Design of a Team of Soccer Playing Robots

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Abstract. This paper describes the design of the RoboRoos, a fully autonomous robot soccer team. A soccer robot has similar needs to a human soccer player; fast and agile motion, good control of the ball, strong kicking ability, robust navigation and coordination of actions with other members of the team. Each robot is mechanically designed to meet these needs of a competitive soccer player. Mechanically the RoboRoos feature a fast, simple and compact omni-directional drive system, a powerful kicker and a ball control mechanism. The electrical hardware controls these mechanical systems and interfaces to a high speed, low error rate wireless communication module. Software on the microcontroller controls the actuators and provides intelligence in the form of behaviour selection, computationally fast and robust navigation and motion control. The RoboRoo team has competed in the last five RoboCup competitions, demonstrating good performance against other robot soccer teams. The RoboRoos have also demonstrated superiority against human controlled robots, scoring 196 – 24 at a public demonstration.

1 Introduction

The University of Queensland's RoboRoos robot soccer team is a long standing competitor in the annual RoboCup competition [1], [2], [3]. The goal of the RoboCup competitions is, 'By the year 2050, develop a team of fully autonomous humanoid robots that can win against the human world soccer team' [4]. Robot soccer represents a standard problem for research towards autonomous robots. The international contests compare the performance between different approaches to multi-robot control in an uncertain, dynamic environment against unknown, competing external forces.

Just like a human soccer player, a competitive robot soccer player must be able to; move fast and be agile, control and kick the ball, navigate robustly in the desired direction and coordinate its actions with the rest of the team. The RoboRoo robots are able to achieve these requirements. The focus of this paper is on the design of the individual robot's mechanical, electrical and software components, emphasising the aspects that allow the robot to effectively compete in robot soccer games.

The major features of the RoboRoos robots compared to other teams robots is their,

- robust, very low maintenance mechanical and electrical design,
- powerful crossbow kicker, capable of kicking the ball at 5.0m/s,
- fast, simple and compact omni-directional drive system,
- high speed, low error rate wireless communication system (250kbps @ < 5% error),
- robust, computationally fast reactive navigation system.

2 The F180 League

The RoboRoos compete in the F180 league (also known as the small size league) of the annual RoboCup competitions. Each team has five robots that each must physically fit inside a cylinder with a diameter of 180mm and a height of 150mm. Devices to dribble and kick the ball are permitted as long as they do not hold the ball and 80% of the ball is kept outside of the convex hull of the robot. The field is approximately 3 × 4 metres, with an orange golf ball acting as the soccer ball. Generally teams use global overhead vision as the primary sensor although some teams mount cameras on their robots.

The rules are similar to the human version of the game (FIFA), with exceptions such as the elimination of the offside rule and changes required to make sense for wheeled robots. There are two 10 minute halves, with the clock stopping for any break in play (such as a foul or the ball going out of bounds). The robots are fully autonomous in the sense that no strategy or control input is allowed by the human operators during play. Humans referee the matches.

3 RoboRoos System Overview

The complete RoboRoos system is a layered set of competent subsystems that are shown in Figure 1. An overhead camera captures global images of the field. The vision software processes the images to identify and locate the robots and the ball. This state of the field is passed to the Multi-Agent Planning System (MAPS). MAPS is the highest level planner in the system, responsible for distributing the overall goal of the team amongst the individual robots [5]. MAPS is responsible for the multi-robot coordination and cooperation by selecting an action and an action location for each robot. Some example actions include KICK and DEFEND. The MAPS actions and action parameters along with the field state are broadcast to the robots over a high-speed wireless communication system.

The rest of the intelligence software is executed onboard each of the robots. The MAPS actions are interpreted by the Action Execution System (AES). Each action has a set of associated parameters and a notion of the overall desired robot motion. The NAV module attempts to achieve the desired motion behaviour while avoiding obstacles. The NAV module determines the immediate desired heading and distance for the Motion system. The Motion system accelerates and decelerates the robot to the desired heading and distance by creating force-limited trajectories that ensure wheel slip is kept to a minimum.

