Design and Modeling of a Redundant Omni-directional RoboCup Goalie

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Abstract. This paper covers the mechanical design and modeling of a redundant omni-directional mobile robot developed for the Ohio University RoboCup goalie. The goalie robot is actuated redundantly with four wheels for good mobility. In the paper, first the overall mechanical design of the system is discussed. Second, the inverse kinematics solution is obtained using the principle of virtual work. Third, dynamic equations of motion of the system are derived in a symbolic form resulting in coupled nonlinear differential equations. Finally, a simulation demonstrates the inverse kinematics solution and simple independent PD wheel control of our redundant omni-directional goalie robot.

1. INTRODUCTION

Omni-directional drive is the ability to move in any direction (0 to 360 degrees) at any given orientation. Using this type of drive system enables a robot to move in a given direction while being able to rotate during linear travel. Time is saved by eliminating the need to rotate the robot before translating from point A to point B. Omni-directional drive gives the goalie robot the ability to always face the ball while being able to move in any direction. In addition, it provides simpler inverse kinematics solution for path planning. For these reasons, many research groups are studying omni-directional (holonomic) mobile robots and vehicles [1-5].

The Ohio University (OU) RoboCup Team incorporates the omni-directional drive into their mobile robots. The OU RoboCup Team consists of 4 players and 1 goalie; the players and goalie each have separate mechanical, electrical, and software design in order to meet different performance specifications. For example, the players are designed to optimize forward motion, while the goalie is designed to optimize side-to-side motion. This paper will focus on the mechanical design, dynamic modeling, and simulation of the redundant, omni-directional RoboCup goalie.

2. DESIGN

The design for the goalie has two main functions. The major function is to have the ability to quickly move side-to-side to guard the goal. This has been accomplished by having the wheels aligned horizontally for quick movement. The other function is the kicking of the ball. The current design not only allows for a strong kick but also the ability to catching ball under control.

2.1 Constraints

In order to compete in the Robocup tournament, robots have to meet specified size constraints. The goalie robot can be no taller than 22.5 cm if local vision is to be used, and must fit within a 18 cm diameter cylinder. Any part that may extend outward on the robot must be fully extended when placed inside the 18 cm cylinder. These size constraints greatly limit the arrangement of drive and kicking systems. Kicking and drive systems are rectangular in shape and designing a layout to meet the robot size constraints results in "wasted space" around these systems. To utilize these irregularly shaped spaces, one has to be creative

in making them useful for housing various system components. Currently a circular chassis is being used to explore various drive/kicking system layouts that will make use of these valuable spaces (*Figure 1*).
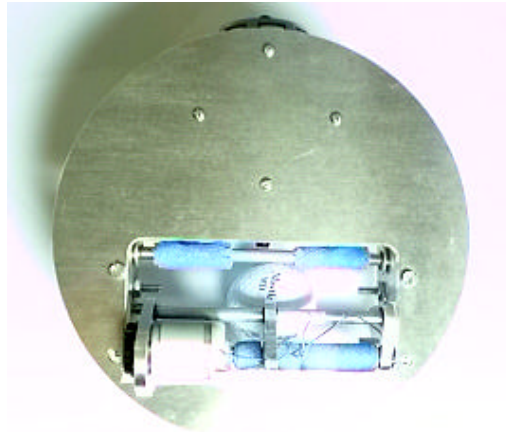

Figure 1: Top View of OU Goalie (circular chassis)

2.2 Performance Specifications

Through testing various radio controlled toy cars, experiments were performed to better visualize what kind of performance we desire for the goalie robot. High value was placed on making the robot "zippy" which means it can move or change direction quickly but doesn't have a high maximum velocity. An acceleration of 2 m/sec and a maximum velocity of 1 m/sec were the performance specifications decided upon for the goalie's locomotion.

The kicking mechanism used on the goalie needed to be powerful enough to propel the ball at least half the length of the playing field. This distance would "clear" the ball out of our defensive zone giving the defensemen time to regroup. The kicker should not be able to kick the ball so hard that it is able to roll over the boundary fence at the opposing end of the field, which would result in a penalty. Controlling the kicking power is accomplished by using a variable speed motor on the kicking mechanism.

