A Control System for Active Ball Handling in the RoboCup Middle Size League

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Abstract: This paper describes the design, realization and testing of an active ball handling mechanism which is designed for dribbling the ball in the RoboCup Middle Size League used by our team NuBot. First, a virtual model of the simplified ball handling mechanism is derived. Afterwards, a control system including a feedback controller and a feedforward controller is designed and developed step by step. Experimental results show that the ball stays in contact with the robot using the proposed mechanism and control system when the robot is driving forwards, backwards and rotating.

Key Words: Motion control, Robotics, Ball handling, Sliding mode, RoboCup.

1 INTRODUCTION

1.1 RoboCup

RoboCup [1] (Robot World Cup) is an international initiative established in 1997 to promote the research on Multi-Agent System (MAS) and Distributed Artificial Intelligence (DAI) by providing a standard problem. The ultimate goal of the RoboCup is that by 2050, a team of fully autonomous humanoid robots can win against the human world champion team.

1.2 MSL and referred rules

In the RoboCup Middle Size League (MSL), up to five robots play the soccer game with a regular size FIFA ball on a field with the dimension of 18m*12m. All the robots are autonomous and distributed. All sensors are on-board. Robots can use wireless network to communicate.

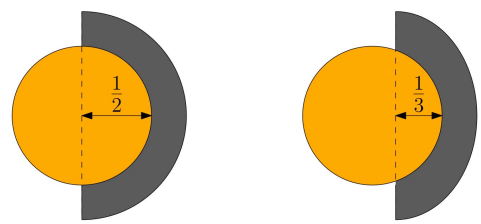
Ever since its birth, it has been a league where software and hardware develop dramatically at the same time. Many teams create their robots by themselves, and they are also willing to share with others. Because of the stimulation triggered by rule changes and due to the efforts made by MSL community, there have been many progresses achieved over the past nineteen years.

As to the ball handling in this league, there are some rules and regulations that have to be compliant with [2], as shown in Fig. 1:

•The convex hull of the robot may not enclose the ball for more than a third of the ball's diameter except when the player is stopping the ball. In addition, only when the ball is being stopped, the rules allow the ball to enter the convex hull of a robot by half of its diameter.

•The robot may exert a force onto the ball only by direct physical contact between the robot and the ball.

•The ball should rotate continuously in its natural direction which means that the ball is rotating in the direction of its movement.



(a) Ball stopping (b) Otherwise

Fig 1. RoboCup MSL rules related to ball handling

In this paper, we present the mechatronic design of an active ball handling mechanism, and then propose a control algorithm including a feedback controller and a feedforward controller, which can effectively solve the ball handling control problem. The rest of this paper is organized as follows: in Section II, related research about the ball handling mechanism will be introduced; Section III will present our RoboCup MSL soccer robot-NuBot, including the mechatronic design of the active ball handling system; a simplified theoretical model of the ball handling mechanism and the control algorithm will be presented in Section IV and Section V respectively. The experimental results will validate the effectiveness of the proposed design in Section VI; Section VII will conclude this paper.

2 RELATED WORK

In the RoboCup MSL, it is crucial to have a good ball handling ability during dribbling motion aiming at maneuvering fast through the defence of opponents. The RoboCup MSL competition has been organized from 1997 onwards [5]. Since 1997, several research efforts have been done in different types of ball handling devices. In the beginning, almost all the teams used passive dribbling devices. The typical passive ball handling mechanisms were used by Tribot team [6], Hibikinomusashi team [7].

In 2003, Mu-Wallabies team presented a robot with an arm like kicker, and Philips team demonstrated some prototypes for ball stopping devices. Later, some research was done concerning ball stopping devices. However, approaches to control the ball without continuous robot-ball contact are rarer [4], and most of the teams used some form of concavity or pusher bar for ball control. For example, some teams developed basic horizontal dribbler bars [5]. In RoboCup 2010 technical challenge, the Tech United team presented a control behavior to dribble the ball forwards with small taps, and in 2011 ISePorto's team whose robot is shown in Fig.2 started using only small kicks to move the ball forwards in the field and to intercept the ball.

For many of these methods relying on passive systems, the ball handling problem is shifted to a trajectory planning problem. In such systems a force can only be exerted on the ball with a component pointing away from the robot. To slow down the ball the robot has to rotate 180 degrees around the vertical axis of the ball, which should be considered in the trajectory planning [8].

