Conceptual Design of a Robot for the RoboCup Competition

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Project Outline

The overall goal of the RoboCup program is to promote the development of robotic technologies and artificial intelligence systems. The first official competition was held in 1997 with over 40 participating teams and thousands of spectators. Since then the number of teams and participants has grown significantly. The stated ultimate goal of the RoboCup program is:

> "By mid-21st century, a team of fully autonomous humanoid robot soccer players shall win a soccer game, complying with the official rule of the FIFA, against the winner of the most recent World Cup."

The RoboCup soccer competition is divided into 5 leagues: the simulation league, the small Size Robot League (F-180), the middle size robot league (F-2000), four-legged robot league, and the humanoid league. At present, the focus of the program will be to develop a team for the F-180 league. The F-180 team represents a systems integration of multiple disciplines. A seamless integration of mechanical engineering, electrical engineering, and computer science is essential for success in the league. A team in the F-180 league will allow students from each of these backgrounds to participate in the program. The purpose of this research project is to develop the conceptual design of a robot for the future Lehigh team. Included in this report is an investigation into the key design elements, an outline of the project costs, and a set of recommendations for the future course of action for the team.

Resources

To develop the conceptual design for a RoboCup robot, the primary source of information used were the publication made available by past competitors in the competition. The design presented in this reports is based upon an evaluation of the strengths and weakness of each of their design elements. Below is a listing of the teams used as a reference for this investigation:

- Cornell University Big Red – 1999, 2000, 2002, 2003 World Champions
- Free University of Berlin F.U. Fighters – 2004 World Champions
- University of Buffalo – 2004 American Open Champions
- University of Queensland, Australia RoboRoos – 2004 Runner-Up
- Carnegie Mellon University – 1997, 1998 World Champions
- Brigham Young University
- Ohio University RoboCats
- Technical University of Eindhoven, Netherlands

Refer to the “References” section for links to each of these teams’ websites as well as additional helpful publications regarding the RoboCup competition.

Competition Outline

The rules of the RoboCup competition are based upon the actual FIFA laws of soccer. Game play consists of two ten minute halves for a total of twenty minutes. Rules such as indirect/direct kicks, corner kicks, goal kicks, and penalty are included within the competition. The match is played on 4.9m x 3.4m field and the ball is essentially of standard orange golf ball. Each team is limited to a maximum of five robots and one of those robots may be designated as a goalie. Robots may be interchanged; however this may only be done at halftime or during stoppages of play. Each robot on the team must fit within a 180mm cylinder and is limited to a maximum height of 150mm if a global vision system is used or 225mm if local vision is used. The complete rules for the

RoboCup comeptiton can be found at:

http://www.itee.uq.edu.au/~wyeth/F180%20Rules/f180rules400.htm.

Also, a drawing of the field of play can be found at:

http://www.itee.uq.edu.au/~wyeth/F180%20Rules/f180_2004_field.pdf

Mechanical Design

The mechanical design of the robot is directly tied to the performance of the robot on the playing field. Robust mechanical design is crucial to success in the RoboCup completion. There are three main actions associated with the mechanical design of the robot: movement, kicking, and dribbling. Mechanical design also includes the design of the chassis and mounting of the electrical components. For the design of the mechanical system the following broad goals have been established:

- Maximize acceleration
- Minimizing the weight, maintain low center of gravity
- Maximizing kick velocity and accuracy
- Optimize dribbler ball control

Based upon the performance capability of past robots in the competition, a more specific set of goals are listed in Table 1:

Acceleration	5-10m/s^2
Maximum Velocity	1-3 m/s
Kick Speed	5-6 m/s
Weight	2-3 kg

Table 1: Performance Goals

To be competitive in the RoboCup tournament, the Lehigh performance statistics of the Lehigh team must be able to achieve this level. These minimum standards will be kept in mind as the design of the robots is developed.

Drive Architecture

The first step in the mechanical design of the robot is deciding the overall drive architecture that will be used. As the F-180 has evolved, so has the drive architecture of the robots in the competition. In the early stages of the competition, many robots featured a bi-directional drive as shown in Figure 1.

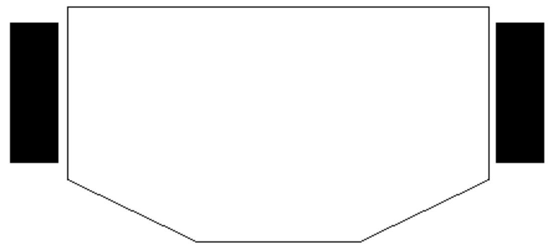
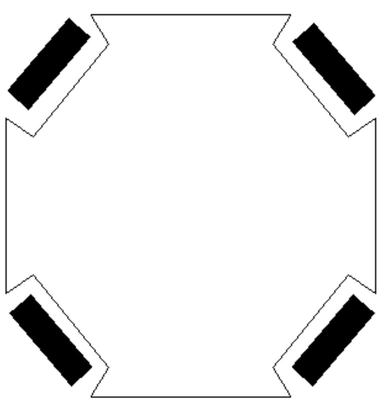


Figure 1: Bi-Directional Drive Architecture

In this layout two independent wheels are mounted on parallel axles and either a small caster or skid plate is used to balance the robot. The robot is limited to forward, backward, or rotational movement, but is unable to move form side to side, or “strafe.” Due to these limitations, the bi-directional architecture has become obsolete and been replaced by the omni-directional drive system. This layout, shown in Figure 2ab, is the most prevalent design in the F-180 league.



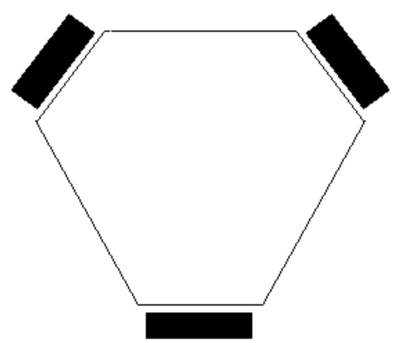


Figure 2a: 4 Wheel Omni-Directional   Figure 2b: 3 Wheel Omni-Directional

The omni-direction design features either four wheels mounted at 90 degree angles or three wheels at 120 degree angles. This design, though more difficult to control, allows for nearly equal acceleration in all directions. The key to this design is the wheel, which allow for rotation both perpendicular and parallel to the drive axle. Wheel design and selection is discussed later in the report.

One of the key decision points with regard to the drive architecture is to use three or four wheels. The following is a comparison of advantages and disadvantages that have been identified in literature from past RoboCup teams:

3 Wheel Advantages

- Less control problems
- Lower weight
- More space efficient

4 Wheel Advantages

- Lower strain on the motors
- Increased traction which corresponds to higher acceleration
- Lower risk of burning out motors

For the Lehigh RoboCup, a four-wheel omni-directional drive architecture is recommended. Overall, this approach, with proper design, appears to offer better performance than the three wheeled design. This conclusion is largely based upon a comprehensive study by the 2002 Cornell Big Red RoboCup team. The key comparison of the two designs was the acceleration map. This plot, generated by MATLAB illustrated the acceleration capabilities of the robot in each direction. This plot is shown in Figure 3:

