R$, the robot rotates around the midpoint of the wheel axle, the ICC is at I, $v = 0$ and $\omega = \frac{2v_R}{L}$.
- $v_L = 0$ and $v_R \neq 0$, the robot rotates around its left wheel $\omega = \frac{v_R}{L}$, vice versa, $v_L \neq 0$ and $v_R = 0$, the robot rotates around its right wheel and $\omega = -\frac{v_L}{L}$.

$$\begin{aligned} \begin{bmatrix} v \\ \omega \end{bmatrix} &= r \begin{bmatrix} 1/2 & 1/2 \\ -1/L & 1/L \end{bmatrix} \begin{bmatrix} \omega_L \\ \omega_R \end{bmatrix} \\ &= \begin{bmatrix} 1/2 & 1/2 \\ -1/L & 1/L \end{bmatrix} \begin{bmatrix} v_L \\ v_R \end{bmatrix} \end{aligned} \tag{1}$$

C. Wheel speed controller

As shown in (1), the wheel speed must be maintained to satisfy the linear velocity as well as the angular velocity of the robot. Two closed-loop PI controllers are implemented on the ESP32 micro-controller. The coefficients of the PI controllers are estimated using MATLAB PID Tuner. Fig. 6 shows that the response of two wheels with the same step input signal has a slight different in settling time. However, their stable values match quite well.

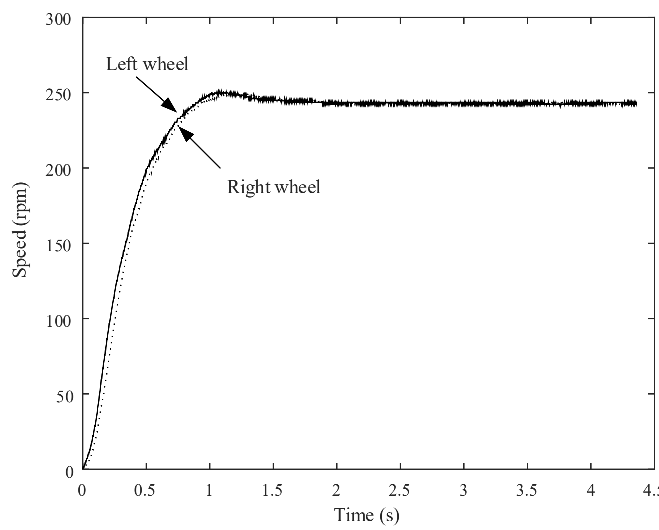

Fig. 6. Speed response of two wheels

IV. Vision-based robot localization

Before processing the image, the camera must be calibrated to obtain the position and orientation of the objects on the field. The calibration steps follow Zhang's method [8]. Then, the image processing algorithm is applied to obtain the position of the robots and the ball on the field. The coordinate of the objects in the real world and in the image has the relation as follows:

$$\mathbf{p}_{img} = \mathbf{K} * \left[\begin{array}{c|c} \mathbf{R} & \mathbf{T} \\ \hline 0 & 1 \end{array} \right] * \mathbf{p}_{real} \tag{2}$$

where:

$\mathbf{p}_{real}$: coordinate of a point in the real-world system
$\mathbf{p}_{img}$: coordinate of that point in the image
$\mathbf{K}$: intrinsic parameters of the camera

$\mathbf{R}, \mathbf{T}$: rotation and translation matrices

In this study, the Logitech C922 Pro webcam is used with resolution of 640×480 and frame rate of 30 FPS. The camera is hung at 2 m high so that it covers the field of 1700×1000 (mm). The camera matrix $\mathbf{K}$, and the matrices $\mathbf{R}_0, \mathbf{T}_0$ concerning the origin of the soccer field can be found by using OpenCV library implemented on python programming language.

$$\mathbf{K} = \begin{bmatrix} 913.2081 & 0 & 645.4051 & 0 \\ 0 & 912.4480 & 364.1755 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (3)$$

$$\mathbf{R}_0 = \begin{bmatrix} -1 & 0.0014 & -0.0069 \\ -0.0014 & -1 & -0.0089 \\ -0.0069 & -0.0089 & 0.9999 \end{bmatrix} \quad (4)$$

$$\mathbf{T}_0 = \begin{bmatrix} 456.6 \\ 214.7 \\ 1924.4 \end{bmatrix} \quad (5)$$

After the calibration, some image processing methods are applied to detect the ball as well as the robots on the field. For the ball, circle Hough transformation (CHT) is used to recognize the ball shape by searching the circle with the given radius on the field. Then position of the ball center is obtained, and by calculating it in two consecutive image frames, velocity of the ball is known, as shown in Fig. 7.