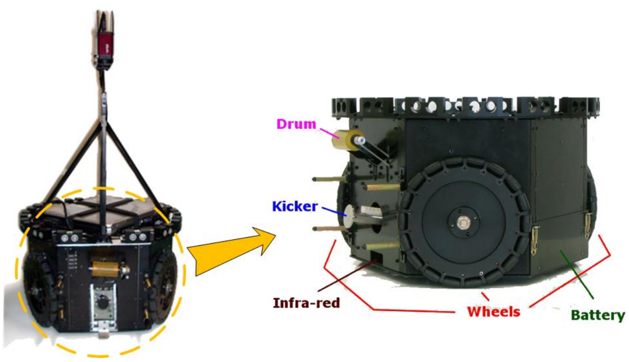


Fig 2. Team ISePorto's robot.

Another method use active open-loop mechanisms in which wheels or rollers spin backward in order to retract the ball, i.e. towards the robot [9]. However, due to variations in the field the ball is prone to spinning backward or lying still during a forward movement, which is against the prescribed rules and regulations[10]. Touching sensitive ball handling is investigated in [11], where a combination of four sensors is implemented to give the robot the opportunity to have force and position feedback with respect to the ball. The closed loop control is still under investigation to improve the ball handling. Future work of [11]will focus on using the force and position measurements to adjust path planning algorithm.

Our previous control architecture has two levels [12]. On the high level, a supervisory loop is implemented to determine whether or not the ball handling system needs to be activated such that the wheels are driven to match the velocity of the robot. On the low level, the velocities of the wheels are controlled. The advantage of this closed-loop controller is that it provides the possibility to drive backwards while having the ball possessed, thus the trajectory planning problem becomes simpler. However, there is no position measurement of the ball relative to the robot to determine if the wheels are actuated correctly. When the ball has a slightly di□erent radius, the ball might spin backwards or lay still during robot's movements, which is against the prescribed rules and regulations.

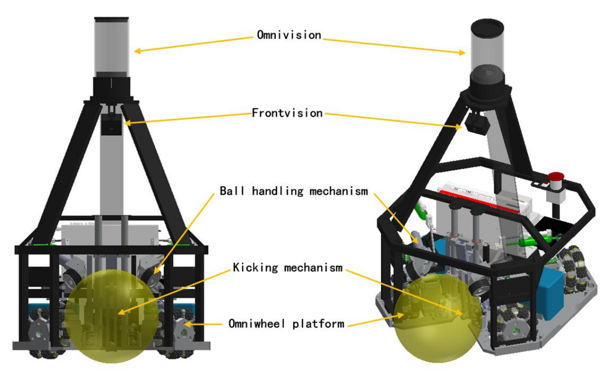
Currently several MSL teams like Water team, Tech-United team [13] and NuBot team use sophisticated mechanic roller based ball handling devices to have more precise kicks, but that type of ball handling limits the capability to kick a moving ball without stopping it and sucking through short skillful taps or kicks. And the desire to make games similar to human soccer games, associated to the increase of game dynamics in RoboCup MSL, motivates a radical change in the ball manipulation skills.

The goal of this paper is to present a new approach in ball manipulation which is adopted by our team NuBot in the RoboCup MSL competition. The combination of the constructive hardware design and the robust closed-loop motion control design solves the ball handling control problem effectively and is much superior to the commonly used ones. The rest of this paper will describe the realization of this robust adaptive ball handling system in details, and several tests will be given to show the effectiveness of this new ball handling system.

3 EXPERIMENTAL PLATFORM

This section describes the experimental platform which is used to test the proposed control algorithm in practice. As showed in Fig.3, our soccer robot acts as the testbed. The mechanical platform is subdivided into five main modules: the omniwheel platform, the ball handling mechanism, the electromagnet shooting system, the omnidirectional vision system and the front vision system.

The robot is driven by four omniwheels. Each omniwheel is driven by a DC motor. Beckhoff [14] EtherCAT [15] modules are used for the real-time data acquisition. These modules are connected to an industrial PC running all control algorithms. To be able to kick, a solenoid is designed. The ball handling wheels are driven by 20W DC motors, while the angles of the levers can be measured with potentiometers. The robot is equipped with an omnidirectional vision system that is used for self localization and ball and obstacle detection, and a front vision system which offers more accurate ball information.



a.Front view b.Isometric drawing

Fig 3. The regular soccer robot of our team NuBot.