One advantage of the goalie is the ability to capture the ball and completely enclose it. Enclosing the ball and hiding it from opposing robots operating on the global vision system can lead to confusion if they cannot locate the ball. However if the goalie is to capture the ball, teammates can be notified of the ball's location.

2.3 Layout

The goalie layout consists of the drive system and kicking mechanism *(Figure 2)*. To maintain traction on the drive wheels, the robot center of mass should be located on the central axes of the drive wheels. Four wheels are being used to drive the robot omni-directionally. Keeping the goalie's center of mass near these axes becomes difficult once the kicker mechanism is added to the system. The kicker mechanism shifts the center of mass toward the center of the robot, which can cause the rear wheel to slip. Shifting the center of mass to compensate for the weight of the kicker can be accomplished through shifting battery positions toward the rear of the robot. Additional ballast can be added to maintain drive wheel traction, but care must be exercised to not impede robot performance through weight addition.
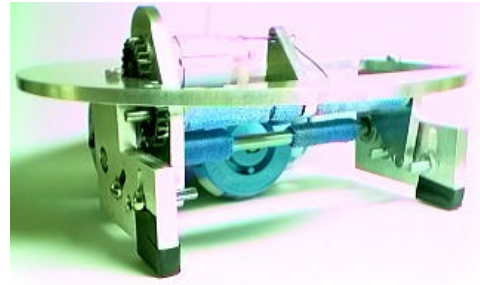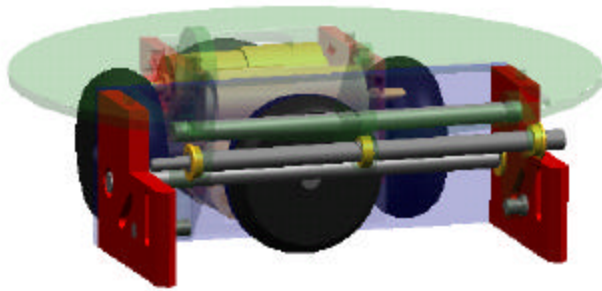
Figure 2:   OU Goalie   (a) CAD model   (b) Hardware Photograph

There are 6 motors utilized in the robot assembly. Four are placed in the wheel assembly to drive wheels. One is in kicker assembly and rotates the drive bar. There is also a servomotor associated with the kicker assembly.

2.4 Omni-Directional Drive

The Kornylak Corporation manufactures the Omniwheel that appears in *Figure 3(a).* To minimize wheel width, the original Omniwheel is modified by removing material from the center and outer faces. Removal of material also allowed room to insert a fabricated hub to be used for gear mounting. *Figure 3(b)* shows the modified wheel mounted to an aluminum hub.
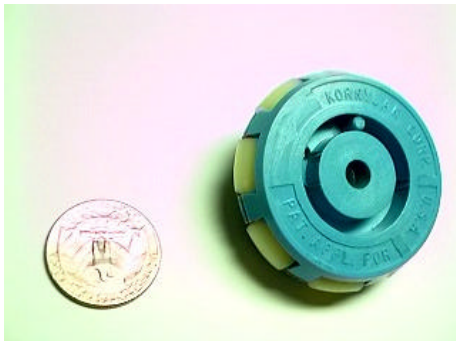

Figure 3: (a) Kornylak Omniwheel   (b) Modified Omniwheel

2.5 Kicking/Dribbling/Capturing Mechanism

The kicking mechanism, *Figure 4*, is structured around one basic principle, capturing the ball. It has the ability to rotate around a pivot point with this rocking motion controlled by a servomotor. The servomotor is located on the goalie base and thus is stationary with respect to the kicker. During the game the goalie will be located near the goal with its drive bar rotating backwards. The drive bar will be encased in rubber tubing. Initially the kicking mechanism will be at its highest point in the arc. When the ball gets near the kicker the drive bar will capture the ball via backspin. At this time the ball will be rotating between the drive bar and the idler bar, located underneath the robot. Being underneath the robot will cause the ball to be hidden from the global camera. The drive bar will then reverse direction and cause the ball to spin in the opposite direction between the two bars. After the ball gains a sufficient amount of forward rotation the kicking mechanism will be rocked backed the servomotor. This will allow the ball to be released while having topspin. After releasing the ball the kicking mechanism will be brought up to its highest position in the rotating arc by the servomotor to wait for the next ball.
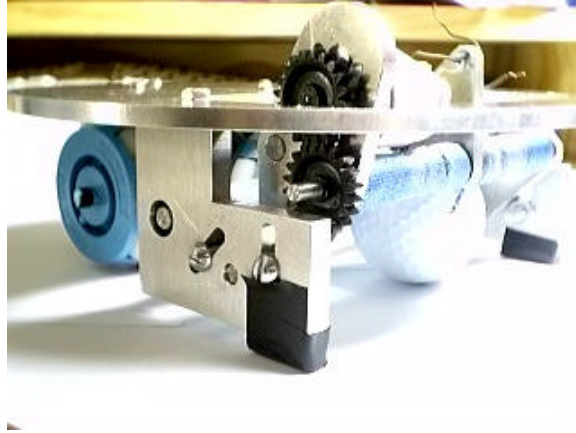
Figure 4: Close-up of Kicker Assembly