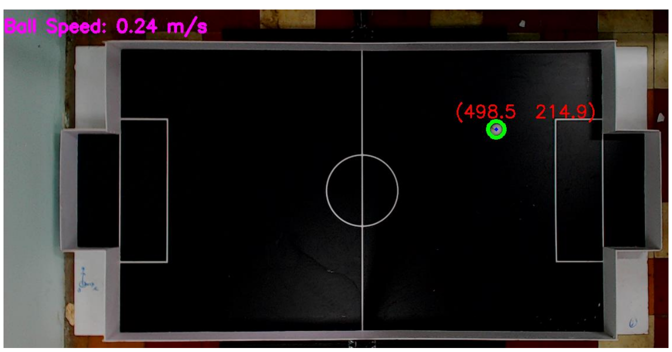

Fig. 7. Position and speed of the ball

For the robots, there are two things to detect: position and orientation. One method to do the task is to place a pattern on the top of the robots to detect as well as to distinguish them. The Aruco marker set is a good approach with some advantages: they are distinguishable and are only black and white, so no need to use color image processing. An Aruco marker is a synthetic square marker composed of a wide black border and an inner binary matrix that determines its identifier (ID) [9], as shown in Fig. 8. The Aruco marker set used in this study is the 4×4 bit set with 50 IDs.

The robots and ball detection runs in parallel processes so it can be done simultaneously. In this system the IDs 0 and 1 are used to detect the two robots. Fig. 9 shows the second robot and the ball. For the ball, only positional coordinates

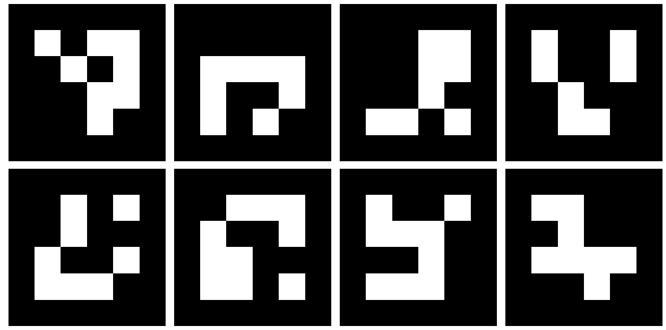

Fig. 8. Aruco markers of 4×4 for robot detection

are enough, while the robot needs both positional as well as oriental parameters. Typically, the position of robot 2 is $(X_2, Y_2) = (240.6, 448.1)$ with respect to the global frame, and the orientation of robot 2 is 55.9 with respect to the X-axis. Similarly, position of the ball is shown in the third column as $(X_{ball}, Y_{ball}) = (394.8, 638.8)$.

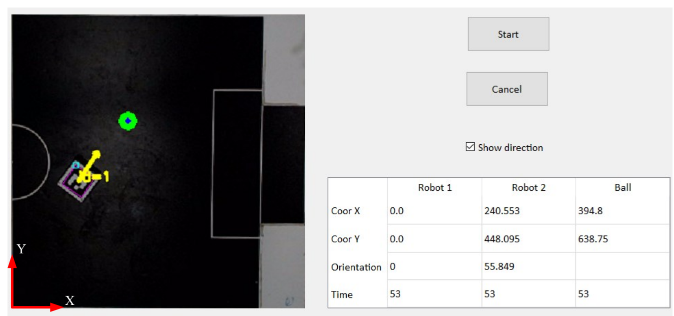

Fig. 9. GUI showing robot and ball detection

V. Development of Motion Control System

A. Host controller implementation

The robot model is decoupled into two single-input single-output (SISO) systems, which are pure rotation and pure translation as shown in Fig. 10. At the first state of development, every motion of the robot is always planned into a series of rotation and translation.

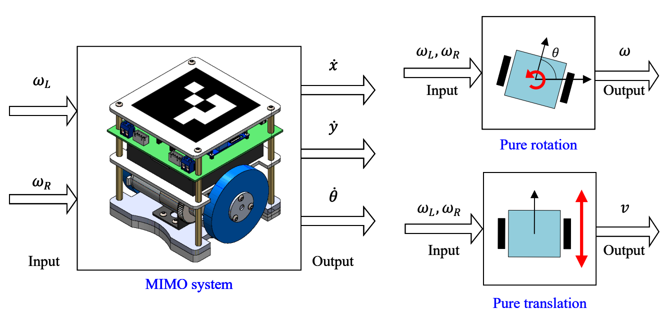

Fig. 10. Decouple the robot into pure rotation and pure translation

Since the prototype itself has uncertainty when moving on the soccer field, the host computer has to play a role in compensating this type of error. Therefore, beside monitoring the pose of the objects, the vision is also integrated in the outer closed-loop control system in Fig. 11.