The ball handling mechanism enables the robot to catch and dribble a ball during the game. As illustrated in Fig. 4, during dribbling, the robot will constantly adjust the speeds of the wheels to maintain a proper distance between the ball and the robot using a closed-loop control system. This control system takes the actual ball distance as the feedback signal, which is measured by the linear displacement transducers attached to the supporting mechanism. As the ball moves closer to the robot, the supporting mechanism will raise, and then compress the transducer, otherwise the support mechanism will fall and stretch the transducer. The information obtained from two transducers can be used to calculate the actual ball distance based on a given detailed geometry model.

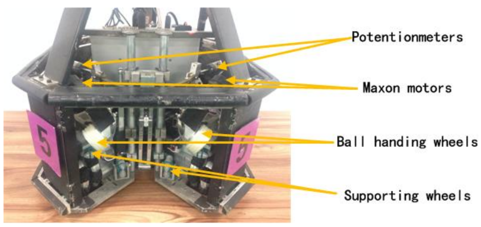


Fig 4. The Front view of ball banding mechanism.

The electrical system of team NuBot robot uses PC-based control technology, which enables automation tasks to be performed through software without the dedicated hardware. All control system and visualization tasks can be carried out by a powerful central CPU and decentralized I/Os. In addition, the system employs the Ethernet-based fieldbus system EtherCAT and the TwinCAT system to realize high speed communication between industrial PC and the connected modules. The Elmo Motion Control is the intelligent miniature digital servo drive for the DC brushless motor. Furthermore, the electrical system also realizes the effective utilization of high-performance multi-core processors. The schematic diagram of the NuBot electrical system is shown in Fig. 5.

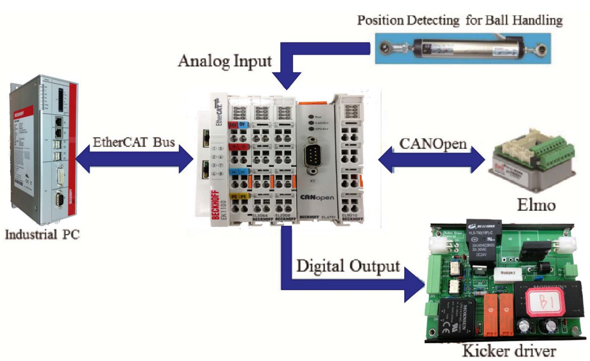


Fig 5. The electrical system of team NuBot.

The relative distance between the robot and the ball measured with two transducers is regarded as feedback signal and the robot velocity is used as the feedforward signal. In order to increase the universal property of the code, we normalize the AD data of the transducers to a scope from 0 to 1, where "1" refers to the condition where the distance between the ball and robot is minimal, and "0" refers to the opposite condition. The data is supposed to be steady at 0.7 which is set within algorithm. The controlling process can be seen from Fig.6.

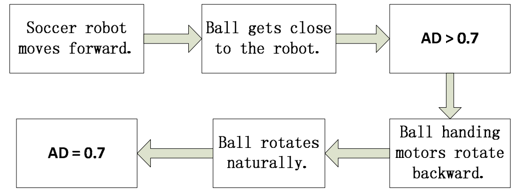
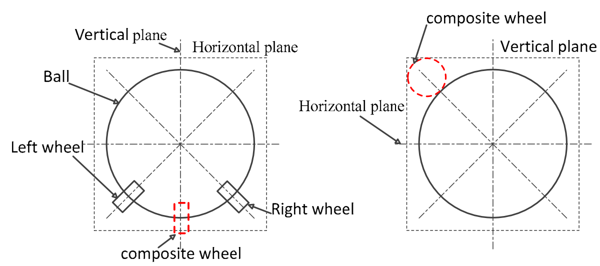


Fig 6. Controlling process of the active ball handling mechanism.

