Segway CM-RMP Robot Soccer Player

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Abstract. The Segway Human Transporter (HT) is a one person dynamically self-balancing transportation vehicle. The Segway Robot Mobility Platform (RMP) is a modification of the HT capable of being commanded by a computer for autonomous operation. With these platforms, we propose a new domain for human-robot coordination through a competitive game: Segway Soccer. The players include robots (RMPs) and humans (riding HTs). The rules of the game are a combination of soccer and ultimate Frisbee rules. In this paper, we describe the rules of the game, the capabilities and limitations of the Segway, the mechanical systems necessary to create a robot Segway Soccer Player, a detailed analysis of several ball manipulation/kicking systems, and the implementation results of the CM-RMP Robot Soccer Player Pneumatic Ball Manipulation System.

1 Introduction

Considerable research has been conducted involving human-robot interaction [8], and multi-robot teams [9, 10, 11]. With the inception of RoboCup robot soccer [7], multi-agent team coordination within an adversarial environment has been studied extensively. But, the dual topic of human-robot coordination in an adversarial environment has not been investigated. This research involves the intelligent coordination of mixed teams of humans competing in adversarial tasks against one another. The results of this research will further the technology necessary to allow humans and robots to work together in many different environments.

In order to further investigate human robot interaction in team tasks, we have developed a new game called Segway soccer in which human-robot teams will play against each other. The humans and the robots will be placed on an equal physical level by utilizing the Segway Human Transporter (HT) and the Segway Robot Mobility Platform (RMP). We present the game of Segway Soccer and the abilities and limitations of the Segway HT and RMP in Section 2, the modifications necessary to create a Robot Segway Soccer Player out of the RMP in Section 3, the design analysis and mathematical models necessary to choose among the different ball manipulation systems in Section 4, the implementation details and experimental results of the CM-RMP Robot Soccer Player in Section 5, and our conclusions and future plans in Section 6.

2 Segway Soccer Game and Goals

We have developed a new game called Segway Soccer, which consists of teams of humans and robots competing in a game where the rules are a combination of soccer and Ultimate Frisbee[1]. The objective of the game is score the most goals by kicking a regular size 5 soccer ball into goal which is 2.5 meters wide. One key contribution from ultimate Frisbee is that once a player is declared to have possession of the ball by a referee, the player cannot dribble the ball. The player has a one meter radius in which to reposition and pass to a teammate. Another similarity to ultimate Frisbee is that one team or the other will have possession of the ball at all times. For safety reasons, robots and humans will not be running towards each other to gain possession. Furthermore, to ensure robots and humans will collectively be involved, a mixed team cannot officially score unless both a robot and a human interact with the ball on the way to the goal.

Placing humans, robots, and robot competitors on an equal physical level using the Segway platform allows different perception and cognitive abilities to be tested. The dynamic balancing, speed, and size of the Segway allows this human-robot interaction at a human scale. The CM-RMP can travel at 3.5m/s, has a footprint of 48cm by 64cm, and its camera is mounted 1.5m above the ground.

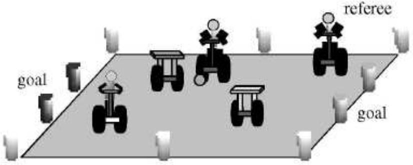

Fig. 1. Segway Soccer field for a 2 on 2 mixed team game

2.1 The Segway Human Transporter and Robot Mobility Platform

The Segway™, developed by Dean Kamen, is a two-wheeled dynamically balanced mobility platform. The Segway has onboard sensors and computer controllers that continually and independently command each wheel in order to maintain balance. The human rider controls the velocity of the Segway by leaning forward, shifting the center of mass, and causing the Segway to drive forward in order to rebalance.

The RMP has provided a robust robotic agent on which to create human-scale robots. The Segway RMP is a 'roboticized' Segway HT consisting of three main modifications. First, a CAN Bus interface is exposed to enable two way, high speed electronic communication with the platform. Second, the Segway's control software is modified to enable a computer to send direct velocity commands to the platform. The third change involves attaching a large mass of about 23kg at a height of 50cm from the robot wheel base. This serves the purpose of raising the robot's center of gravity which slows down the RMP's falling rate in order to allow the control loop to operate effectively.