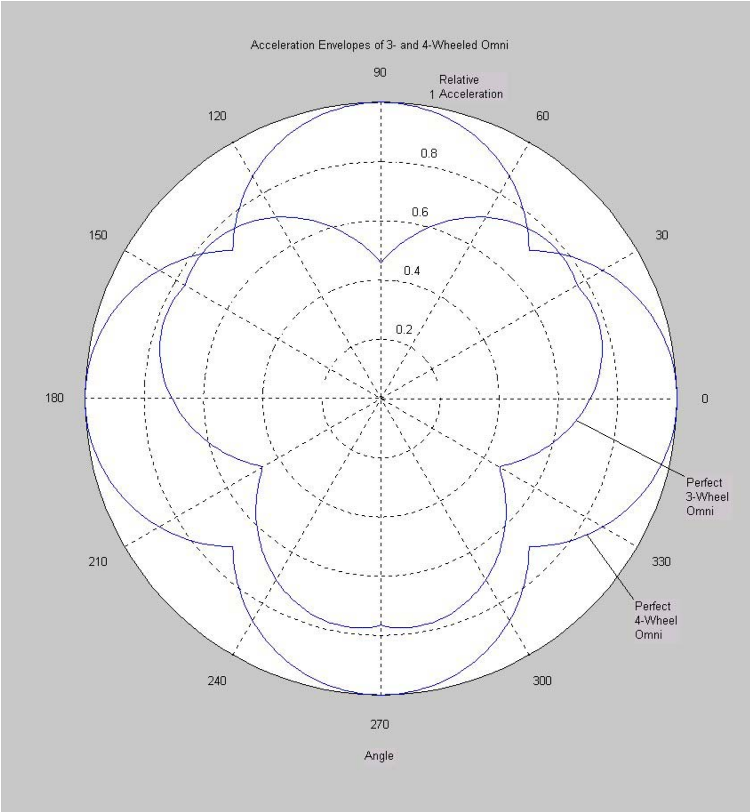


Figure 3: 3 vs. 4 Wheel Omni-direction Acceleration Map

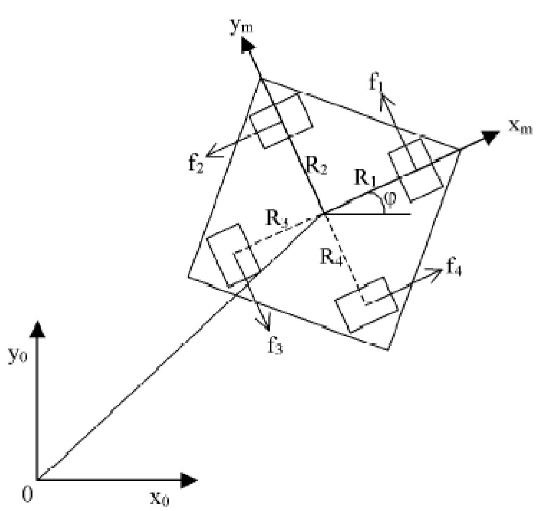
For this simulation, it is assumed that the same motors are used to power each of the drive wheels. For the four wheel system, wheels are located on 45, 135, 225 and 315 degree angle position. For 3 wheel omni directional drive robot, wheels are located 30, 150 and 270 degree location. From the plot shown above, it is clear that the four wheeled architecture is capable of a higher acceleration in nearly every direction. There are several factors contributing to the greater acceleration. It has been identified that one of the main limitations to the acceleration capability of the robots is wheels slipping. Therefore, the four wheels give that design additional traction to the field surface. Additionally, using comparable motors, the four wheels approach uses an additional motor giving it an additional source of power. However there are additional challenges to using a four wheeled approach. Care must be taken in the design of the chassis to

4 wheel approach better for our bot (assuming we can get it to fit) -- even though with 4 wheels, there will be times when 1 wheel is out of action.
Note that bot has noticably (about 33%) better traction going due N/S or E/W than diagonal.

ensure that each wheel is in contact with the surface and that the weight is evenly distributed on each of the wheels. Use of four wheels also pushes the spatial restrictions of the robot to the limits. However, the advantage gained in the performance of the robots far outweighs these concerns. Proper mechanical design of the overall system should be able to overcome these challenges.

Dynamic Model

The challenge associated with an omni-directional robot is that the path planning and control of the motors is much more complicated than a bi-directional approach. The first step in developing the path planning algorithms is the derivation. In a publication from Technical University of Eindhoven, Netherlands, team a dynamic model for a four wheeled omni-directional robot is derived. The results of this analysis, which can be found at http://www.ie.wtb.tue.nl/Robocup/Robots/Drive%20train/Dynamic%20model%20driveline/Dynamic_model.pdf, is shown in Figure 4.



$$\underline{x}_0 = [\ x_0 \quad y_0 \quad \varphi\ ]^T$$

$$\underline{x}_m = [\ x_m \quad y_m \quad \varphi\ ]^T$$

$$\underline{A} \cdot \underline{\ddot{x}}_m + \underline{B} \cdot \underline{\dot{x}}_m = \underline{C} \cdot \underline{u},$$

where:

$$\underline{A} = \begin{bmatrix} \frac{2J_w}{r^2} + m & 0 & \frac{J_w}{r^2}(R_4 - R_2) \\ 0 & \frac{2J_w}{r^2} + m & \frac{J_w}{r^2}(R_1 - R_3) \\ \frac{J_w}{r^2}(R_4 - R_2) & \frac{J_w}{r^2}(R_1 - R_3) & \frac{J_w}{r^2}(R_1^2 + R_2^2 + R_3^2 + R_4^2) + J_m \end{bmatrix},$$

$$\underline{B} = \begin{bmatrix} \frac{2c}{r^2} & 0 & \frac{c}{r^2}(R_4 - R_2) \\ 0 & \frac{2c}{r^2} & \frac{c}{r^2}(R_1 - R_3) \\ \frac{c}{r^2}(R_4 - R_2) & \frac{c}{r^2}(R_1 - R_3) & \frac{c}{r^2}(R_1^2 + R_2^2 + R_3^2 + R_4^2) \end{bmatrix} and$$

$$\underline{C} = \begin{bmatrix} 0 & -\frac{k}{r} & 0 & \frac{k}{r} \\ \frac{k}{r} & 0 & -\frac{k}{r} & 0 \\ \frac{R_1 k}{r} & \frac{R_2 k}{r} & \frac{R_3 k}{r} & \frac{R_4 k}{r} \end{bmatrix}.$$

Figure 4: 4 Wheel Omni-directional Dynamic Model

Motor Selection

With an overall drive architecture selected, the next step in the mechanical design of the robot is selection of the drive motors. The drive motors selected will directly correspond to the acceleration and velocity capabilities of the robot. It will also impact the design of a gearbox as well play an important role the trajectory control loop. The possible motors to be used will range from 6-24 volts DC. A critical decision point is between brushed or brushless DC motors. With respect to the amount of torque that a motor is able to generate, the tradeoff to additional power is increased weight. Therefore in the selection of the drive motors the parameter to be optimized is the power to weight ratio. Overall, brushless DC motors have a much higher power to weight ratio compared to brushed motors. The primary drawback to brushless motors is that they tend to be more difficult to control and require additional circuitry. However, primarily based upon a much higher power to weight ratio, the brushless motor is recommended for this project.

With brushed motor, through direct contact with the commutator the brushes are responsible for the changing magnetic field that drives a DC motor. The brushless motor eliminates these brushes and instead the motor is rotated by varying the magnetic fields in a particular order by changing the state of multiple input leads. The required change in the magnetic field is determined by the current position of the rotor. The position of the rotor is determined by the use of Hall effect sensors. The Hall effect sensors will return either a logic high or low depending upon the orientation of the magnetic field. Coordination of these inputs and determining the required output requires a much more sophisticated electrical design than the brushed motors. More on these design needs is discussed in the electrical design section.