4 MODELING BALL HANDLING MECHANISM AND MECHANICAL ANALYSIS

4.1 Theoretical analysis of the ball handling mechanism

To realize the active ball handling mechanism, we need to take robot body, active wheels, ball, ground and the interaction among them into consideration. In a short time, the movement of the ball can be approximated as one-dimensional linear motion. According to the principle of motion synthesis, the two active driving wheels can be simplified as one driving wheel (composite wheel), thus 2-dimension motion is reduced to be 1-dimension motion. In addition, the soccer ball is supposed to move along the vertical plane, which is equivalent to that the composite wheel is on the vertical plane. Fig.7 shows the procedure that we simplify the model. Fig.8 illustrates the mechanical analysis of the ball when the ball and robot is relatively static.



(a) (b)

Fig 7. Composition of the active wheels.

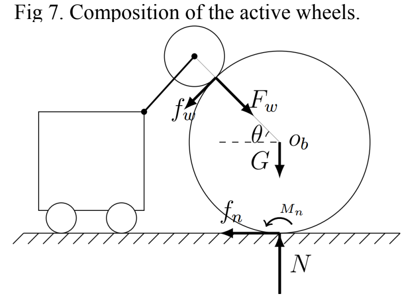


Fig 8. Mechanical analysis of the ball when it is being dribbled.

The ball has a radius R_b, a mass m_b and a rotational inertia J_b. It is subject to pressure F_w from the active wheel, normal force N from the ground, the gravity, the driving force f_w, the friction f_n and the couple M_n due to the interactions among these objects. The whole force exerted on the ball can be decomposed and listed as follows (the acceleration and angular acceleration can be denoted by a_x and ε_b respectively):

$$\sum F_x = F_w \cos\theta - f_w \sin\theta - f_n + M_n R = m_b a_x \quad (4.1)$$

$$\sum F_y = N - G - F_w \sin\theta + f_w \cos\theta = 0 \tag{4.2}$$

$$\sum M = f_w R - f_n R = J_b \varepsilon_b \tag{4.3}$$

Consequently, when DC servo motors do not provide control inputs, the active wheels will press the ball and push it away, which means the original system is not stable and we need to design a feedback control system to achieve dynamic balance.

4.2 Theoretical modeling and linearization

To design the controller for ball handling mechanism, we need to build its physical model and try to get a linear form.

The 2-dimensional simplified model of the ball handling mechanism is schematically depicted in Fig.10. In this figure, the cart represents the soccer robot. On the robot a lever is mounted that can freely rotate around a fixed point of the robot by means of a hinge. The height of this point is h above the barycenter of the ball. The length, the mass and the rotational inertia of the lever are l , m_l and J_l respectively. At the end of the lever a wheel with mass m_w and rotational inertia J_w is mounted. The radius of the wheel is denoted by R_w . A torque T can be applied to the wheel by a motor to control the angle of the lever and to counteract the viscous damping d . The motion of the robot is prescribed and is denoted by $s(t)$. Besides, the radius, the mass and the rotational inertia of the ball are R_b , m_b and J_b respectively. Furthermore, it is assumed that during dribbling the wheel is in contact with the ball at all times and there is no slip between the wheel and the ball nor between the ball and the ground. The idea is to measure the angle of the lever ϕ and maintain this angle at a preferred angle, which corresponds with a desired distance between the ball and the robot.

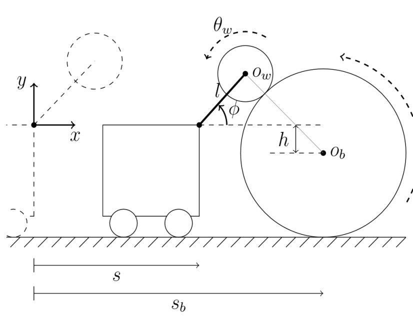


Fig 9. The simplified model of the ball handling mechanism.