3. Modeling

The dynamic equations for the four-wheeled Ohio University RoboCup goalie is derived from the model shown in *Figure 5,* similar to [1].
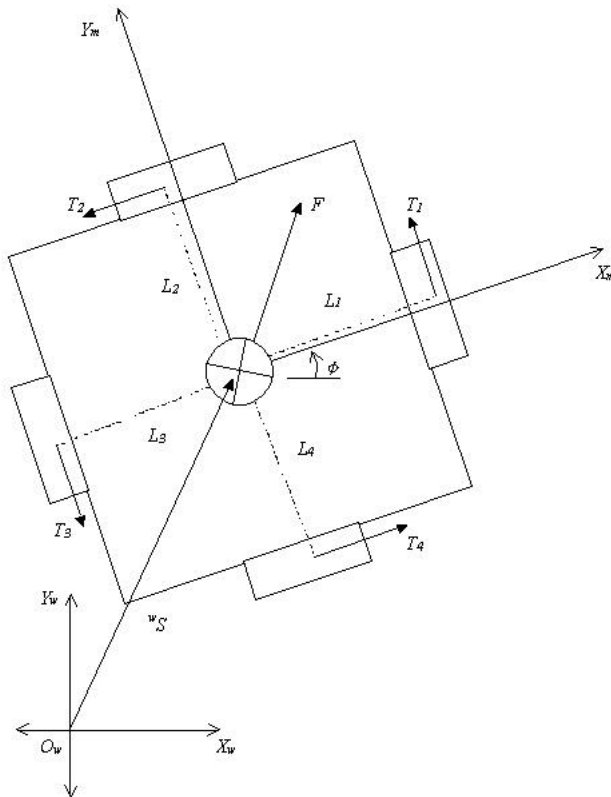

Figure 5: Kinematic/Free-Body Diagram

It is assumed the mobile robot is moving on a horizontal playing field. As it is shown, the inertial coordinate frame $X_w Y_w$ is fixed on the plane and the moving coordinate frame $X_m Y_m$ is attached to the mass center of the mobile robot. L_i is the distance from the mass-center to the center of the corresponding wheel.

$\boldsymbol{f}$ is the orientation of the mobile robot with respect to ^{w}S. As previously stated this robot is omni-directional, giving us no nonholonomic constraint equations. Also, it is important to point out that the OU RoboCup goalie has three degrees of freedom, but has four actuators meaning that the system is redundantly actuated.

First, we define the position and force vectors of the mass-center for the OU RoboCup Goalie in the absolute coordinate frame as:

$$^{w}S = \{x_w \quad y_w \quad \boldsymbol{f}\}^{T}$$
$$^{w}F = \{F_x \quad F_y \quad M_G\}^{T}$$

where M_G is the torque applied to the robot. The coordinate rotation matrix $_{m}^{w}R$ giving the orientation of the moving frame with respect to the inertial frame is:

$$_{m}^{w}R = \begin{bmatrix} \cos \boldsymbol{f} & -\sin \boldsymbol{f} & 0 \\ \sin \boldsymbol{f} & \cos \boldsymbol{f} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

The following two equations relate Cartesian pose and wrench for the moving and inertial frames:

$$^{w}\dot{S} = {_{m}^{w}R}\,^{m}\dot{s}$$
$$^{w}F = {_{m}^{w}R}\,^{m}f \tag{2), (3}$$