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[1] Ultimate Players Association, [*http://www.upa.org*]

With this basic infrastructure in place, we added two laptop computers to interpret the world and control the RMP. One laptop is used to provide the RMP with the capability to process data from a pan/tilt CCD camera and another laptop to quickly decide what action to take and send commands to control the actions of the RMP. The Segway HT and RMP are great platforms to place humans and robots on an equal physical level, but many modifications and additions are necessary to make the RMP capable of playing Segway Soccer.

Fig. 2. Segway RMP and Human on Segway HT

2.2 Segway Physical Challenges and Limitations

This new domain of human-robot interaction raises the requirements of robot mechanical systems to a more sophisticated level. The challenge becomes designing adequate hardware that will allow a robot to safely and robustly operate in an outdoor environment along with humans in a competitive soccer game.

The Segway moves forward by tilting over and driving the wheels in order to rebalance. This motion can lead to the ball becoming stuck underneath the body and wheels of the Segway. This causes the wheels to lose contact or traction with the ground making the Segway unable to sufficiently maintain balance. Any fall could potentially damage equipment.

Another challenge introduced with Segway soccer is that there is no unique playing surface; it can be played on grass, Astroturf, or cement. Changes in grass height, ground softness, and surface texture alter the dynamics necessary to manipulate the ball. Unlike other robotic soccer platforms, the Segway tips up to +/- 20 degrees with respect to the vertical; thus, any attached kicking plate and system will also tip. This requires the manipulation system to be robust enough to manipulate the ball under changing conditions.

3 Turning the Segway RMP into a Soccer Player

Guards, consisting of modified rubber mud flaps, placed in front of the wheels along with computer control software which prevents the RMP from interacting with the ball unless it knows the manipulation system can kick it will prevent the soccer ball from lodging underneath the center of the Segway. This same software allows the manipulation system to adjust to the changing playing surfaces along with a properly sized kicking plate.

Hardware must be able to protect the components of the Segway from damage during a fall. The laptop computers and ball manipulation system components are mounted as close as possible to the bottom of the Segway reducing their falling distance and the shock they will absorb. The laptops are also securely fastened with straps preventing them from being ejected from the confines of the RMP body. Steel safety stands were added to reduce the total distance the Segway will fall once it is no longer capable of dynamically balancing. The stands mount onto the side of the RMP and only allow it to fall over 30 degrees from the vertical.

4 Ball Manipulation Systems

The main challenge lies in designing a ball manipulation system that allows a Segway platform to kick a ball to the scale of an outdoor human game. The design analysis must consider the previous outlined problems and result in a system that allows the game of Segway Soccer to be possible by equipping the RMP with the ability to pass the ball to teammates and shoot the ball into the goal. We present the information necessary to design and implement a ball manipulation system for a Segway platform and similar mobile robots.

4.1 Kicking System Design Considerations

A ball manipulation system can be described as a mechanical manipulator used to accelerate a ball to a desired velocity. This can be achieved in many different ways with various actuators. The most common systems come from the realm of robot soccer as seen in RoboCup [7] competitions. These include pneumatic, spring, solenoid, rack and pinion, and rotating plate systems. A careful analysis of the following factors is needed to determine which kicking system best fits your platform and the environment in which the game is being played:

- **Speed**-How fast should the ball be kicked?
- **Accuracy**- What distribution is acceptable? Should it only kick straight?
- **Kick capacity**- How many kicks are possible or needed in a game?
- **Response time**-How long will is take for a signal to result in a kick?
- **Recovery time**- How long before a second kick is possible?
- **Safety**- Is the system likely to injure a human player or bystander?
- **Complexity**- What is the build time? What parts are required?
- **Weight**-Can the robot carry the payload?
- **Size**- Will the system fit on the robot and perform adequately?
- **Price**- Is it worth the extra money?
- **Power**-Can the robot carry the power supply? How long will the supply last?
- **Reliability/Maintenance**-How likely will parts break under normal competitive play? How expensive and complex is the maintenance?
- **Transportability**- Can the system be transported in an airplane? Are spare parts readily available?