The position vectors of the bodies' barycenter $\vec{r_l}$, $\vec{r_w}$, $\vec{r_b}$ are derived as a function of the generalized coordinate ϕ and $s(t)$.

$$\vec{r_l} = \begin{pmatrix} s(t) + \frac{1}{2} l \cos(\phi) \\ \frac{1}{2} l \sin(\phi) \end{pmatrix} \tag{4.4}$$

$$\vec{r_w} = \begin{pmatrix} s(t) + l \cos(\phi) \\ l \sin(\phi) \end{pmatrix} \tag{4.5}$$

$$\vec{r_b} = \begin{pmatrix} s(t) + l \cos(\phi) + \sqrt{(R_b + R_w)^2 - (l \sin(\phi) + h)^2} \\ -h \end{pmatrix} \tag{4.6}$$

The velocity vectors of the bodies can be calculated as follows ($\dot{\phi} = \frac{d\phi}{dt}, \dot{s} = \frac{ds}{dt}$):

$$\vec{v_l} = \frac{d\vec{r_l}}{d\phi}\dot{\phi} + \frac{d\vec{r_l}}{ds}\dot{s} \tag{4.7}$$

$$\vec{v_w} = \frac{d\vec{r_w}}{d\phi}\dot{\phi} + \frac{d\vec{r_w}}{ds}\dot{s} \tag{4.8}$$

$$\vec{v_b} = \frac{d\vec{r_b}}{d\phi}\dot{\phi} + \frac{d\vec{r_b}}{ds}\dot{s} \tag{4.9}$$

Moreover, the rotation of each body θ_l , θ_w , θ_b and the rotational velocities $\vec{w_l}$, $\vec{w_w}$, $\vec{w_b}$ can be derived and calculated similarly. And with these results the kinetic energy of the system becomes as

$$V = \sum_{i \in \{l,w,b\}} \left(\frac{1}{2} m_i \vec{v_i}^T \vec{v_i} + \frac{1}{2} J_i \vec{w_i}^T \vec{w_i} \right) \tag{4.10}$$

The potential energy can be written as (g is the gravity constant)

$$U = \frac{1}{2} m_l g l \sin\phi + m_w g l \sin\phi - m_b g h \tag{4.11}$$

Thus the Lagrange's equations of motion can be calculated as

$$\frac{d}{dt}\left(\frac{\partial (V-U)}{\partial \dot{\phi}} \right) - \frac{\partial (V-U)}{\partial \phi} = Q^T \tag{4.12}$$

where Q is the non-conservative force consisting of the applied torque T and the torque T_d caused by the damping d modeled as $T_d = d\left(\dot{\phi}_w - \dot{\phi}_l\right)$. These non-conservative forces are formulated as

$$Q = \left(\frac{\partial \theta_w}{\partial \phi} - \frac{\partial \theta_l}{\partial \phi} \right) (T_d - T) \tag{4.13}$$

Finally, a non-linear model can be constructed as follows:

$$\ddot{\phi} = f\left(\phi, \dot{\phi}, \dot{s}(t), \ddot{s}(t), T\right) \tag{4.14}$$

For the design of the feedback controller, the non-linear model is linearized around the following desired equilibrium point which satisfies the preferred distance between the ball and the robot. The torque T_{eq} , associated with the chosen equilibrium point, can be calculated by substituting the values of (4.15) into (4.14)

$$\phi_{eq} = \frac{\pi}{4},\ \dot{\phi}_{eq} = 0,\ \dot{s}_{eq} = 0,\ \ddot{s}_{eq} = 0,\ T_{eq}. \quad (4.15)$$

Linearization around the point of operating results in the following second order linear model:

$$G: \begin{cases} \dot{\vec{x}} = A\vec{x} + Bu \\ y = C\vec{x} \end{cases} \quad (4.16)$$

In this model, the state vector is given by $\vec{x} = \begin{bmatrix} \phi - \phi_{eq} & \dot{\phi} \end{bmatrix}^T$, the input u is given by $T - T_{eq}$ and the output y is defined as $\phi - \phi_{eq}$, The system matrix A, input matrix B and output matrix C are given by

$$A = \begin{bmatrix} 0 & 1 \\ \dfrac{df}{d\phi} & \dfrac{df}{d\dot{\phi}} \end{bmatrix},\ B = \begin{bmatrix} 0 \\ \dfrac{df}{dT} \end{bmatrix},\ C = \begin{bmatrix} 1 & 0 \end{bmatrix}. \quad (4.17)$$

For our NuBot soccer robot, we have the following precise expression:

$$G: \begin{cases} \dot{\vec{x}} = \begin{bmatrix} 0 & 1 \\ 20.18 & -23.61 \end{bmatrix} \vec{x} + \begin{bmatrix} 0 \\ 757.24 \end{bmatrix} u \\ y = \begin{bmatrix} 1 & 0 \end{bmatrix} \vec{x} \end{cases} \quad (4.18)$$

5 ROBUST CONTROLLER DESIGN

5.1 Feedback Design

By disassembling the state vector $\vec{x}$ into x_1, x_2, Eq.(3.18) can be rewritten as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = 20.18x_1 - 23.61x_2 + 757.24u \end{cases} \quad (5.1)$$

Then we can get the control object:

$$\ddot{x}_1 = -23.61\dot{x}_1 + 20.18x_1 + 757.24u = f(x_1, t) + bu(t) + d(t) \quad (5.2)$$

where $d(t)$ is the outside interference.