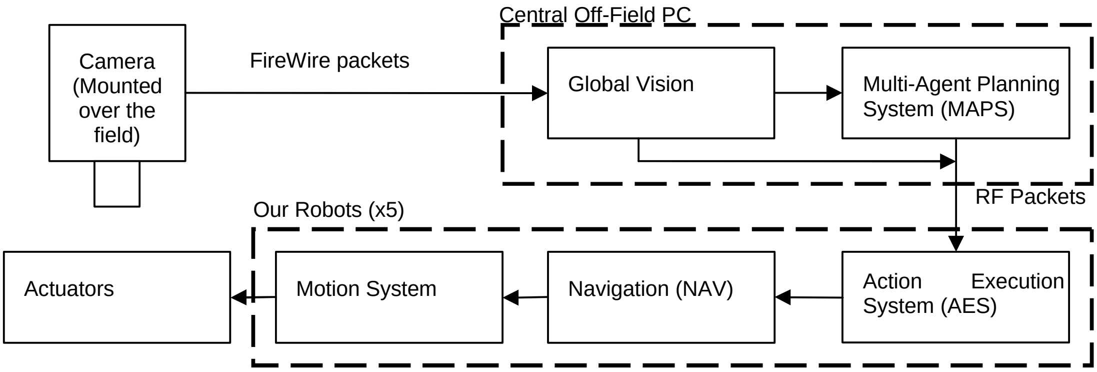

Figure 1. Complete RoboRoo System. The figure shows the path of information from when the camera observes the state of the field to the robot's actuators.

4 Mechanical Design

The RoboRoos are mechanically designed to meet the needs of a competitive soccer robot. The major mechanical features of a RoboRoo robot are the omni-directional drive, powerful kicker and a ball control mechanism. All RoboRoos are of the same mechanical design, each having a mass of 1.5 kilograms. The RoboRoos are constructed using aluminium that gives them a strong but light frame. A polycarbonate cover protects the internals of the robots and has markings on top for the vision system. The robots have a low centre of mass, achieved by placing the batteries and the drive system on the clearance plane at the base of the robot. The low centre of mass reduces weight transfer between wheels as the robot accelerates. Consistent weight transfer leads to less slip of the wheels across the playing surface.

4.1 Omni-Directional Drive System

The omni-directional drive system allows the RoboRoos robot to be agile. This is because it gives three independent degrees of motion: two translational and one rotational. For more information on the basics of omnidirectional drive systems see [6]. This means that the desired rotation and position can be achieved independent of each other, as opposed to a typical differential drive robot that can only translate in the direction to which the robot has rotated. Not only can the omnidirectional drive robots have the right heading when they reach their goal but also can move towards their goal without having to first orientate in that direction. This gives the RoboRoos a significant advantage over differential drive robots.

The RoboRoos omni-directional drive is implemented using three DC motors each with two castor wheels. Each motor is mounted at 120^o from each other. The wheels are placed at the extremity of the robot to prevent rocking. The wheels have a moulded rubber surface for good grip with the surface. A photo of the RoboRoos drive system is shown in Figure 2.

The DC motors are the MiniMotor 6 Volt 2224's with mounted encoder. This motor has a recommended speed up to 8000RPM and continuous torque up to 5mNm. The gear ratio from the motors to the drive shafts is 4.2:1. When running at the peak recommended performance, the drive system is capable of an acceleration of $2.3 m/s^2$ and a maximum velocity of 2.3m/s. To be competitive the robots are run at higher accelerations. This is typically between $3.0 m/s^2$ and $4.0 m/s^2$ dependent on the surface and the team that the RoboRoos are competing against. This implies a 50 – 80% torque overload of the motors, which is acceptable provided that thermal limits are monitored.