With these considerations in mind, the actuating system must be chosen. For each option, we present the basic system components, the mathematical models necessary to properly specify an appropriate actuator, and an example comparing each option to the pneumatic system implemented on the CM-RMP.

4.2 Spring Loaded Mechanisms

Spring kicking mechanisms are extension or compression springs used to store and then release energy to propel the ball. As such, a mechanism is needed to tension the spring and a trigger to instantaneously release the stored energy into the ball. Such mechanisms must be robust, and are non-trivial to design. Specifically, the design time is lengthy due to the necessity to specify the appropriate number and strength of the springs and the motor size necessary to tension the springs quickly. This complexity leads to the potential for problems during a dynamic soccer game. The time to reload the spring can also take several seconds if a cheaper less powerful motor is used. Springs do provide the best power density out of the given the options [4, 5]. A spring can effectively propel a soccer ball on grass field.

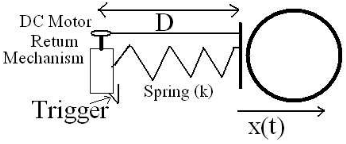

Fig. 3. Spring Kicking Mechanism Schematic

For a spring with spring constant of *k*, a kick length of *D*, and a kicking mass of m, the equations of motion for the spring mechanism are:

$$\ddot{x} = -kx \cdot m^{-1} \qquad x(0) = D \quad \dot{x}(0) = 0\,. \tag{1}$$

$$x(t) = D\cos\left(\sqrt{k/m}\,t\right)\,. \tag{2}$$

For the Segway RMP, the pneumatic kicking system model predicts the ball will be kicked at a 4.3 m/s max velocity. Using the above equations, one can determine the spring constant, *k*, necessary to achieve a similar speed with a similar stroke length to the pneumatic model. Assuming a kicking mass of 0.85kg, a spring constant of 676 N/m would be necessary. This would require a force of 103N in order to load and hold the spring at 0.1524m for a kick. This requires a geared DC motor. Using an 80W Maxon motor [12] geared 6:1, the spring could be reloaded in 0.15 seconds. Although this is an appropriate design, an equivalent DC motor would cost in the hundreds of dollars.

4.3 Rotating Plate Mechanisms

Rotating plate kickers consist of two or more flat surfaces, bars, or other contacts arranged in a balanced paddle boat configuration. [1] The shaft of the paddle wheel is connected to a DC motor. The angular velocity of the paddle wheel determines the end velocity of the ball. Pulse Width Modulation can be used to vary the speed of the wheel and thus vary the power of the kick. Rotating plate mechanisms require a significant amount of space to mount the paddle wheel and the drive motor. Furthermore, as the size of the robot increases, rotating plates become extremely dangerous to human operators. A rotating plate mechanism scaled to the size of a Segway would have to be approximately 18cm by 38cm. The plates would be rotating fast enough and with enough power to cause injury to humans who happen to fall off of their HT into a kicking device. As a result, we do not consider a rotating plate mechanism in depth.

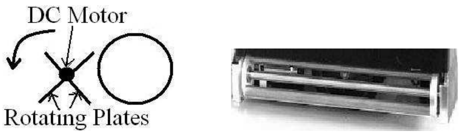

Fig. 1. Rotating Plate Kicker Schematic and Physical Example

4.4 Rack and Pinion Systems

Rack and pinion systems are driven by DC motors and thus the ball velocity is dependent of the output power of the motor. For a rack and pinion motor system with a back emf of k_e, voltage of *V*, forward torque per amp of *K*, terminal resistance of R, pinion radius of *r*, gear ratio of *N*, and total kicking components mass of *m*, the following are the equations of motion:

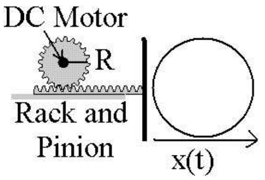

Fig. 5. Rack and Pinion Kicking System Schematic

$$\ddot{x} = \frac{K}{mr^2R}(Vr - k_e \dot{x}) \qquad x(0) = 0 \quad \dot{x}(0) = 0 \ . \tag{3}$$

$$x(t)=\frac{Vr}{k_e}t-\frac{mr^3RV}{NKk_e^2}\left(1-e^{-\frac{k_eKN}{mr^2R}t}\right). \tag{4}$$

A rack and pinion system is comparable to the other options but the price and design requirements are more significant. Using the same 80W Maxon motor [12] used to illustrate the spring kicking system with a 0.015m pinion radius, 1:1 gear ratio, and a total kicking mass of 1.3 kg, the rack and pinion system can accelerate the ball to a theoretical velocity of 6.7 m/s in 0.1524 m (6in). With a motor efficiency around 75% and the friction forces acting against the sliding rack, the actual velocity will be closer to 3.5 m/s. This model also does not take into account the inertia forces of the sliding rack which increase the reloading time.