We define the error signal as the discrepancy between the output of the system $\phi(t)$ and the desirable behavior of the system $\phi_{eq}(t)$:

$$e(t) = \phi(t) - \phi_{eq}(t) \quad (5.3)$$

The tracking control problem could be solved by sliding mode method and Lyapanuv theory, which will be discussed later. The first step to perform this approach is to define a sliding surface. The following expression presents an intuitive suggestion for the sliding surface:

$$s(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \dot{e}(t) \quad (5.4)$$

According to Eqs. (5.3) and (5.4), the first derivative of sliding surface with respect to time $\dot{s}(t)$ could be computed as follows:

$$\begin{aligned} \dot{s}(t) &= K_p \dot{e}(t) + K_i e(t) + K_d \ddot{e}(t) \\ &= K_p(\dot{\phi}(t) - \dot{\phi}_{eq}(t)) + K_i(\phi(t) - \phi_{eq}(t)) + K_d(\ddot{\phi}(t) - \ddot{\phi}_{eq}(t)) \\ &= K_p \dot{\phi}(t) + K_i(\phi(t) - \phi_{eq}(t)) + K_d(f(x_1, t) + bu(t) + d(t)) \end{aligned} \quad (5.5)$$

To make the system approach sliding mode in a fast speed, we adopt exponential approach law:

$$\dot{s} = -\varepsilon sat(s) - ks \qquad \varepsilon > 0, k > 0 \quad (5.6)$$

Sliding control law can be derived from Eqs. (5.5) and (5.6):

$$u(t) = \frac{1}{K_d b}(-\varepsilon sat(s) - ks - K_p \dot{\phi} - K_i(\phi(t) - \phi_{eq}(t)) - K_d f(t) - K_d d(t)) \quad (5.7)$$

In next step, a Lyapanuv function is contemplated. The following equations state the assumed Lyapanuv function and its first derivative with respective to t, respectively:

$$V = \frac{1}{2}s^2 \quad (5.8)$$

$$\dot{V} = s\dot{s} \le 0 \quad (\dot{V} = 0 \text{, while } s = 0) \quad (5.9)$$

Since $s(t) \neq 0$, $V(s(t)) > 0$ and $\dot{V}(s(t)) < 0$, from Lyapanuv theory it can be inferred that the error approaches zero which means the output of the system tracks the desired output.

Consequently, a robust control strategy using sliding model method is designed and identified in our system. In other words, the control signal is computed according to Eq.(5.7) and is applied on the ball handling mechanism.

To investigate the tracking ability of this method, we adopt MATLAB to simulate a tracking problem. Fig.10 shows the simulation results of using the proposed sliding model control method to track a sinusoidal signal. We can see that the tracking signal can follow the ideal signal fast and precisely. What's more, the experiments results in the next section can demonstrate this more convincingly.

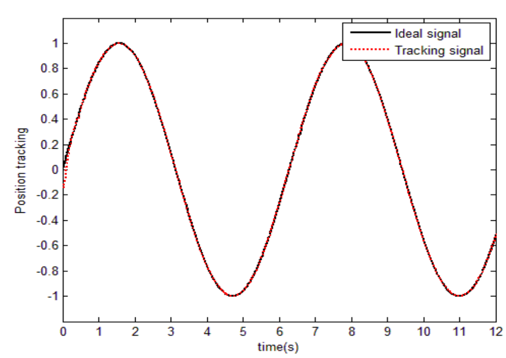


Fig 10. Robust position tracking results of sliding mode control.