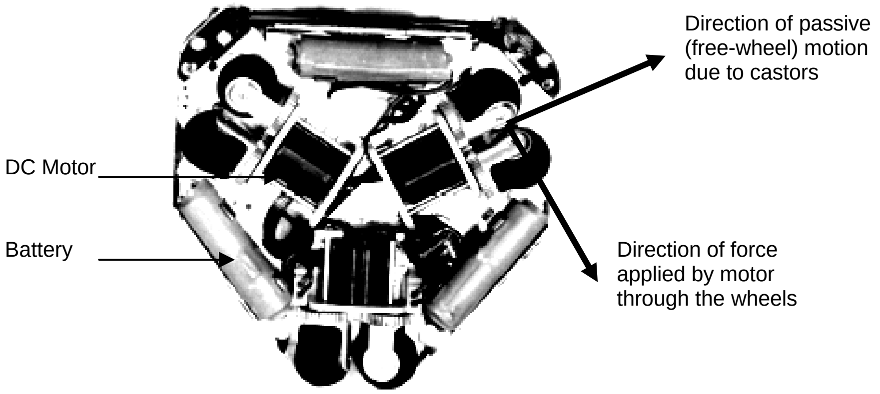

Figure 2. The underside of a RoboRoo showing the omni-directional drive. Note the placement of the batteries in the same plane as the motors.

The Cornell Universities' Big Red team (who achieved first place at RoboCup 2002) have used omni-directional drive systems since 2000 [7]. In 2001 their drive system design achieved similar accelerations as the RoboRoo robots drive system however their design did not have all of their drive motors and batteries in the same plane as the drive system wheels. This means that their design has a high centre of mass and more complexity, especially in the height dimension.

4.2 Crossbow Kicker Mechanism

A kicking mechanism allows a robot soccer player to take shots at the opponent's goal and pass the ball to other members of it team. The kicking mechanism for the RoboRoos is of a crossbow design and it is shown in Figure 3. In its "hard kick" mode, it can kick a golf ball at approximately 5.0m/s. A "soft kick" mode allows a kick of 2.0m/s. The kicking mechanism, while mechanically complex, uses only one DC motor to both retract and release the kicker. The following is a list of the major components of the kicker mechanism.

- Striker - This flat plate strikes the ball.
- Rack - The rack is joined to the striker and allows it to be retracted and released.
- Elastic Cord - The elastic cord provides the energy storage. It projects the striker forward when it is released. (Not shown in figure.)
- Slot - Two slots are cut in the striker for the hard kick and the soft kick.
- Trigger - The trigger is engaged in the slot and holds the kicker until it is released.
- Micro-switches – The micro-switches provide feedback the location of the striker.
- DC motor - A single motor is used to retract and release the striker.
- Swivel bracket - This bracket houses the gear train that connects to the rack.
- Pinions - The pinions are located in the swivel bracket. A pinion engages the rack.
- Claws - The claws at the front of the robot contain a local infrared ball sensor.

The kicker works as follows. The DC motor rotates the pinions clockwise to retract the striker against the force of the elastic cord. This retraction continues until the desired micro switch is closed (hard or soft kick) and then the striker's rack settles back so the trigger rests in the slot. To release the kicker the swivel bracket lifts the pinion from the rack and then pushes the trigger until the striker is released. The stored force in the elastic cord now projects the striker forward to hit the ball.

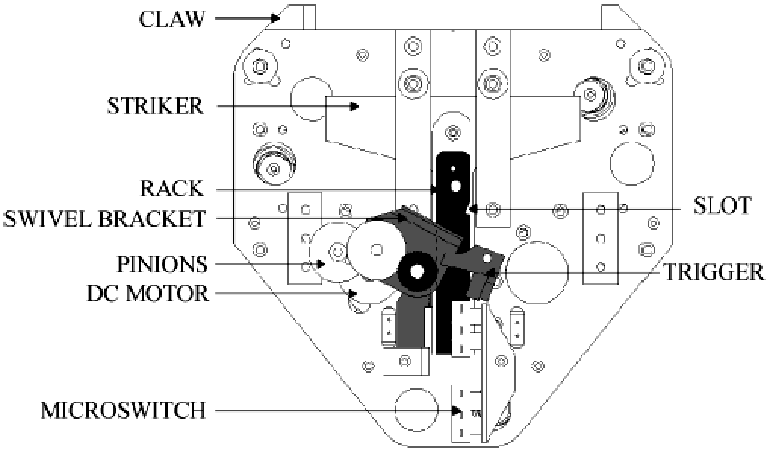

Figure 3. The RoboRoo's kicker mechanism. In the figure the striker is shown locked in soft kick mode. This view is from the top and some of the supports are cut away. The front of the robot is towards the top of the page.