The Segway does not have enough space to implement a rack and pinion system. Two rack and pinions would be needed since one rack and pinion could not be placed in the middle of the Segway due to the handle bar mounting. This would require two motors or a much larger single motor to actuate both rack and pinions. This requirement makes this system unfeasible for use on a Segway platform. The two high power motors can easily cost over a thousand dollars [3].

4.5 Solenoid Systems

A solenoid kicker consists of a solenoid that creates a magnetic field around a shaft that is propelled by the field and accelerated away from the solenoid. The shaft is returned by a built in return spring. Consider a solenoid kicking system with a current of *I*, ampere turns of *N*, plunger radius of r, a return spring constant of *k*, a total kicking mass of *m*, and a stroke length of *S*. The formal differential equation of motion is given in equation (5). Since this equation can only be solved by numerical means, we can approximate the result for analysis purposes by treating the solenoid force as being constant for the duration, as the average force exerted by the solenoid over its stroke length. The resulting equation is given by equations (6) and (7).

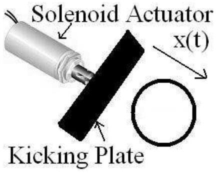

Fig. 6. Solenoid Kicker Schematic

$$\ddot{x}=m^{-1}\left(\tfrac{1}{2}\mu_0\pi\left(\tfrac{rNI}{x}\right)^2-kx\right),\ x(0)=0\quad \dot{x}(0)=0. \tag{5}$$

$$\ddot{x}=\mathrm{m}^{-1}\left(\mathrm{F}_{\mathrm{avg}}-kx\right)\qquad x(0)=0\quad \dot{x}(0)=0\ . \tag{6}$$

$$x(t) = {}^{F_{avg}}\!/_{k}\left(1-\cos\left(\sqrt{{}^{k}\!/_{m}}\,t\right)\right) . \qquad \textbf{(7)}$$

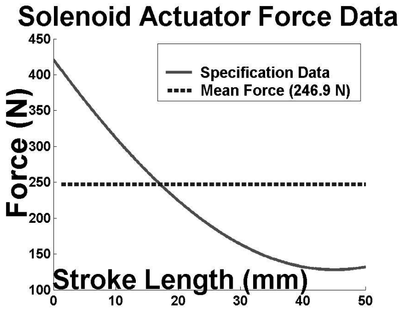

Fig. 7. Solenoid Force v. Stroke Curve and Approximation

A solenoid system becomes more impractical with a large robot platform. The largest solenoids available produce approximately 400N of force and generally have small stroke lengths less than one inch (0.254m) which limit its ability to effectively contact a ball. For a the solenoid shown in figure (7) [13], assuming a spring constant k=99 N/m, and a kicking mass of 1.5 kg, a ball would be kicked at 4.1 m/s over a 2 inch stroke length. With the effects of friction and motor efficiency the actual speed will be close to 3 m/s. This is comparable to the pneumatic system but the smaller stroke length limits is ability to effectively manipulate a ball during a game. The high voltage requirement also raises safety issues. A solenoid solution is simply impractical for use on larger mobile robots like the Segway RMP.

4.6 Pneumatic Systems

Pneumatic piston systems usually consist of one or two actuating cylinders, an air reservoir, solenoid valves to control the air flow, a source of compressed air in the form of an air compressor or liquid carbon dioxide (CO_2), and a regulator to maintain a specified pressure. The decision between carbon dioxide and compressed air depends on the availability of CO_2 . CO_2 can fill a tank to a much higher pressure due to the ability of the tank to be filled with liquid CO_2 . Air compressors normally only operate up to 150 psi while CO_2 tanks fill to several thousand psi. This higher pressure allows the cylinders to be fired with a higher output force resulting in a stronger kick. The higher pressure also significantly increases the kick capacity of the system. The draw back of carbon dioxide is that it is not easily transportable. As a result, the Segway RMP kicking system uses compressed air.