5.2 Feedforward Design

In the previous section, Eqs. (4.15) assumes that the velocity and acceleration of the robot is set to zero, but this situation is rare during a game. Therefore, it is necessary to take the movement of the robot into consideration. We replace the torque T_{eq} with $T_0\left(\dot{s}(t),\ddot{s}(t)\right)$ which is associated to the velocity and the acceleration of the robot.

Since $\dot{s}(t)$ and $\ddot{s}(t)$ can be measured, we use them as feedforward inputs in the control system to decrease the tracking error of the preferred reference angle significantly, leading to a better dribbling behavior. Furthermore, the controller can be expanded to be able to deal with turning and driving sideways. Fig.11 illustrates the total control scheme.

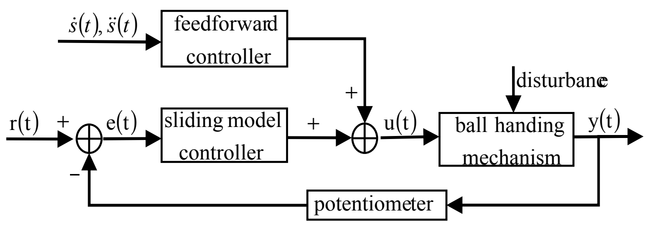


Fig 11. The control scheme.

6 EXPERIMENTAL RESULTS

The first experiment is to catch the ball. The horizontal lines indicate the start and end of each movement. The measured outputs of the potentiometers are given in Fig.12. From these figures we see that the wheels are actuated such that the ball is kept within the ball handling mechanism. If this was not the case, the output would drop to 0. At t = 0.5 second, the ball approaches the robot and is catched by the ball handling mechanism. It can be seen from this figure that the ball handling mechanism reacts fast, and the steady state position is reached within 1 second.

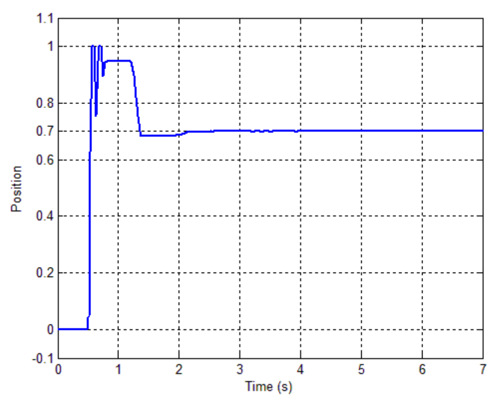


Fig 12. Handling the ball by the left ball handling mechanism.

Secondly, a test was performed to evaluate the ball handling performance of the robot while the robot is moving. During the experiment the robot first has a positive velocity in y direction, then a negative velocity. This can be seen in the Fig.13 and Fig.14 which show the longitudinal velocities. It can be observed that when the soccer robot is moving forwards, after catching the ball, outputs of the potentiometers are a little higher than 0.7, and it is opposite to the case when the robot moves backwards. This is because the ball should rotate continuously in its natural direction, thus it's not allowed to catch the ball too closely.

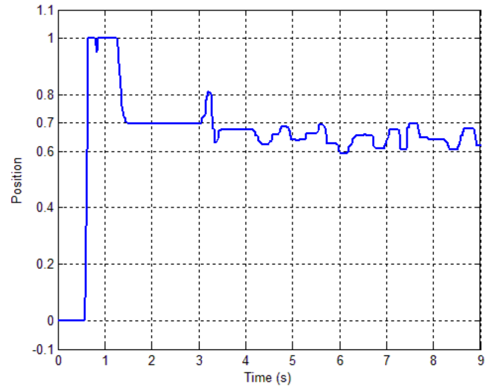


Fig 13. Handling the ball by the left ball handling when the robot is moving forwards.

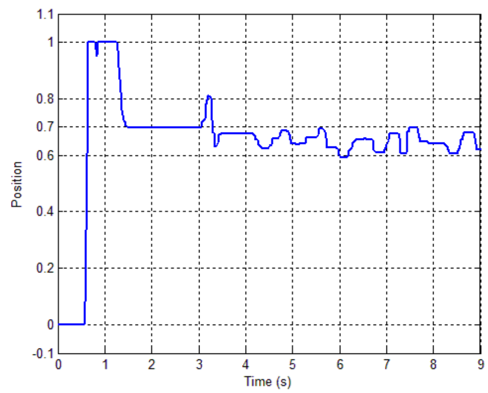


Fig 14. Handling the ball by the left ball handling when the robot is moving backwards.