Having selected brushless DC motors, the next step in the design is the selection of the specific motor. The first step in the selection of the motors was the identification of the desired operating range of the motors. This was done using a simplified model of the four wheeled drive platform. This is shown in Figure 5 below:

F_1	Drive thrust provided by motor 1
F_2	Drive thrust provided by motor 2
F_3	Drive thrust provided by motor 3
F_4	Drive thrust provided by motor 4
F_R	Total forward thrust of the robot

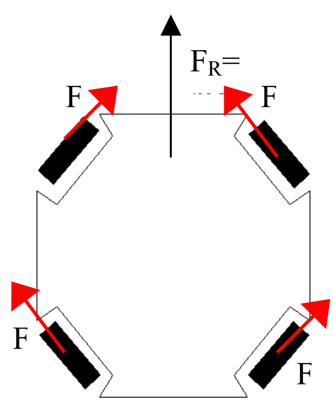


Figure 5: Simplified Omni-directional Model

The total forward thrust of the robot is the sum of the force generated by each of the drive wheels where the force of the wheel is product of the torque and the radius of the wheels. The target acceleration for the robot is $10m/s^2$. This target is above the performance capability of all robots in the competition, however designing with this goal in mind will provide a solid acceleration even with losses due to friction and other limiting factors. The equation used to calculate the max torque is shown below:

$$\tau = \text{sqrt}(2)/2 * m * a * R$$

τ	Motor torque (Nm)
m	Robot mass (kg)
a	Target acceleration (m/s^2)
R	Wheel radius (m)

Substituting the predicted values yields a maximum required torque of .4490 Nm. For the target motor speed, the calculation is similar. The equation used is shown below:

$$\Phi = V \cos 45 * (1/2\pi r) * 60$$

Φ	Motor speed (rpm)
V	Target velocity
r	Wheel radius

The target max velocity of the robot has been identified is 4 m/s. Therefore using the equation above, the required max speed of the motors is 1063 Rpm.

There are two primary suppliers of motors that teams in the past have used, Maxon motors (www.maxonmotor.com) and MicroMo electronics (www.micromo.com). Using the desired performance characteristics for the motors identified above, a set of candidate motors was identified. An additional constraint to motor selection is the length of the motor. Given that the robot must fit within approximately a 7” diameter cylinder, the motor length cannot exceed 2”. A total of 6 brushless DC motors were found. Using their torque/speed characteristics, the motors were plotted against the operating range with MATLAB. For each motor a gear ratio was applied that would best optimize the performance to fit the design targets. These plots are shown in Figure 6 and a summary of the performance characteristics of this set are shown in Table 2.

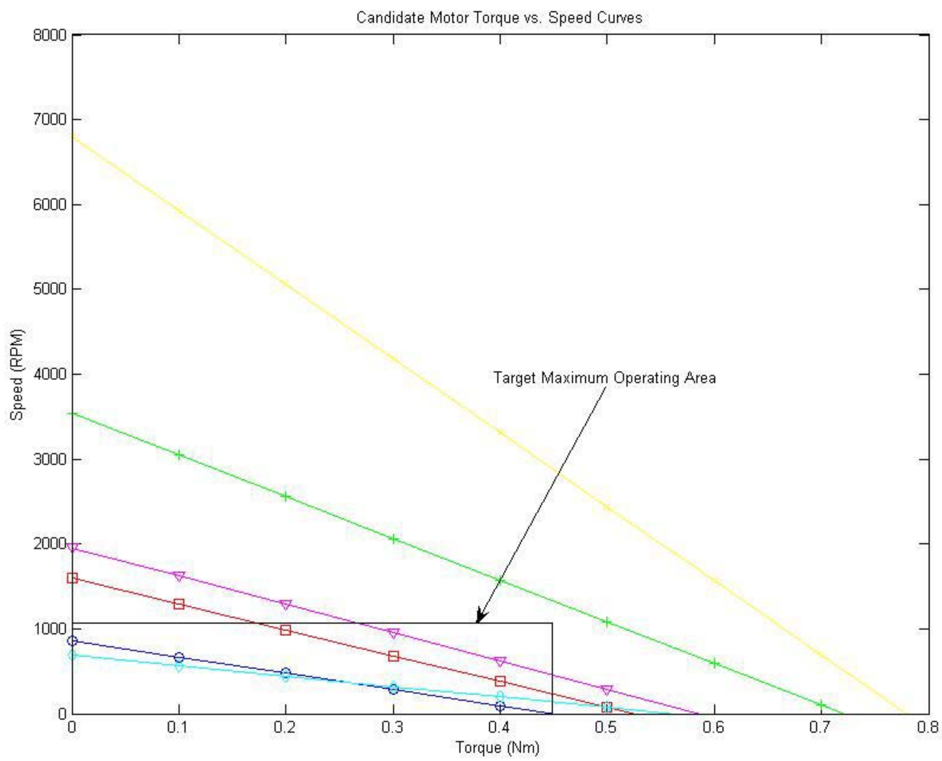


Figure 6: Motor Torque/Speed Performance Comparison

	Faulhaber 2036-012-B	Faulhaber 2444-024-B	Faulhaber 3056-012-B	Maxon EC 32-15W	Maxon EC 45-30W	Maxon EC 45-50W
Nominal Voltage (V)	12	24	12	24	12	12
Stall Torque (Nm)	0.02189	0.1109	0.09533	0.085	0.26	0.78
No-Load Speed (rpm)	17600	23000	8790	4500	4400	6600
Gear Ratio	20.55	6.5	5.5	5.244	5.25	1
Plot Color/Style	Blue -o-	Green -+-	Red –□-	Cyan -◊-	Magenta ▼	Yellow -x-

Table 2: Motor Specification Data

Based upon the results of this evaluation, there are two motors that meet the performance needs the Maxon EC 45 30 and 50W models. An additional advantage of the 50W motor is that there is no gear box required. With a 1:1 ratio, it is able to more the meet the desired operating range. The next step in the design of the drive system is the design of the control loop. This is discussed the electrical design section.

Motor Recommendation Summary

Maxon EC-45 50W

Supplier Name	Maxon Motors USA
Contact Phone	1-800-865-7540
Website	http://www.maxonmotorusa.com/
Part Number	251601
Estimated Cost	$75.15 each
Teams using product	2004 Cornell

Table 3: Motor Recommendation Summary

Wheel Selection

One of the key elements of an omni-directional drive system is the wheels. The wheel found on an omni-directional robot allow for rotation perpendicular to the axle as well as parallel to the drive axle. There are two wheel designs that are most commonly used in the RoboCup competition. The most common design is the dual-staggered roller (DSR) wheels. These wheels are commercially available through the Kornylak (http://kornylak.com/wheels/omniwheel.html) and are shown in Figure 7.

Figure 7: Kornylak Dual Staggered Roller (DSR) Wheels

DSR wheels use a total of 6 rollers that are mounted in a staggered configuration perpendicular to the drive axle. An important design concern is the material used for these rollers. Proper material selection will ensure a high coefficient of friction with the playing surface, maximizing the robot's traction.

A second design that teams in the competition have used is a single inline roller configuration, shown in Figure 8.


Figure 8: Single Inline Roller (SIR) Roller Wheel

This design again features rollers mounted perpendicular to the drive axle. Small rubber o-rings (not shown) are mounted to the independent aluminum rollers. This layout is a custom design that is based upon an initial design by the FU Fighters of the Free University of Berlin. Teams at Cornell and the University of Buffalo have developed their own designs based upon the SIR model. The main advantage of this design is that it is much more compact than the DSR wheel, allowing for much more space for the motors and gearboxes. An additional advantage is that these wheels provide greater traction on the playing field. The individual “cleats” allow the wheel to better grip the surface.

Of these two wheel designs, the SIR wheel will be able to provide the best performance. However for the Lehigh RoboCup team, it is recommended that the DSR wheels are used initially. The SIR wheels must be custom designed and this process may take a significant amount of time. The DSR wheels shown are commercially available and the cost is relatively low at $4-5 per wheel. Using the DSR wheel, a prototype robot can be developed much quicker and allow the team to spend more time working on other design issues rather that fabricating the wheels. However, it is recommended that, as a side research topic, the team investigate the design of a custom SIR wheel. The additional space gained by using the SIR wheel can allow for larger motors to be used, improving the overall performance of the robot.