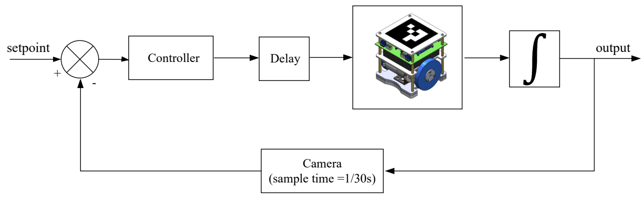

Fig. 11. Control diagram of the system

For pure rotation, a discrete PI controller is applied with the parameters are shown in (6), where $T_s = 1/30\ s$ is the sample time of the camera, $K_P = 8.026, K_I = 0.07672$ are the parameters also tuned by MATLAB PID Tuner. When implement on the model, the test result shows that the steady state error stay within $\pm 10°$, the settling time is less than 5s and the overshoot is less than 10%.

$$K_p + K_I \times T_S \times \frac{1}{Z-1} \tag{6}$$

For pure translation, a trapezoidal motion profile is applied, as in Fig. 12, the acceleration and deceleration time are chosen as $t_{acc} = t_{decc} = \frac{2}{10} t_{total}$, with $t_{total} = t_{acc} + t_{max} + t_{decc}$. With a given setpoint distance d_0, the distance travel in each stage are calculated as in (7). From the experiment, $v_{max} \approx 0.5\ m/s$ so $d_{acc}, d_{max}, d_{dec}$ can be calculated.

$$\begin{cases} d_{acc} = d_{dec} = 0.1 \times v_{max} \times t_{total} \\ d_{max} = 0.6 \times v_{max} \times t_{total} \\ d_0 = d_{acc} + d_{max} + d_{dec} = 0.8 \times v_{max} \times t_{total} \end{cases} \tag{7}$$

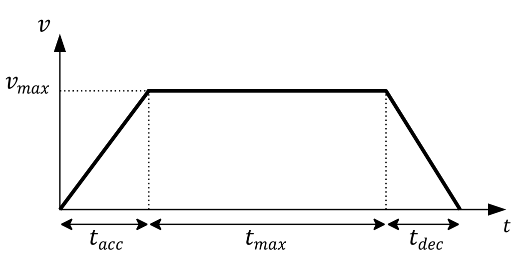

Fig. 12. Velocity-time graph in trapezoidal motion profile

B. Experimental result.

From the design above, two robots are created as in Fig. 13. When applying the control method, these robots can achieve the accurary of $\pm 10°$ for pure rotation and $\pm 50\ mm$ for pure translation.

Fig. 14 shows the GUI to control the robot to kick the ball at rest following a simple strategy. The lower left table indicates the pose of robots and ball in real-time while the right panel provides connection information and control for the robots. Considering a case study where the robot is at an arbitrary position on the field and the ball is placed near the goal. The strategy is constructed as follows:

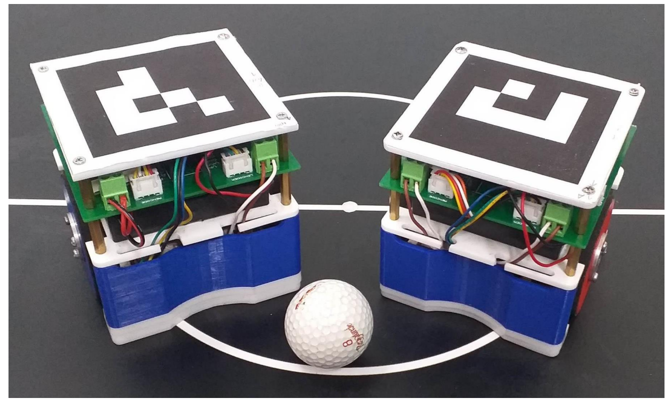

Fig. 13. Two soccer robots and the ball

- Draw a line from the center of the goal G to the ball B.
- Extend the line outward the goal by a distance d (segment BC). The distance d is chosen from the experiment, it must be large enough for the robot to accelerate, in this case $d \geq 200\ mm$.
- Then draw a line from the robot position A to point C.