The pose and wrench vectors of the goalie in terms of the moving coordinates are:

$$^{m}s = \{x_m \quad y_m \quad \boldsymbol{f}\}^{T}$$
$$^{m}f = \{f_x \quad f_y \quad M_G\}^{T}$$

Applying Newton's 2nd Law:

$$^{w}F = M\,^{w}\ddot{S} \tag{4}$$

where M is a positive-definite diagonal matrix with the mobile robots mass M on the diagonal. Equation (4) can be rewritten in terms of the moving coordinates using Equations (1)-(3):

$$M\left({_{m}^{w}R^{T}}\,{_{m}^{w}\dot{R}}\,^{m}\dot{s} + {^{m}\ddot{s}} \right) = {^{m}f} \tag{5}$$

Simplifying Equation (5), the dynamic equations of the robot are:

$$M\left(\ddot{x}_m - \ddot{y}_m\,\dot{\boldsymbol{f}} \right) = f_x$$
$$M\left(\ddot{y}_m + \ddot{x}_m\,\dot{\boldsymbol{f}} \right) = f_x \tag{6), (7), (8}$$
$$I_m\,\ddot{\boldsymbol{f}} = M_G$$

where I_m is the mass moment of inertia for the mobile robot. To compute the relationship between the robot Cartesian coordinates and the wheel angles, the principle of virtual work is used. Summing the forces and moments gives:

$$\begin{Bmatrix} f_x \\ f_y \\ M_G \end{Bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 1 \\ 1 & 0 & -1 & 0 \\ L_1 & L_2 & L_3 & L_4 \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{Bmatrix} \tag{9}$$

or

$$^m f = Q\, T$$

where Q is the Jacobian matrix based upon the system geometry, and T_i is the traction force from each wheel. Since the virtual work done is same for the wheel and Cartesian coordinates, we write:

$$T^T \dot{q} = {}^m f^T \, {}^m \dot{s} \tag{10}$$

assuming that there is no slip in the wheel spin direction. Thus, we can obtain the inverse kinematics solution of the OU RoboCup goalie from Equations (9) and (10). Given the Cartesian velocity, we may find the wheel angular velocities:

$$\dot{q} = Q^T \, {}^m \dot{s} \tag{11}$$

or

$$\begin{Bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{Bmatrix} = \frac{1}{r} \begin{bmatrix} 0 & 1 & L_1 \\ -1 & 0 & L_2 \\ 0 & -1 & L_3 \\ 1 & 0 & L_4 \end{bmatrix} \begin{Bmatrix} \dot{x}_m \\ \dot{y}_m \\ \dot{f} \end{Bmatrix}$$

$$r w_1 = \dot{y}_m + \dot{f} L_1$$
$$r w_2 = -\dot{x}_m + \dot{f} L_2 \qquad (12), (13), (14), (15)$$
$$r w_3 = -\dot{y}_m + \dot{f} L_3$$
$$r w_4 = \dot{x}_m + \dot{f} L_4$$

where r is the wheel radius and w_i is the wheel rotational rate. The wheel dynamics for each assembly as given by [1] are as follows:

$$I_w \dot{w}_i + c w_i = k u_i - r T_i \qquad i = 1,2,3,4 \tag{16}$$

Where I_w is the mass moment of inertia for the Omniwheel, c is the viscous friction factor of the Omniwheel, k is the driving gain factor or the gear ratio, and u_i is the driving input torque

Then combining Equations (6)-(16) we have the following equations of motion written in matrix-vector form:

$$P\left\{ \,^{m}\ddot{s} \right\} + N\left(\,^{m}\dot{s} \right) = R\{U\}$$ (17)

where:

$$P = \begin{bmatrix} \dfrac{I_w}{r^2} + M & \dfrac{I_w}{r^2} & \dfrac{I_w}{r^2}(L_4 - L_2) \\ 0 & 2\dfrac{I_w}{r^2} + M & \dfrac{I_w}{r^2}(L_1 - L_3) \\ -\dfrac{I_w}{r^2}L_2 & \dfrac{I_w}{r^2}(L_1 - L_3 + L_4) & \dfrac{I_w}{r^2}(L_1 + L_2 + L_3 + L_4) + I_m \end{bmatrix}$$