Two other commonly used kicker mechanisms are the solenoid actuated (where the solenoid is connected to bar that strikes the golf ball) and the rotating bar kicker mechanisms (where a pair of metal bars rotates about a central axis that is halfway between them). The major problem with solenoid kicker mechanisms is that they are unable to kick the ball as fast as the RoboRoos crossbow kicker. The major problem with the rotating bar kicker mechanism is that they take significant time to reach a high rotational velocity meaning that dribbling then immediately kicking is impossible.

4.3 Ball Control Mechanism

It is desirable for soccer robots to control and move the ball about the field without losing possession. In real soccer this is called dribbling. A RoboRoo has a ball control mechanism, generally called a “dribble bar”, that allows it to move the ball around the field. The ball control mechanism is shown in Figure 4. The RoboRoos ball control device is a rotating rubber cylinder that applies backspin to the golf ball when in contact. This backspin gives the ball motion towards the robot, and this effectively ‘holds’ the ball against the robot. A small DC motor drives the shaft onto which the rubber is vulcanised.

The RoboRoos ball control mechanism has two features. One feature is a 15mm gap cut in the centre of the bar. When the ball is located in this gap the RoboRoo has some control over the sideways motion of the ball. It has another benefit as the crossbow kicker gives a more accurate and powerful kick to a ball located in the centre of the ball control mechanism. The second feature is the screw shape cut into the rubber. This gives the ball a component of force towards the centre of the dribbler. The ball then becomes trapped in the centre gap.

The Cornell Universities’ Big Red team also has a ball control mechanism. It uses a simple horizontal bar for the main dribbling. It also has two diagonal rotating bars located on either end of the horizontal bar that stop the ball from rolling off the side their main rotating bar. These impart an active force on the ball towards the centre of their horizontal bar. Their dribblers are also rotated at much high rotational velocities than the RoboRoos ones. This gives their robots superior dribbling performance compared to the RoboRoos robot, but at the expense (cost, mechanical design, power requirements) of two more actuators.

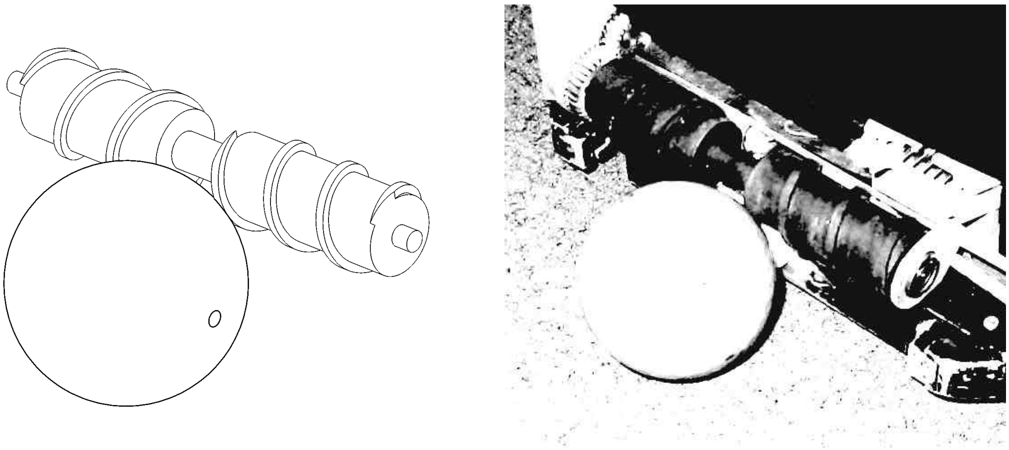

Figure 4. The Figure shows the golf ball in contact with the RoboRoo’s ball control mechanism. The “dribble bar” is made by vulcanising rubber to the metal shaft, and then cut into shape. It is rotated in such a way as to give backspin to the golf ball so that it is ‘held’ against the robot. The diagram on the left is from the CAD drawing, while on the figure on the right is an actual picture.