Wheel Recommendation Summary

Kornylak Omniwheel 2.570

Supplier Name	Kornylak Corporation
Contact Phone	1-513-863-1277
Website	http://kornylak.com/wheels/omniwheel.html
Part Number	OMNI 2.570
Estimated Cost	$2.50 each
Teams using product	Technical University of Eindhoven, Cornell (2002), Ohio University, Carnegie Mellon

Table 4: Wheel Recommendation Summary

Dribbling Bar

The dribbling bar is the mechanical system responsible for ball control. It will be used to dribble the ball up the field as well as receive passes from other robots. Unlike the other mechanical devices, this system does not vary significantly among the RoboCup teams. The dribbling bar consists of a horizontal cylinder mounted to the front of the robot. A motor rotates the bar at a high speed imparting a back spin on the ball. This will allow the robot to maintain control of the ball when moving about the field. The key rules restriction is that the dribbling bar may not cover more than 20% of the ball.

An additional rule restriction in that the spin imparted on the ball must be perpendicular to the field surface. In past years many robots featured vertical or partially vertical dribblers in addition to the horizontal bar. The main function of these vertical dribblers was to allow the robot to maintain possession while strafing. With the elimination of vertical dribblers, many teams have devised new ways to control the ball during these maneuvers. Some of these include a notch at the center of the dribbling bar and an hourglass shaped horizontal bar. The notched dribbling bar design has an additional advantage of centering the ball on the kicking mechanism.

The main design consideration for the dribbling bar is the design of the dribbler face. The most common approach is a simple flat rubber face. The important decision is material selection. An ideal material for the bar has a high coefficient of friction with the ball, but is also soft to help soften the initial contact with the ball during passing or in loose ball situations. Some of the materials used include santoprene and sorbothane. It is recommended that the future team spend time to investigate the performance characteristics of several materials and select the one that best fits design.

A more advanced approach to the dribbling bar is to alter the shape from a standard cylindrical layout. Some of the ideas include a ramped shape or hourglass design that will funnel the ball toward the center of the kicking mechanism. The 2003

RoboRoos of the University of Queensland, Australia, team designed a corkscrew shaped roller face to help move the ball to a center notch. This mechanism is shown in Figure 9.

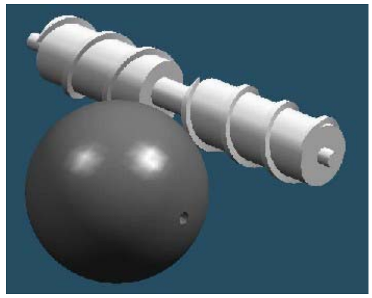


Figure 9: RoboRoos Corkscrew Dribbling Bar

One of the drawbacks identified was that in order to be effective, the roller must be operated at a lower speed. At lower speeds, less of a backspin is imparted on the ball, limiting the control of the ball. These alternative design have some merit, however it is recommended that the Lehigh team start with the standard cylindrical design.

An additional element of ball control is the ability to receive and intercept passes and pick up the ball in loose ball situations. A static dribbler wheel was found to knock the ball away rather than gain control. To overcome this teams have incorporated some form of a suspension mechanism for the dribbler bar. Shown in Figure 10 is a vertical “swing” suspension.

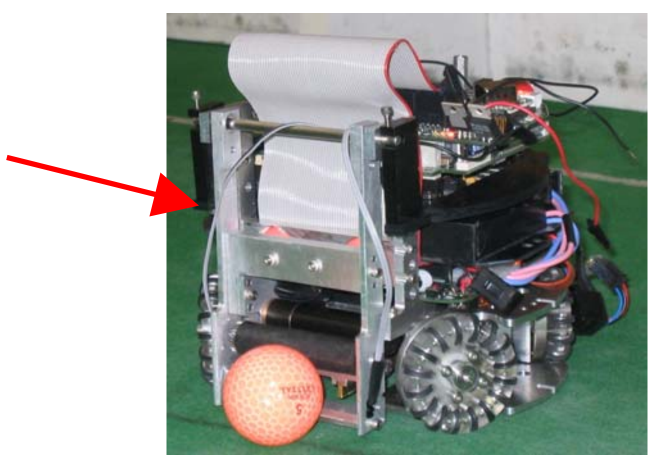


Figure 10: Cornell University 2005 Swing Suspension

Some form of suspension for the future team is recommended as it can greatly enhance the team's ability to maintain possession of the ball.

Kicking Mechanism

The kicking mechanism is one of the most important mechanical systems after the motors. A robust and efficient kicker will significantly enhance the team's ability to score goals and win in the RoboCup competition. The kicker is also the design component that seems to vary most across different teams. The kicking mechanism is typically mounted on the front of the robot below the dribbling bar. In the design of the kicking mechanism, there are three key design needs: velocity, accuracy, speed variation, recoil time, and repeatability. Note the speed variation criteria; this has been identified as one the most important qualities. Not only must the robot be able to take shots at a high velocity, but it is also desirable for the robot to be able kick at softer speeds with greater accuracy in passing maneuvers. Each of the design options should be weighed according to these categories. To meet these needs, both the selection of the actuator and the kicking surface are important. In this section several of the design options for the kicking mechanism are explored.

One of the more interesting approaches that have been explored by many teams is the use of CO_2 cartridges to propel a kicking bar. Such an approach has the potential to generate extremely high kick velocities but also allow for a broad range of variable speeds by limiting the CO_2 flow. However nearly all teams have disregarded this option because of logistical concerns. Because of travel restrictions, the cartridges would have to be purchased locally, an unwanted problem for international competitions. An additional concern is the limited number of shots that a robot would be able to take during a match. When the cartridge had fully discharged, a team would not be able to recharge or replace empty cartridges until the end of the match.

Another approach is the use of a spinning bar or paddle that strikes the ball. One of the teams that have taken this approach is the FU Fighters of the Free University of Berlin. Their 2003 robot and kicking mechanism is shown in Figure 11.

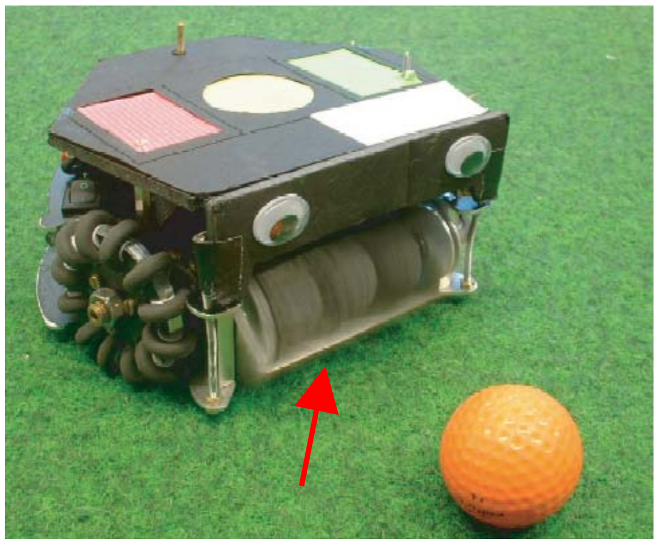


Figure 11: F.U. Fighters Rotating Kicker

For their design, an aluminum bar rotates about the dribbling bar, striking the ball below the dribbler. The kicker is driven by a DC motor and is able to achieve high velocities. The main disadvantage associated with this approach is that the kicker must first accelerate to a sufficient speed before it can strike the ball. There is also limited control over the accuracy of the shots or passes.

One of the most common approaches is the “crossbow” design of the kicking module. In this design, the kicking surface is mounted to either a set of springs or some other elastic material. A single DC motor “cocks” the kicker back and locks it into a loaded position. When the microcontroller gives a “kick” command, that same DC motor releases the striker which kicks the ball. One of the teams that utilizes this mechanism is the University of Queensland RoboRoos. Their system is shown in Figure 12.