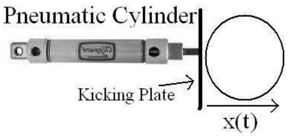

Fig. 8. Pneumatic Kicker Schematic

The pneumatic cylinder pistons connect to a kicking plate that contacts the ball. The plate can vary in material and shape dependent on application. The one or more pistons can be fired at the same time or in a synchronized order to achieve a directional kick. A pneumatic system offers a wide range of options in its configuration and employment. The cylinders produce significant force for their size. For a pneumatic system with power factor, *f*, combined kicking mass, *m*, return spring constant, *k*, and operating at a pressure, *P*, the equations of motion are:

$$\ddot{x} = m^{-1}\left(fP - kx \right) \qquad x(0) = 0 \quad \dot{x}(0) = 0 \ . \tag{8}$$

$$\ddot{x}(t) = fP \cdot k^{-1}\left(1 - \cos\left(\sqrt{k/m}\, t\right)\right) . \tag{9}$$

A Segway Soccer sized cylinder would be approximately 10 in long, ¾ in diameter and produce 66.6 lbs (274N) for force at 140 psi. The pistons are the only moving parts and the air tank consumes the most space. The price of a pneumatic system is also fairly cheap. An entire system can be bought for less than $100. The air used to power the cylinders is easily accessible and can be refilled quickly during a soccer game with an onboard air compressor. The system has a low chance of malfunctioning and becoming inoperable during a game because the only moving parts are the cylinder shafts. [2, 8].

5 Implementation and Results

With the considerations presented thus far, we chose to use a pneumatic approach due to its relative simplicity, low cost, and transportability. Figure (9) shows the resulting arrangement

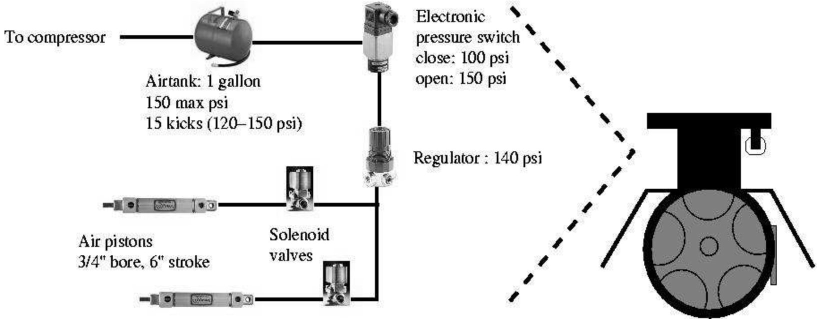

Fig. 9. Schematic diagram of the implemented CM-RMP pneumatic kicking system

Two ¾ inch bore, dual acting pneumatic cylinders were chosen as the main actuating components. A ¾ in bore provides adequate power with a sturdy shaft that can sustain unexpected stress. Dual acting cylinders do not have a return spring to reset the cylinder shafts back to their original position. This allowed us to implement a return mechanism with just enough force to reset the kicking plate without significantly affecting the output force. We used (4) No.64 (3.5in x 1/4in) rubber bands to return the kicking plate. Two cylinders also allow for 3 directional kicking.

5.1 Air Reservoir Options

The air reservoir can be designed in two different ways. The reservoir can be large enough to hold enough kicks for the entire game or an onboard air compressor can refill a smaller reservoir. If the robot has enough room to house a larger tank, not having an air compressor allows the overall system to be simpler. The Segway kicker uses a one gallon tank, which provides a sufficient number of kicks as seen in figure (10). We have an onboard compressor that turns on after 15 kicks and shuts off when the tank pressure reaches 150 psi. The compressor is controlled by a microcontroller that also monitors a mechanical pressure switch that opens at 150 psi. As a result, the operation of the compressor is completely automated.