5 Electrical Design

The electrical system allows the software to control the robots actuators. Two PCB's make up the electrical design, one is the central CPU board that controls the motors and the other is a RF communication interface board. A block diagram of the electrical hardware is in Figure 5.

5.1 Central CPU Board

The RoboRoos central CPU board uses Motorola's MC68332 32 bit microcontroller. This microcontroller executes some intelligence software and the low level motor control loop. The major benefit of using this microcontroller is its built-in Time Processor Unit (TPU). The TPU has 16 channels (I/O pins) that can be configured independently for a variety of tasks, including quadrature decoding (QDEC), input capture (IC) and Pulse Width Modulation (PWM) generation. Except for the kicker mechanism, the motors have encoders for fast and immediate local feedback. The QDEC function removes the need for either the central CPU to process the incoming encoder signals or a dedicated FPGA/CPU for the task. A separate semi-discrete H-bridge controls the voltage to each motor. This H-bridge consists of a MOSFET driver, two n-channel and two p-channel MOSFETS. The central CPU board has an external 256 kilobytes of FLASH and 128 kilobytes of RAM.

5.2 Wireless RF Communication

The RoboRoos receive broadcast communications from the central PC, informing them of the state of the field and the actions they should be attempting. As the environment is highly dynamic it is important that this communication has low latency and low error rate. At a RoboCup competition multiple transmitters are in use at any one time causing high levels of interference. This makes achieving a low error rate particularly hard. The RoboRoos use 250kbps 900Mhz spread spectrum RF transceiver modules from Innomedia.

Unfortunately the RF modules have a complex custom communication interface of multiple synchronous serial channels for transmit mode, receive mode and initialisation mode. The interface board uses a PIC16F873 microcontroller to hide this complex communication interface and allows the central CPU to communicate using standard UART serial. This makes easy conversion from the commonly used RadioMetrix modules. For our communication packet of 50 bytes the latency is approximately 6ms. Error rate are always low, for example at RoboCup 2002 they were always under 5%.

This is a high level of performance compared to the commonly used 418/433Mhz RadioMetrix RF modules by F180 league teams. Communications were found to be reliable (under 5% error) only at rates of 19.2kbps or less. This is approximately 13 times slower that the Innomedia system. Another disadvantage of this method is that only one transmitter in the competition area can use a channel at a time. Therefore only two teams can use these modules at any one time.

5.3 Batteries

The RoboRoos use Nickel Metal Hydride batteries for power. Six 1.2 Volt 1000mAh batteries are connected in serial to provide 7.2 Volts. A robot can typically run for 15 minutes in continuous use. As a half lasts for 10 minutes of play time, the batteries must be changed at half time.

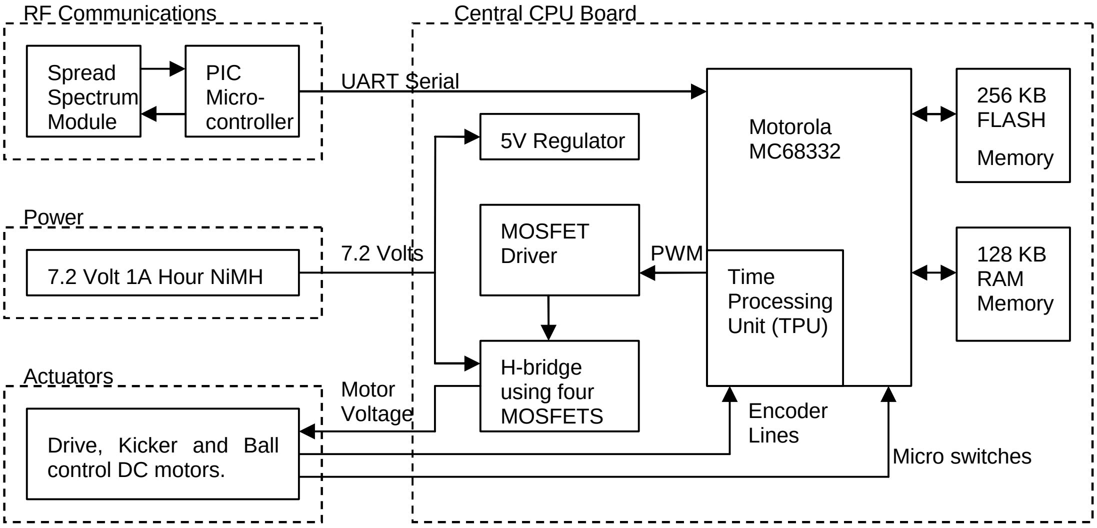

Figure 5. Diagram of the RoboRoo robot's electrical hardware.