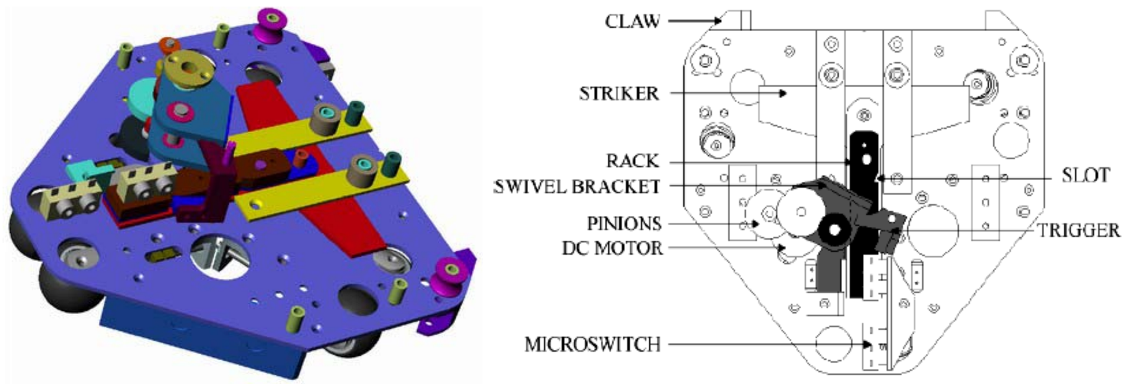


Figure 12: RoboRoos' Crossbow Kicker

Using the crossbow kicker, the RoboRoos are able to generate both high velocity shots at approximately 5 m/s as well as softer kicks at approximately 2 m/s. The primary concern with the crossbow approach is the complexity of the system. Within the mechanism, there are several moving parts. Each of these components is a potential failure point during the competition. Loss of the ability to kick severely cripples a robot. Additionally, there is limited control over the kick speed. The RoboRoos' kicker only has two speed settings, hard and soft. In the competition, it would be desirable to have a much broader range of speeds so that the robot can adapt to many game conditions.

The fourth, and perhaps the most common, kicker design is the solenoid actuator. In this design, a high powered solenoid drives an aluminum kicking plate at variable speeds. This is the kicking module that the successful Cornell Big Red team has used on their robots during their championship runs. The kicking module used on the 2003 team is shown Figure 13:

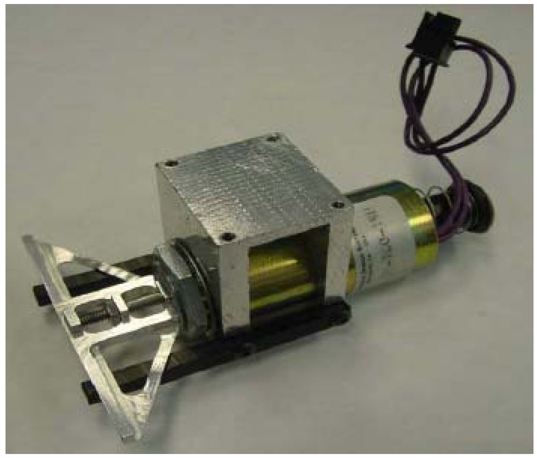


Figure 13: Cornell Solenoid Kicker

The solenoid is driven by at 110V input that comes from an additional DC-DC converter circuit. This additional circuit converts the 12V battery power supply into the required 110V. Also note the black guide rails. These are used to provide additional stability for the kicker as it actuates. This significantly helps to improve the overall accuracy of kicks. With their design, the Cornell team was able to achieve maximum kick velocities of 4-5 m/s. By changing the power input, the team was also able to achieve a broad range of softer kicks.

For the future Lehigh team, the solenoid actuation approach is recommended. The solenoid actuator is able to provide high kick velocity yet also be scaled back to produce softer kicks. Overall the solenoid module is a much simpler and robust design than the crossbow kicker. It will be much easier for the team to integrate this kicker into the first generation of Lehigh RoboCup robots. The recommended solenoid for the mechanism is the S-20-150 series from Solenoid City. This solenoid is comparable to that used on several of the other teams in RoboCup competition. The design of the kicker bar should be developed by the future Lehigh team. One of the key design issues identified is that the kick face must remain as rigid as possible. Note the webbed design on the Cornell kicker bar. This provides additional support away from the center axis. In past teams it was found that during kicks, the kicking face flexed, resulting in deviation from the intended kick direction.

Future research for the team should include investigation into the development a chip kick capability. The 2004 Cornell team successfully implemented a kicker that was able to loft the ball into the air and clear a robot up to 150 mm away. A small DC servo motor was used to adjust the angle of the kicker downward, increasing the vertical thrust imparted on the ball during impact. Such a mechanism greatly enhances the abilities of the team, especially on defense. For example, a robot defender could take a loose ball in its own half of the field and clear it deep into the opposing team's end of the field.

Kicking Mechanism Recommendation Summary

S-20-150-H D-Frame Push Type Solenoid

Supplier Name	Electromechanics Online
Contact Phone	1-818-785-6244
Website	http://www.electromechanicsonline.com/
Part Number	SOODH030052
Additional Information	http://www.solenoidcity.com/solenoid/openframe/OpenFrameCatalog.pdf
Estimated Cost	$28.42 each
Teams using product	Cornell (2003-2004), University of Buffalo

Table 5: Kicking Mechanism Recommendation Summary

Chassis Design

The goal of the chassis design is efficiently use the limited space of the robot. As stated in the "Rules Outline" section, each robot must fit within a 180mm diameter cylinder and is limited to a maximum height of 150mm for global vision robots. The chassis must incorporate mountings for the motors and wheels, dribbling mechanism, circuit boards, and kicker. Use of a CAD program to layout the robot and its equipment is strongly recommended. The main body of the chassis is typical machined from aluminum; however some robots have used plexiglass as all or part of the body. In either case the goal is to minimize the total weight of the robot. It is also desired to lower the center of gravity. This will help to eliminate the risk of tipping and reduce the effects of mass transfer. The overall design of the chassis must be sturdy, provide easy access to make adjustments to the robot components, and be easy to disassemble/reassemble.

Electrical System Design

The electrical system of the robot is essentially its central nervous system. The electrical system receives commands from the off-board coach computers and activates the appropriate mechanical systems. The electrical system is also responsible for acquiring sensory feedback from those mechanical systems and making adjustments as necessary. Discussed in this section are the components that make up the electrical system and their functions. Additionally recommendations for the future system are outlined.

Microprocessor

The microprocessor can be thought of as the brains of the robot. Each of the mechanical devices, including the drive motors, dribbling mechanism, and kicking modules, are controller by the microprocessor. Additionally, it is responsible for monitoring sensory inputs such as the accelerometers, gyroscopes, and ball positioning sensors. The wireless communication subsystem is also managed by the chip. The selection of the microprocessor depends upon the overall design architecture. Robots in the F180 league typically fall under two classifications: centralized intelligence and distributed intelligence.

Centralized intelligence is the most common approach taken by teams. In this architecture, the vision data is processed by a centralized "coach" computer. This computer extracts the robot and ball positions from this data and applies the high level game strategies. The computer generates the course of action for the robot team and transmits these action commands to each robot via the wireless communication system. The microcontroller receives these commands from the off-board "coach" and activates the appropriate mechanical system. The microcontrollers typically used in the centralized intelligence include Motorola 68HC series and the Microchip PIC series. These microcontroller are fully programmable, but have relatively limited processing power. This family of microcontrollers is fully capable of controlling the functions of the robot, however is not able to perform the higher level game strategies, therefore requiring an off-board computer. A more advanced approach is to employ a more advance microprocessor with much greater processing power.