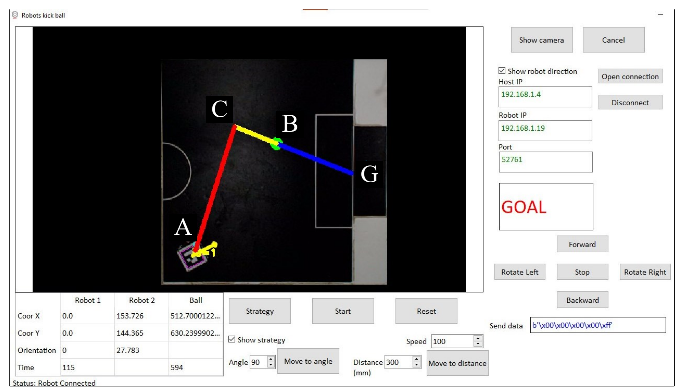

Fig. 14. GUI showing the control for robot to kick the ball

After creating the strategy, now the robot applies the strategy to score a goal in 4 steps:

- Step 1: First, the robot rotates to the direction $\overrightarrow{AC}$ (using pure rotation).
- Step 2: Next, it runs to point C (using pure translation).
- Step 3: After that it rotates toward the ball (using pure rotation).
- Step 4: Finally, the robot runs toward the ball (using pure translation).

With the steps planned above, Fig. 15 plots the change in position and orientation of the robot as well as the ball every second. It is observed that:

- From second 1 to 6, the robot rotates at point A.
- In the interval 6 to 11 seconds, the robot translates in a straight line to point C.

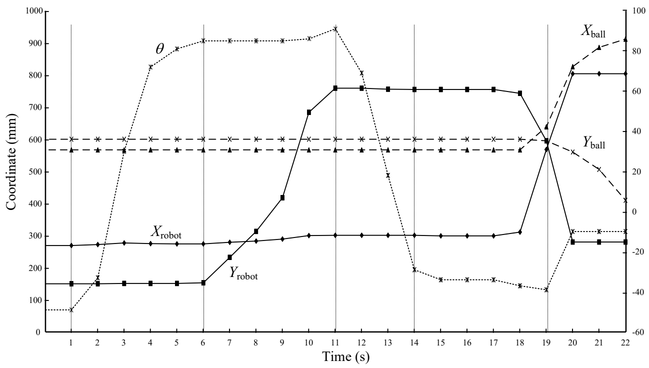

Fig. 15. Postures of robot and ball with respect to time

- Next, it rotates at point C during the time 11 to 14 seconds.
- Then, the robot translates toward the ball and kicks it in the duration 14 to 19 seconds.
- The collision happens at around the 19^{th} second. After that, the ball starts moving to the goal and the robot slows down.

VI. Conclusion

This study presents the design and implementation of the robot soccer system. Two modular compact prototypes of soccer robot have been designed and fabricated. The vision-based robot localization, which makes sure the system works as desired, has been deployed. The experimental results with respect to time illustrates the success of the controller system. However, the accuracy performance of the system is not very good, which definitely limits the robot ability in team co-ordination. Therefore, together with the simultaneous motion between the rotation and translation that makes the robot move smoothly, the improvement in system performance will be our future works.

Acknowledgment

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References

[1] Ching-Chang Wong, Wei-Wen Wang, and Ya-Ling Lee, "Soccer robot design for FIRA MiroSot League," IEEE International Conference on Mechatronics, 2005, ICM'05., pp. 457–460, IEEE, 2005.
[2] Itsuki Noda, Sho'ji Suzuki, Hitoshi Matsubara, Minoru Asada, and Hiroaki Kitano, "RoboCup-97: The first robot world cup soccer games and conferences," AI magazine, 19(3), pp. 49, 1998.
[3] Alfredo Weitzenfeld, Joydeep Biswas, Mehmet Akar, and Kanjanapan Sukvichai, "Robocup Small Size League: Past, present and future," Robot Soccer World Cup, pp. 611–623, Springer, 2014.
[4] Pratomo, Awang Hendrianto, et al, "Position and obstacle avoidance algorithm in robot soccer," Journal of Computer Science 6.2 (2010): 173–179.
[5] S. Hamidreza Mohades Kasaei and S. Mohammadreza Mohades Kasaei, "Design and implementation an autonomous mobile soccer robot based on omnidirectional mobility and modularity," International Journal of Computer and Electrical Engineering 3.5, pp. 616, 2011.
[6] P. Brodhead, G. Hope, and S. Kim, "Soccer playing robot goal scoring algorithm using fuzzy petri nets." CATA, 2020.
[7] Worldwide CDIO Initiative. Accessed on: Sept. 18, 2021. Available: cdio.org
[8] Zhengyou Zhang, "A flexible new technique for camera calibration," IEEE Transactions on pattern analysis and machine intelligence, 22(11), pp. 1330–1334, 2000.
[9] MF. Sani and G. Karimian, "Automatic navigation and landing of an indoor AR. drone quadrotor using ArUco marker and inertial sensors," 2017 international conference on computer and drone applications (IConDA), pp. 102–107, IEEE, 2017.

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