$$N = \left\{ \begin{matrix} \dfrac{c}{r^2}\dot{x}_m + \left(\dfrac{c}{r^2} - M\dot{f} \right)\dot{y}_m + \dfrac{c}{r^2}(L_4 - L_2)\dot{f} \\ M\dot{x}_m\dot{f} + 2\dfrac{c}{r^2}\dot{y}_m + \dfrac{c}{r^2}(L_1 - L_3)\dot{f} \\ -\dfrac{c}{r^2}L_2\dot{x}_m + \dfrac{c}{r^2}(L_1 - L_3 + L_4)\dot{y}_m + \dfrac{c}{r^2}(L_1^2 + L_2^2 + L_3^2 + L_4^2)\dot{f} \end{matrix} \right\}$$

$$R = \begin{bmatrix} 0 & -\dfrac{k}{r} & 0 & \dfrac{k}{r} \\ \dfrac{k}{r} & 0 & -\dfrac{k}{r} & 0 \\ L_1\dfrac{k}{r} & L_2\dfrac{k}{r} & L_3\dfrac{k}{r} & L_4\dfrac{k}{r} \end{bmatrix}$$

After manipulation we have three coupled MIMO nonlinear differential equations of motion with wheel torques as the inputs and the robot Cartesian position and orientation as the outputs.

4. SIMULATIONS

First, the inverse kinematics solution is simulated using Matlab. The robot follows an arbitrary straight line from *(-0.5, 0) m* to *(0.5, 2.5) m* while maintaining the orientation as shown in *Figure 6(a) and 6(b)*. *Figure 6(c)* shows the corresponding wheel angular position and velocity via the inverse kinematics solution.
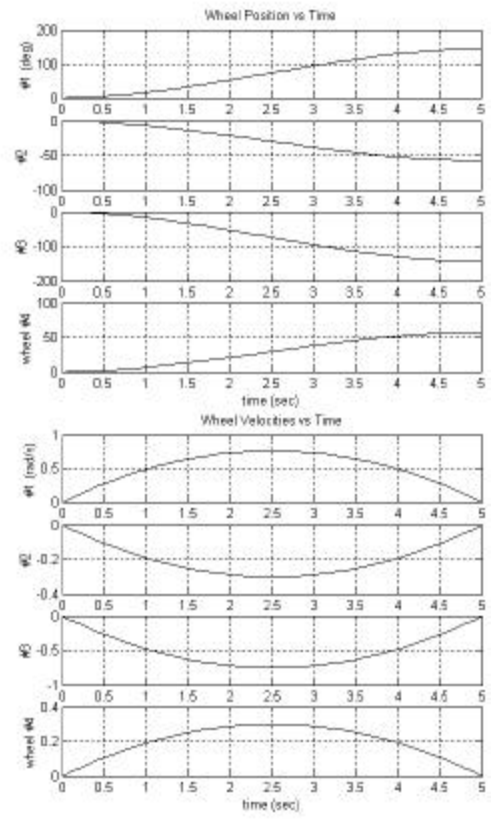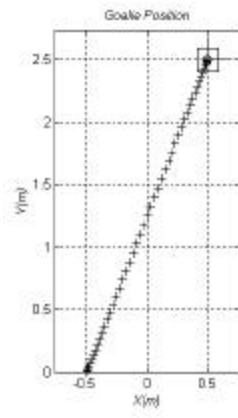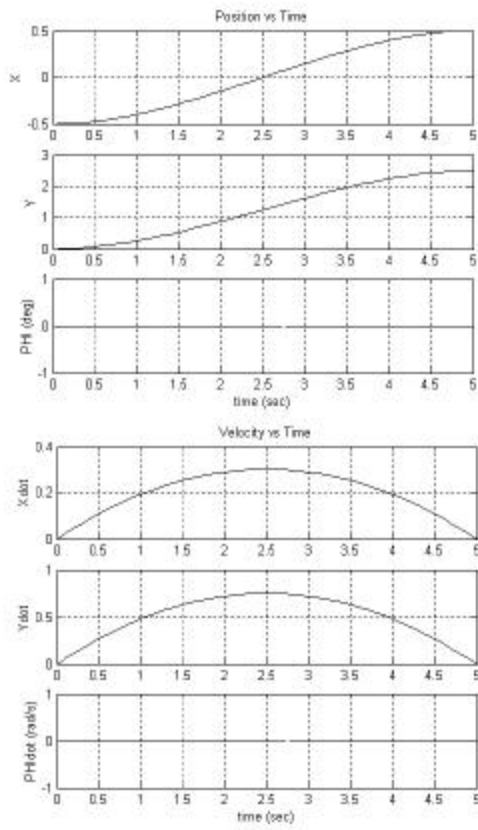
(a)   *(b)*   *(c)*