In the distributed intelligence approach, demonstrated by the 2004 Cornell RoboCup teams, a more advanced microprocessor with much higher processing power is used to transfer the game control strategies to the individual robots. The vision data is still processed by an off-board computer and the robot positions and current trajectories are extracted, however this data is then sent directly to the robots. The onboard microprocessor will then take this data and apply the game strategy algorithms and activate the appropriate mechanical systems. The microprocessor used for this approach is the PC104/PC104+ single board computer. The PC104+ boards utilize a 200-300 MHz Pentium class chip. Crudely compare to the 20-40 MHz speed of the microcontroller discussed above, the processing power of the PC104+ is a significant upgrade.

PC104/PC104+ is a relatively new technology designed for embedded systems. From an architecture standpoint, these boards are similar in design to a PC computer or laptop. The PC104 technology retains much of the functionality of these systems; however it is contained within a single printed circuit board. These microprocessors are capable of running the Windows CE operating system from Microsoft, which is typically found on many PDAs and handheld computers. The PC104 modules also offer many other standard PC features, such as dual RS232 ports, USB capability, onboard Ethernet, video, and keyboard. Additional information on the specifications and distributors of PC104 boards can be found at www.pc104.org and www.pc104.com.

The advantage of the distributed intelligence approach is that it removes much of the latency in a robots reaction to sudden changes in the field conditions. The distributed intelligence approach present several additional challenges. With a central intelligence approach, there is a single computed employing the game strategy. Therefore it is much easier to coordinate the actions of the robots as a single unit. Distributed intelligence therefore requires additional inter-robot communications to coordinate their actions. An additional disadvantage of the PC104/PC104+ boards is that the board is not able to accept analog/digital input and outputs in the same manner as the microcontrollers. An additional digital I/O as well as an additional analog board is required to interface the microprocessor with the mechanical systems. Because of these added complexities of the distributed intelligence approach, the centralized intelligence approach is recommended for the initial Lehigh RoboCup team. The microcontrollers offer much more of a "plug and play" situation that would be beneficial to a team with limited experience in the RoboCup competition. Experience with the simpler microcontrollers will help to give the team the additional background necessary to develop a design using the more complicated distributed intelligence approach. The eventual goal for the team should be to shift to a distributed intelligence approach because that is the first step toward the overall goal of a team of completely autonomous robots. The next section outlines the selection of an appropriate microcontroller for the centralized intelligence approach.

The selection criteria for the microcontroller are listed below:

- 20-40 MHz process or speeds
- 16-32 bit data paths
- 4+ pulse-width modulation (PWM) outputs
- 32kB + flash memory
- 5+ external interrupts
- 40+ I/O pins
- 5+ timers
- 2+ hardware serial ports
- 4 + channels A/D conversion

These desired characteristics are based upon approximately performance requirements identified by past RoboCup teams in their literature. Based upon these requirements, several commercially available microcontrollers were identified. A comparison of the available microcontrollers is shown in Table 6.

	PIC16	PIC18	ATMEL	HCS12
Maxiumum Frequency	20	40	33	25
Internal Datapath	8 bit	8 bit	32 bit	16 bit
Flash Memory	8k	16k	n/a	256k
Timers	3	5	6	8
PWM Outputs	2	5	12	8
Serial Ports	1	3	4	2
A/D Channels	8	12	8	16
External Interrupts	4	4	7	12
I/O Pins	34	68	147	91

Table 6: Microcontroller Comparison

Of the available microcontrollers, the best fit, based upon the design criteria, appears to be the HCS12 microcontroller. Of that family, the specific product number is MC9S12DG256 and is available from Freescale (www.freescale.com). This microcontroller offers a good balance of speed and functionality.

In the past, many teams in the RoboCup competition have custom designed their own circuit boards. For the initial Lehigh team it is recommended that the team use a commercially available development board to mount the microprocessor. Though there is a much higher cost associated with using a commercial development board, the team will save a significant amount of time by avoiding the custom design and etching of a circuit board. Note though teams often custom design their own printed circuit layouts due to space restriction, the recommended development board fits well within space constraints. Of the available development boards for the HCS12 microprocessor, the recommended board for this project is the HCS12 T-Board from Elektronik Laden, shown in Figure 14.

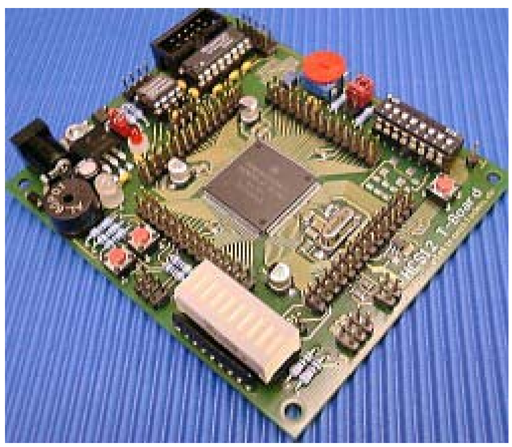


Figure 14: HCS12 T-Board

The development board will allow the team to easily interface the mechanical, communication, and sensory systems with the microprocessor. For this particular board there is also a significant amount of support documentation and development tool available.

Microprocessor Recommendation Summary

Elektronik Laden HCS12 T-Board featuring MC9S12DG256 microprocessor

Supplier Name	iMAGEcraft
Contact Phone	n/a
Website	http://www.imagecraft.com/software/orderhardware.html
Part Number	HCS12 T-Board
Additional Information	http://elmicro.com/en/hcs12tb.php, http://www.freescale.com/
Estimated Cost	$175.00 each
Teams using product	Cornell (2003)

Table 7: Microprocessor Recommendation Summary

Battery Selection

An actual RoboCup match consists of two ten-minute halves for a total of twenty minutes of game play. During that time the robot will be quickly accelerating, dribbling, and kicking repeatedly, requiring a large amount of energy. According to one estimate, the current drain at any time approaches 20A. A robust battery system is required to endure the entire match. The final number and layout of batteries needed for each robot will be determined by the final team. In this section the selection of the type of batteries to be used will be explore.

As mentioned above, the most important design consideration is the lifetime of the batteries. In 2004, the Cornell team did a comprehensive investigation of available batteries. The summary of the batteries in that report is reproduced in Table 8.

Type	**Voltage/cell**	**Capacity** (available)	**Cyles**	**Weight/cell**	**~Cost/cell**	**Weight/robot**	**~Cost/robot**
Zinc Carbon	1.5 V			9g-99g			
Lithium Polymer	3.7 V	300-8000 mAh	500	25 g	$15	300g	$150-500
Nickel Metal-Hydride	1.2 V	550-7000 mAh	500	8g-160g	$4	800g	$50-250
Nickel Cadmium	1.2 V	500-1100 mAh	1000	23 g	$4	2200g	$50-100
Lithium Ion	2-4 V	180-5000 mAh	400	6-45 g	$20	500g	$200-$500

Table 8: Battery Comparison Chart

The Zinc-Carbon batteries were eliminated immediately because the number of batteries that would have to be used in series would be impractical to support the current draw of the robot. Additionally the Ni-Cd and Ni-MH batteries were eliminated because of weight concerns. The Li-ion and Li-poly batteries were both identified as viable options for the robot. In their final design they chose Li-poly batteries because relative to the Li-ion they were lighter and cheaper, but still able to meet the performance needs. Refer to the 2004 Cornell electrical design documentation for additional information on the Li-poly battery including drain curves. The final design for that Cornell robot used four sets of three batteries connected in parallel for a total of 12 batteries. However as discussed above, the team must determine the final configuration based upon the needs of the final robot design.

Battery Recommendation Summary

Litihum Polymer Batteries

Supplier Name	UltraLife Batteries
Contact Phone	1-315-332-7100
Website	http://www.ulbi.com
Part Number	UBC425085
Additional Information	http://www.ulbi.com/techsheets/UBI-5127_UBC425085.pdf
Estimated Cost	$15.00 each
Teams using product	Cornell (2004)

Table 9: Battery Recommendation Summary

The Motor Control Loop

The use of brushless DC motors presents several challenges in the operation and control of the motors. As stated earlier, the brushless motor is operated by changing the magnetic field in a circular motion. The next position in the sequence is determined by the state of the Hall effect sensors. Table 10 lists the necessary motor inputs as a function of the state of the Hall sensors.