6 Software Design

Software in the RoboRoos system is distributed across the off-field central PC and the individual robots. The central PC determines the state of the field and each robots action and action location. This means that the individual robots must select an appropriate behaviour, perform navigation and control the actuators. More explicitly the modules are: the Action Execution System (AES), the Navigation System (NAV) and the Motion System. The AES and NAV systems run at the same frequency as the incoming RF packets (i.e. the same frequency as MAPS and Vision). The Motion System runs at 1 kHz.

This part of the intelligence is on the robots so that they are able to use local feedback from the motor's encoders and ball sensor. This was important as the latency of the system was originally high and identification of the robots by vision was poor.

6.1 Action Execution System

The Action Execution System is responsible for selecting the immediate robot behaviour. The field state and the MAPS assigned action are used as resources to determine this behaviour. The AES system fills in the details of the assigned actions from MAPS by decomposing it into a series of small tasks that can be performed using simple behaviours. The AES then decides on the immediate task to be achieved.

Each behaviour has a set of associated parameters and desired robot motion. Parameters associated with a robot include accelerations, application specific actuator state and desired repulsive strength of obstacles.

In a real soccer match the most important and complex actions that a field player performs is kicking and dribbling the ball. As such the kick action provides a good example of the role of the AES. The kick action sequence involves acquiring the ball then dribbling until the robot is lined up for the kick to the MAPS assigned location.

The AES breaks the kick action into a series of smaller tasks. These are:

1. *Move to near the ball.* This step moves the robot to near the ball at high accelerations and speeds. If the robot already controls the ball then skip to step 3.

2. *Acquire the ball.* Acquiring the ball is dependent on its position relative to the field and the opponent robots. If the ball is amongst other objects a modified version of navigation is used to acquire the ball, otherwise the robot drives directly at it.

3. *Dribble until kick.* Once the ball is acquired the robot must assume a pose that allows kicking to the MAPS specified location. AES chooses the appropriate motion to maintain control of the ball.

4. *Kick the ball.* Activate the kicking mechanism while maintaining kick angle.

6.2 Navigation System (NAV)

A soccer robot requires a navigation system so that it can achieve the desired motion while avoiding obstacles. Just like in human soccer a soccer robot may be removed from the field if it pushes players from the other team. A competitive navigation system must not only allow robust avoidance of the other players, but still allow the robot to move into and around cluttered areas. This is difficult due to the highly dynamic nature of the environment and the need for a real time implementation.

The AES system provides the desired pose and the relative avoidance strength for each obstacle to the NAV system. The NAV system determines the desired direction and distance for the robot to travel in. Obstacles may be physical objects such as the robots and the field boundaries. They may also be virtual obstacles that can be used to keep a robot out of a particular area.

NAV is a biologically plausible reactive navigation system that is appropriate to the highly dynamic environment [8]. The different influences in the environment are represented using multiple schemas. Schema theory is a behaviour-based approach whereby overall robot behaviour results from the interaction of many simple schemas operating in parallel. In this navigation system, multiple schemas are represented by polar mappings that are centred on the robot. The Goal Direction Map represents the attraction of the desired goal location and the Obstacle Map represents the repulsion of the obstacles around the robot. The Motor Heading Map determined by a piecewise substraction of the Obstacle Map from the Goal Direction Map. The largest peak forms the desired navigation direction.

The NAV system has shown itself a capable system for achieving desired motion behaviour while competently avoiding obstacles in the highly dynamic environment. This is because:

- The complex problem of navigation is broken down into simple schemas that represent the different navigational influences.
- Reaction to environment change is fast as navigation is based on reaction, not on a plan.
- Navigation maintains competence even with poor behaviour selection by AES due to robust avoidance of obstacles.