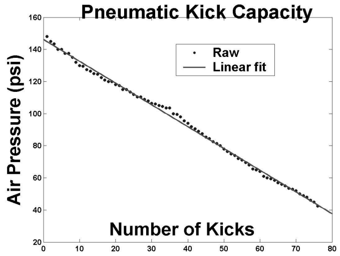

Fig. 10. Number of Kicks v. Reservoir Pressure

5.2 Velocity Test Results

The cylinders accelerate the ball to a max velocity of approximately 3.5 m/s, which is sufficient for a two on two game of Segway soccer. The velocity can increase to 4.5 m/s if the Segway RMP is running at the ball and kicks it. The theoretically predicted top speed for a stationary kick is approximately 4.3 m/s. The loss in velocity is due to the efficiency of the pneumatic cylinders, an imperfect impact with the ball, and ground friction. An experiment was setup using one of the cylinders, a small kicking plate, and a golf ball. The velocity of the golf ball was measured on a cement floor. This experiment was designed to significantly lower the effects of impact and friction losses. Through these tests, it was determined that the pneumatic cylinder alone had an efficiency of 75%. These losses are due to several factors including cylinder friction, exiting air resistance, and flow rate limitations. Impact losses and ground friction account for an additional 2% loss. The theoretical and experimental kick speed versus cylinder pressure plot is shown in figure (11). Furthermore experiments were conducted measuring the speed of the ball when the Segway RMP played back a kick motion in which it swung its base forward and simultaneously kicked. These results are seen in figure (12).

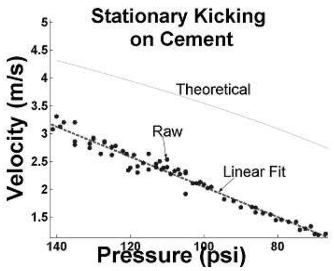

Fig. 11. Experimental and Theoretical

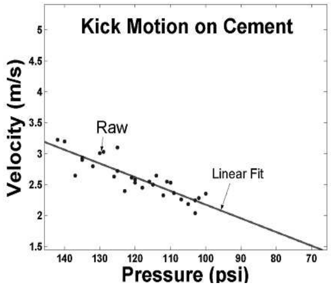

Fig. 12. Pressure v. Kick Motion Velocity

5.3 Accuracy

The kick is sufficiently accurate as seen by the distribution in figure (13). The mean is 122 mm and the standard deviation is 175 mm. The mean error can be mostly accounted for by experimental error in lining up the kick. In practice, this mean and variance will be modified by the robots ability to position itself next to the ball.

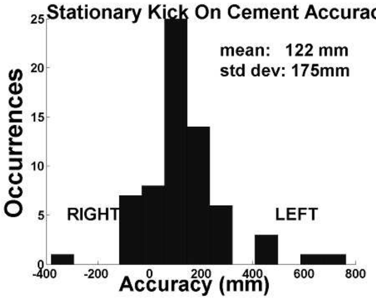

Fig. 13. Histogram of Stationary Kicking on a Cement Surface

6 Conclusions and Future Work

Currently, the Segway CM-RMP is physically capable of robustly interacting with a size 5 soccer ball. The ball can be passed to a human or robot teammate who can in turn pass or shoot the ball into the goal. The RMP is safe to operate with human teammates and its components are protected from damage. After considering all the advantages and disadvantages of the different types of kicking systems, a pneumatic solution best fits the Segway Robot Mobility Platform and performs well. The game of Segway soccer is now physically possible with the engineering design analysis described

In the future, other mechanical components can be added to improve the Segway Soccer playing abilities of the Segway CM-RMP. If the RMP falls over and is unable to balance itself, a system is being designed to allow the RMP to lift itself from the ground, rebalance, and continue to play. Another system, the Dynamic Mass System, is being designed to increase the acceleration and deceleration abilities of the RMP. With these and other improvements, the Segway-RMP platform will begin to approach the soccer playing abilities of humans.

Acknowledgements

Thank you to Mike Sokolsky and David Rozner for their help in the construction of the mechanical devices. Finally, we would like to thank the funding sources, who supported and guided this research and development to address this specific problem. This research was sponsored by the United States Army under Grant No. DABT63-99-1-0013. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing official policies or endorsements, either expressed or implied, of DARPA, the US Army, or the US Government.

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