Hall 1	Hall 2	Hall 3	Motor A	Motor B	Motor C
1	0	1	V_{batt}	Ground	High Z
1	0	0	V_{batt}	High Z	Ground
1	1	0	High Z	V_{batt}	Ground
0	1	0	Ground	V_{batt}	High Z
0	1	1	Ground	High Z	V_{batt}
0	0	1	High Z	Ground	V_{batt}

Table 10: Motor Inputs by Hall Sensor State

In order to apply these inputs to the motor, the design uses half H-bridges to control each of the three inputs. A half H-bridge is simply two transistors contain within a single dual inline package. One transistor controls current flow from the battery and one controls current flow to ground. Therefore, when the top transistor is on the motor input sees battery voltage, when the other is on the input sees ground, and when both are off it sees high impedance. This will allow gate signals to control the motor inputs indirectly.

In order to control the sequencing of logic necessary to control the H-bridges as well as receive the feedback from the Hall sensors, an additional chip is required. A device used effectively in the recent Cornell designs is a fully programmable gate array (FPGA). The microcontroller receives trajectory commands from the central intelligence computer and then determines the required motor output levels. The characteristics of the PWM signal for the motors is determined by the microcontroller, however it is the FPGA that does all of the logic manipulation and generates the actual PWM signals for motor control. In selecting the FPGA for this application, the main goal is to find the smallest chip that has the minimum number of I/O pins needed. The 2003 Cornell team uses the EPM7160STC100-7 FPGA from the Altera Max 7000. Their electrical system approach is similar in many ways to the planned Lehigh approach so this chip should sufficiently fit the design needs.

The omni-directional drive architecture that will be used for the Lehigh team requires a significant amount of feedback to properly adjust the motor speeds as necessary to ensure the desired trajectory is taken. That trajectory will be communicated to the robot from the central coach computer. The microcontroller will then control the motors accordingly. Conceivably, it is possible to provide feedback on the motor heading from the global vision system. However, there is an inherent delay in the processing of that data, making a direct measurement more effective. In the control of the motors, one of the key feed back elements is the current velocity of the motors. This can be accomplished using the Hall sensors; however at 48 counts for revolution, the resolution is not high enough to achieve the level of control desired. The desired resolution is at least 1000 counts per revolution. To accomplish this, the recommended encoder is the ED-15 series from encoder devices (www.encoderdevices.com). This encoder can be manually mounted to the back of each motor and offers 4096 counts per resolution, far exceeding the design needs.

The ED-15 encoders will output a quadrature encoding signal that can be used to extract the rotational speed of the motor. To decode the quadrature signals, the FPGA discussed above will also be used. The FPGA will then send the velocity data back to the microcontroller which will compare this to the desired velocity set-point and adjust the motors accordingly. In addition to the encoder signals, both an accelerometer and rate gyroscope sensor will be used to give trajectory feedback data. The ADXL203EB dual axis accelerometer from Analog Devices (www.analog.com) outputs a two analog voltage signals which corresponds to the acceleration in the x and y directions. Based upon these two signals, the microcontroller can determine the relative heading of the robot. The ADXRS300EB rate gyroscope outputs a single analog voltage signal that corresponds to the rate of rotation of robot about its center axis. The uses of these two additional sensors will significantly help to stabilize the control of the robot as well as help to reduce the error between the planned path and actual path.

Motor Control Design Recommendation Summary

L6203 H-Brige

Supplier Name	Digikey
Contact Phone	1-800-344-4539
Website	http://www.digikey.com
Part Number	L6203
Estimated Cost	$10.29 each
Teams using product	Cornell (2002-2003)

Table 11: H-Bridge Recommendation Summary

Altera 7000 Max Series FPGA

Supplier Name	Arrow Electronics
Contact Phone	1-800-777-2776
Website	http://www.arrow.com
Part Number	EPM7160STC100-7
Additional Information	http://www.altera.com/products/devices/max7k/m7k-index.html
Estimated Cost	$15.00 each
Teams using product	Cornell (2004)

Table 12: FPGA Recommendation Summary

ED-15 Digital Encoder

Supplier Name	Encoder Devices
Contact Phone	1-757-766-1500
Website	http://www.encoderdevices.com
Part Number	ED-15A-1024-1
Estimated Cost	$25.00 each
Teams using product	Cornell (2004)

Table 13: Encoder Recommendation Summary

Analog Devices Dual-Axis Accelerometer

Supplier Name	Analog Devices
Contact Phone	1-800-262-5643
Website	http://www.analog.com
Part Number	ADXL203EB
Estimated Cost	$29.95 each

Table 14: Accelerometer Recommendation Summary

Analog Devices Single-Axis Rate Gyroscope

Supplier Name	Analog Devices
Contact Phone	1-800-262-5643
Website	http://www.analog.com
Part Number	ADXRS300EB
Estimated Cost	$50.00 each

Table 15: Gyroscope Recommendation Summary

Wireless Communication

Due to the limited processing power of the microcontroller, the robots are dependent upon the central computer to be told where to move. In order to react to rapid changes in the game conditions, it is an important design consideration to minimize the time it takes from data to be transferred from the “coach” computer to the robot team. The system that facilitates this process is the wireless communication scheme. The most common mode of wireless communication is through radio transmission in the 400-800 Mhz bands. However there are more advanced approaches that some teams have taken such as 802.11 and Bluetooth communication methods. It should be noted that as of the 2004 competition, use Bluetooth communication is prohibited. The 802.11 wireless system offers much greater capacity and speed that the RF communication, however it would be more difficult to implement. The recommended approach is to implement the RF communication and to reconsider the 802.11 for future design, especially those that will incorporate the PC104/PC104+ board.

According to the F-180 rules each team must be equipped to communicate over at least two channels. The most commonly used RF communication modules are either the TX/RX2 or TX/RX3 wireless modules. The TX2/RX2 operates in the 433 MHz Band as well as the 418 MHz band. These modules offer many distinct advantages including:

- Higher Bandwidth (160 kbps)
- Small Physical Footprint
- Low Latency (less than 4ms)
- Easy to operate with Serial RS232 interface
- 5V logic device
- Useable range 300m

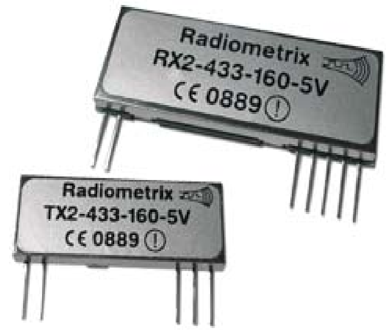


Figure 15: TX2/RX2 Modules

The TX3/RX3 modules are almost identical to the TX2/RX2 modules, but operate at 869 MHz and 914 MHz. These modules will be used a backup to the TX2/RX2 modules, as they do not offer quite all the advantages of the other pair.

These modules feature:

- Medium Bandwidth (64 kbps)
- Small Physical Footprint
- Low Latency (less than 4ms)
- Easy to operate with Serial RS232 interface
- 5V logic device
- Useable range 120m
- Almost identical footprint to TX2 RX2 modules

Figure 16: TX3/RX3 Modules

It is recommended that the team use the TX2/RX2 modules as the primary system as it offers a higher bandwidth a greater usable range. Because the TX3/RX3 modules are nearly identical in both construction and implementation, they can be used a backup system.