What's more, when the robot is turning right, it can be seen from the Fig.15 and Fig.16 that outputs of the potentiometers are absolutely different from the left handling mechanism and the right one. This is because when turning left, the case in left hand is similar to that when the robot is moving backwards, which means the distance between the ball and ball handling mechanism will be a little longer. Similarly the case in right hand is alike to that when the robot is moving forwards.

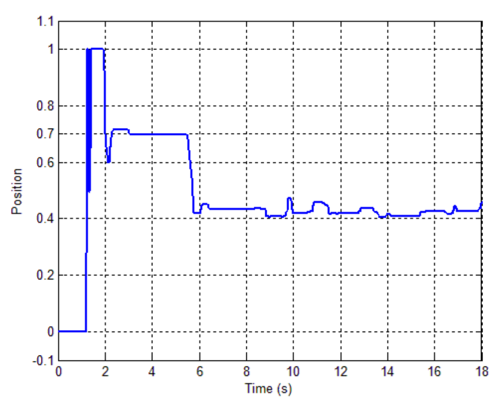


Fig 15. Handling the ball by left ball handling when turning right.

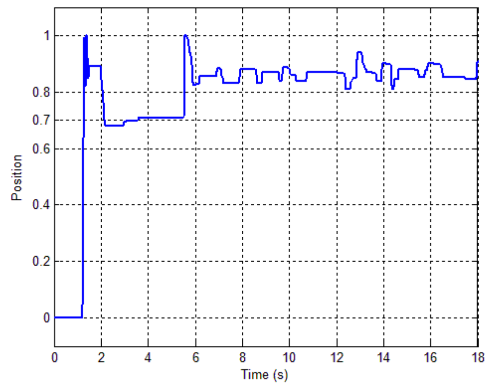


Fig 16. Handling the ball by right ball handling when turning right.

To validate the effectiveness of the feedforward control, a similar experiment is carried out without the use of feedforward based on the velocity of the robot when it is going backwards. The results are given in Fig. 17. From these figures we see that without the use of feedforward, the ball is lost many times, which means that the values drop to 0. Besides, we find from the experiments that the ball is nearly not rolling during a forward movement which is not allowed.

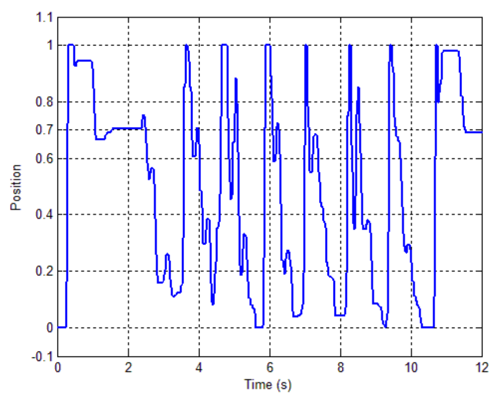


Fig 17. Handing the ball by left ball handling mechanism without feedforward control.

What can be observed from these experiments is that our ball handling system is feasible and valuable. First, the sliding mode controller is robust, because when the system suffered a interference from the outside or the equilibrium point is changed due to the movement of the robot, this system can still adapt to new situation and tack to the equilibrium point quickly. Second, the feedforward controller which leads to a significant decrease of the tracking error is effective and necessary especially when the robot is moving or rotating. Thirdly, during dribbling the ball will rotate in its natural direction every moment owing to using the potentiometer which can get the information of the ball handling condition.

7 CONCLUSION

In this paper we proposed a robust and adaptive ball handling system for our RoboCup MSL soccer robots. A model of ball handling mechanism was derived and the sliding model control was used in the feedback control. Furthermore, to improve the tracking performance of the ball handling system, we integrated a feedforward controller. As to the mechanical part, we use two wheels placed on levers that touch the side of the ball, and the levers exert a force towards the ball to give the wheels good grip on the ball. Catching the ball can be realized by pulling it between the two levers and rotating the active wheels towards the robot. In addition, the ball catching states of these two active wheels are detected based on the information gathered from the linear position sensor. The experimental results are highly promising: the controlled angle ϕ can perfectly track the desired angle ϕ_{eq} when the robot is moving forwards, backwards or rotating.

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