Figure 6: Inverse Kinematics Simulation Results

Second, the dynamics of the system was simulated using Simulink, Matlab's graphical interface. A proportional derivative (PD) controller was implemented for each independent wheel, see *Figure 7*.
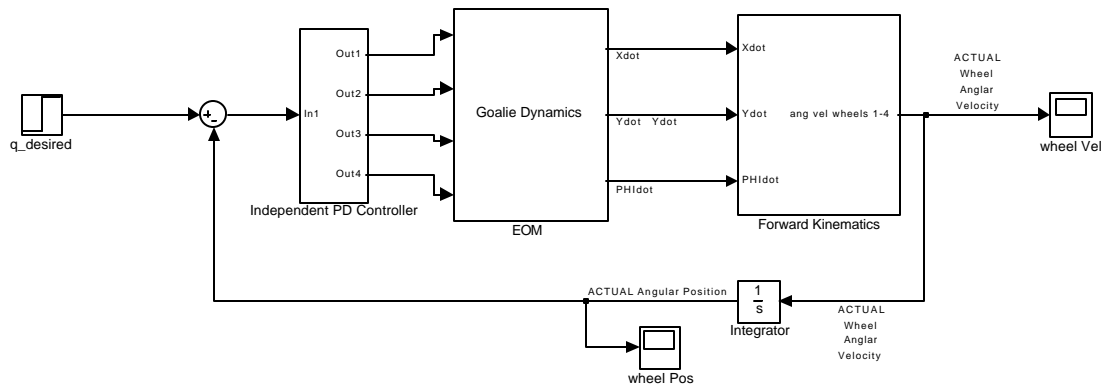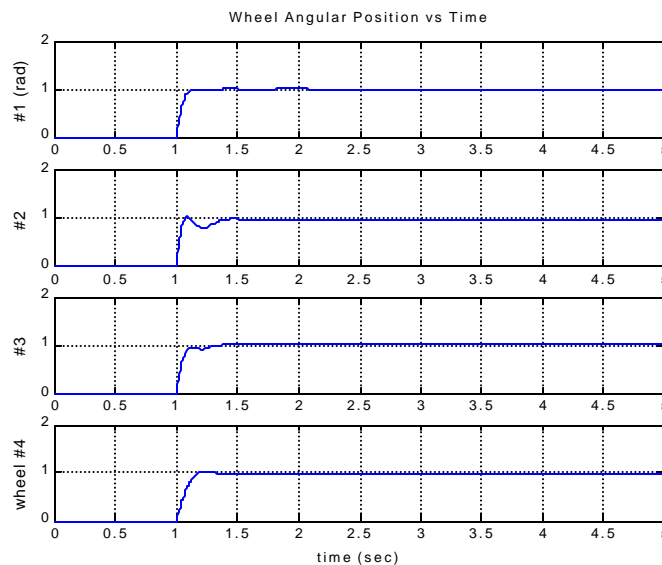
Figure7: Simplified Closed-Loop Diagram

Figure 8: Unit Step Response with Independent PD Wheel Control

The result from step inputs is shown in *Figure 8*. The controller gains are selected such that the robot moves with nearly zero overshoot and with a very little steady state error at reasonable speed. The stability of the PD controller can be proved using Lyapunov and invariant–set theorem (Refer to [6] for details). Also, it is important to note that this simulation deals only with mechanical factors like inertia and not any electrical components or digital control effects. Wheel slip has not yet been modeled, therefore the real-world results may not mimic the simulated results and we will have additional modeling work to perform.

5. CONCLUSIONS

This paper presents the design, modeling and simulation for the Ohio University RoboCup goalie robot. The robot has a unique redundant omni-directional drive system with ball-catching, dribbling, and kicking capability. We have presented the kinematics and dynamics equations, plus control simulation results using simple independent PD wheel control with the coupled nonlinear dynamics.

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