Wireless Communication Recommendation Summary

RadioMetrix TX2/RX2 Radio Communication

Supplier Name	Intec
Contact E-mail	sales@intec-group.co.uk
Website	http://www.intec-group.co.uk/radio_application.htm
Part Number	RS232-TX2-8CH/ RS232-TX2-8CH
Additional Information	http://www.radiometrix.com, http://www.intec-group.co.uk/radio_application.htm
Estimated Cost	$124.00 each
Teams using product	University of Queensland, University of Berlin

Table 16: Wireless Communication Recommendation Summary

Vision System

In the F180 league, there are two approaches taken to the vision system design. The first, and by far the most common is the global vision approach where images are captured by an overhead camera, processed, and commands are sent to the robot team. It should be noted that each of the winning teams in the history of RoboCup has used a global vision approach. However an emerging area of research is the implementation of a local vision system, where each robot is on the field is equipped with a camera and uses that data to act independently from other robots on the field. For the Lehigh team it is recommended that the global approach to vision be taken with future research into local vision system. Based upon the available equipment and the wealth of information available on global vision systems, the global approach will be the easiest for the first Lehigh team to implement.

The design of the global vision system has three primary components. The overhead camera(s) captures images of the playing field and outputs a streaming video signal; the frame-grabber breaks the streaming video signal down into single frames at a rate of around 60 frames per second (fps); the centralized intelligence computer receives the frames from the frame-grabber and applies an image processing algorithm that breaks that identifies color pixel concentrations. This data is then used to determine the position of the robots, the ball, and the opposing robot team. Using the position data, the game strategy algorithm is applied and trajectory data is passed along to the robot team. A sample image taken from an overhead camera is shown in Figure 17.

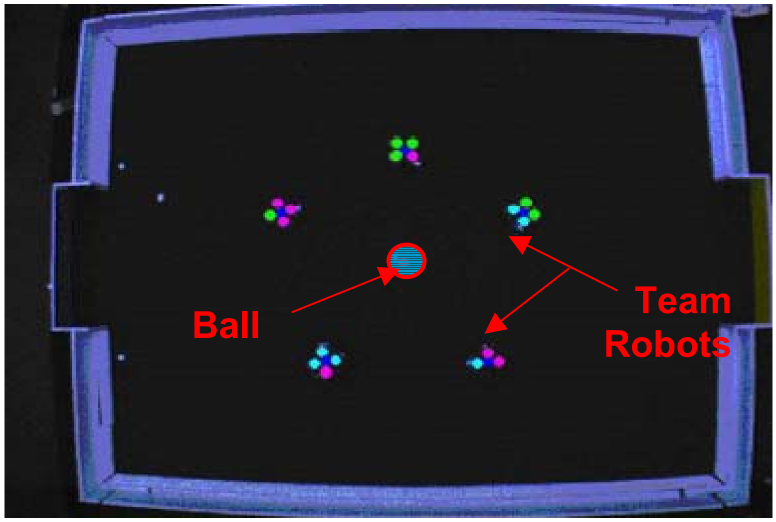


Figure 17: Global Vision Screenshot

There are several approaches taken to the selection and positioning of the overhead camera. Many teams use multiple cameras to gather a complete view of the field. For example, the 2003 Cornell team used a main overhead camera to track the robots on the field while two auxiliary cameras were used to track the ball. One of the difficulties that arises is locating the ball when it is next to or between several robots. Multiple cameras provide redundancy in the vision system, helping to ensure that the position of the ball is known at all times.

It is recommended, at least initially, that a single camera is used for the future team. It will be necessary to gain experience with the image capture process before moving on to a more advanced vision approach. The cameras used for the global vision approach are color charge-coupled device (CCD) cameras most commonly used for surveillance and security. The Pulnix TMC-6700 camera has been used by several teams in past competitions. This camera should be a good starting point for the team. At

Figure 18: Pulnix TMC-6670

approximately $450, it is a much cheaper alternative to some of the more advanced cameras. For example, the DCX-9000 camera from Sony used in the 2004 Cornell vision system costs over $5000. The primary advantage of such a camera is that the Sony camera contains three CCDs to capture images of the field. Each of these CCD is combined into one single output that provides greater definition, especially for moving objects. In the future it may be desirable to move on to more advanced camera, however for this first team, simpler is better.

The frame-grabber used to extract the individual frames from the streaming video signal is fairly standard across teams. The most commonly used device is the Matrox Meteor II frame-grabber from Matrox Imaging (www.matrox.com). This is a PCI device that is mounted to the centralized intelligence computer.

Figure 19: Matrox Meteor II

The final component of the vision system is the centralized computer. The computer used to run the intelligence algorithms varies significantly from team to team. Some of the more common features include a 2GHz + Pentium Class processor with 1 Gb+ RAM. It is recommended that the team research and select the best available product at the time.

Vision System Recommendation Summary

Pulnix TMC-6670 Progressive Scan CCD Camera

Supplier Name	Pulix
Contact Phone	1-800-445-5444
Website	http://www.pulnix.com/Imaging/i-sales.html
Part Number	TMC-6700
Estimated Cost	$449.00 each
Teams using product	Cornell (2003)

Table 17: Camera Recommendation Summary

Matrox Meteor II Frame-grabber

Supplier Name	Courier Tronics
Contact Phone	518-279-9500
Contact E-mail	info@couriertronics.com
Additional Info	http://www.matrox.com/imaging/products/meteor2/home.cfm
Part Number	Matrox Meteor-II
Estimated Cost	$995.00 each
Teams using product	University of Berlin, Yale University, Cornell

Table 18: Frame-grabber Recommendation Summary

Cost Outline

Based upon data presented in past teams' literature as well as information obtained from the various suppliers the total cost of the design presented in this report is $20,719.30. The breakdown of this figure by part is shown in Table 19. This estimate is based upon the goal of developing two teams of five robots for a total of ten robots. Note that this estimate may change depending upon the need to purchase spare parts or build substitute robots in the event that one robot fails.

Part	Supplier	Part Number	Unit Cost	Qty. Per Robot	Cost per Robot	Cost per Team
Motor	Maxon	EC-45 50W	$75.15	4	$300.60	$3,006.00
Wheels	Kornylak	OMNI 2.570	$2.50	8	$20.00	$200.00
Solenoid	Solenoid City	SOODH030052	$28.42	1	$28.42	$284.20
Dribbling Bar	In-House	n/a	$40.00	1	$40.00	$400.00
Chassis	In-House	n/a	$50.00	1	$50.00	$500.00
Batteries	UltraLife Batteries	UBC425085	$15.00	12	$180.00	$1,800.00
MicroController	Freescale	MC9S12DG256	$200.00	1	$175.00	$1,750.00
Wireless Transmitter	Intec	RS232-TX2	$124.00	1	$124.00	$1,240.00
FPGA	Altera Max 7000	EPM7160STC100-7	$61.00	4	$244.00	$2,440.00
Gyroscope	Analog Devices	ADXRS300EB	$50.00	1	$50.00	$500.00
Accelerometer	Analog Devices	ADXL203EB	$29.95	1	$29.95	$299.50
Encoder	Encoder Devices	ED-15	$25.00	4	$100.00	$1,000.00
H-Bridge	DigiKey	L6203	$10.29	4	$41.16	$411.60
Camera	Pulnix	TMC-6700	$449.00	0.2	$89.80	$898.00
Host Computer	t.b.d	t.b.d.	$2,000.00	0.2	$400.00	$4,000.00
Frame Grabber	Matrox	Meteor II	$995.00	0.2	$199.00	$1,990.00
					Total	$20,719.30

Table 19: Cost Outline

Summary

Presented in this report is the conceptual design of a robot for competition in the F-180 league of the RoboCup competition. Note that the primary focus of the investigation is the identification of the ideal components necessary to build a competitive team. The main challenge of the future Lehigh team will be to integrate each individual subsystem to for a whole robot. A team cannot succeed in the RoboCup competition on mechanical or electrical superiority alone; rather it is the team that is able to meld the electrical, mechanical, vision, and computer science elements into a single robust system.

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