The deficiencies of a reactive navigation system, local minima and non path optimal generation are generally not apparent. Local minima are not apparent as the global state is highly dynamic, meaning that problem states do not exist for long. Optimal path generation is wasteful, as the generated path will not exist for long, again due to the highly dynamic nature of the environment.

The Free University of Berlin's FU-Fighters team (who achieved second place at RoboCup 2002) use a best-first search algorithm on a grid to find the cheapest path [9]. Obstacles and the field boundaries are represented as expensive cells and are therefore avoided. Although this can generate shorter paths it can be wasteful as explained above. Also the size of the cells will affect performance. If the cell size is too small finding the solution may take a long time and if the cell size is too large then a solution through close obstacles may not be found.

6.3 Motion System

The primary function of the motion control module is to ensure that the robot complies as closely as possible with the NAV requests without causing the robot to lose traction with the surface. The NAV module provides a desired direction of travel and a total length that remains to the goal location. The motion control software seeks to provide constant force acting from the wheel to the ground. Typically, this force is somewhat less than the normal force applied by the robot to the ground so that good traction is achieved. Consequently, the robot limits straight line acceleration and rotational acceleration, and must adjust speeds when manoeuvring so that the wheels can generate sufficient force.

Maintaining good traction with the ground means that the motion control system can adequately perform its other essential role: keeping track of the robot's position between external sensor updates. In the highly dynamic environment significant rotation and translation can occur between external sensor updates. Furthermore as the global sensor information comes from a delayed source (Vision) the motion control system can account for self motion during the delay period. By accounting self motion between updates and during sensor delays, the motion control system greatly enhances the accuracy of the robot's interactions with the environment.

It is critically important to time and aim kicks correctly. By using the immediate feedback from local sensors, the motion control software can execute timing critical functions with a precision beyond the other software modules.

An interesting functionality in the motion system software is that the point of reference can be changed for navigation commands. Typically, rotation takes place about the centre of the robot. Under direction from the AES, the motion control system can switch the rotation centre to an arbitrary point. This is applied to ball control. When the ball is directly in front of the robot, as detected by the local ball sensor, the motion control system can switch to rotating about the ball's centre. This provides better control of the ball during dribbling operations.

7 Discussion

The RoboRoos have competed in the annual RoboCup competitions with varying levels of success. The RoboRoos were runners up in the 1998 competition, and have been finalists from 1999 to 2001. In 2002, the RoboRoos were eliminated by the eventual world champions, Big Red from Cornell University, in the group stage of the competition.

The RoboRoos robots demonstrated their robustness under the stress of competition at RoboCup 2002. The RoboRoos did not suffer **any** form of mechanical or electrical failure at the competition. In fact, the protective covers were only taken off the robots to show our design to fellow competitors. This is a testament to the solid and robust design of the robots themselves.

When the RoboRoos compete against humans the results are significant especially considering the goal of the competition. In 2001 the RoboRoos competed against humans for five hours of non-continuous play. Humans play using wheel chair robots controlled by Game Pads. Continuous running rules were adopted and the teams were limited to 3 players each. The final score was 196 – 24 with a convincing win for the multi-robot control system. The most notable observation was the relative lack of team coordination and cooperation in the human teams compared to the multi-robot control system.

8 Conclusion

This paper has detailed the design of a RoboRoos soccer robot. The RoboRoos robots are robust and competitive robots due to the design of the mechanical, electrical and software systems. The omni-directional drive system allows the robot to have fast, agile motion but still be mechanically simple. The ball control mechanism allows dribbling and the kicker primarily allows powerful shots to be taken at the opponent's goal. The electrical hardware allows the software on the robots to control its actuators. It also allows the robots to coordinate their actions with the rest of the team using a low latency, low error rate RF system. The robots software navigates the robot using a computationally fast algorithm so that it can achieve its action, while robustly avoiding obstacles. The needs of a soccer robot (similar to those of a human soccer player) have been addressed with this design.

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