2003 Cornell RoboCup Documentation

Mechanical Group Final Documentation

Presented to
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May 1st, 2003

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Abstract

The RoboCup Initiative is an international research group whose aims are to promote the fields of Robotics and Artificial Intelligence. Through the integration of technology and advanced computer algorithms, the goal of RoboCup is to build a team of humanoid robots that can beat the current World Cup champions by the year 2050. Currently, the Cornell team participates in the small sized league which is just one of the many different size leagues in RoboCup. The project requires a team of students and researchers to develop a team of fully autonomous soccer playing robots. The team must follow a stringent set physical size rules as well as follow the governing rules of soccer (FIFA). Once a year, the team will participate in an international competition and symposium.

Following in the success of the 2002 Cornell RoboCup team, the 2003 Mechanical team has focused its energies to the development of more refined and improved systems for the new generation of the Big Red Bots. Looking at the weaknesses exhibited in the past years work, the teams has been able to implement several new features and designs for this year,

The following document will first review the system level organization and structure of the Cornell RoboCup Team. It will outline the development of the system level goals, the subsequent evolution of the Sub-Group goals and the creation of project methods and processes. In addition, the organization and structure of the 2003 Mechanical design team will be presented.

Most importantly, the document contains the chronological design process that each mechanical subgroup followed to arrive at a complete subsystem design. This document will not only contain all the work done prior to the design of the 2003 robots, but also all the design work, the testing, and the results of the final robot. In addition the document contains the integration of the three subsystems into a complete robot. Finally the documentation will cover the fabrication of the 2003 robot. This document fully chronicles the steps that were followed by the Mechanical design team from the initial group formation to the final fabrication of the 2003 robot.

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Executive Summary

The 2003 mechanical design team was challenged early in the year with the task of making a better performing robot than the ones that competed in 2002. Each year, this task has gotten increasingly difficult as improved design practice, more efficient machining methods, and previous research has made each revision of the robot better. In addition the other competing teams have dramatically improved their robots annually, thereby forcing the mechanical team to stay one step ahead of the competition. The Cornell team aims to defend its championship once again by winning with a sound mechanical robot, electrical design and artificial intelligence.

The team began the year getting to know the system. Spending the time learning the system and understanding the things have been done in previous years has lead to the improvements that were made on the 2003 robots. The team spent several hours watching game film trying to understand the flaws and limitations of last years design. In addition a hands-on approach made the team learn, through the maintenance of the 2002 robots, how each subsystem related to another and more importantly the how to implement a modular design approach. The mechanical team was then broken up into smaller sub-groups which then worked on their own part of the mechanical robot.

From the systems level, a set of goals were developed and passed to team of the technical teams (EE, SE and ME) the mechanical teams the goals aligned well with what each subgroup observed and found necessary to improve. The first semester was spent exploring new concepts though applications of analysis and prototype testing. Some of the ideas explored included frictional effects on the wheels, motor analysis, and solenoid power tests. The first semester concluded with the majority of the testing concluded except for a couple of tests that still needed to be finished after winter break.

The mechanical team the proceeded to the Design phase of the project, the conceptual idea of the robot was modeled in Pro-Engineer. Each sub-team fully designed their subsystem to be modular and as compact as possible. The team passed space requirements and design

information many times. The design was iterated and presented to the other Functional groups for a critical design review and commentary.

With a complete design the mechanical team began to fabricate the first 2003 robot. This prototype was the most complex robot ever designed by the RoboCup team. An extensive use of the CNC machine was necessary to fabricate this robot. Even though the robot was complex, the assembly proved to be quite simple as the number of parts had been reduced. The First robot was finally completed and the testing phase began. Each sub-group tested their part of the new robot and has made the necessary revisions to their design. The robot has now been fully tested and is ready to be mass produced.

1 System Engineering Documentation

The RoboCup project is classified as a system Engineering Project. The project requires the cooperation and organization of three distinct fields. The complexity and the interconnection issues between the fields necessitate the use of system engineering tools. In addition, the truncated time table forces the necessity of efficient scheduling and project management.

As in years past, the 2003 RoboCup team uses a Systems Engineering approach to the design process. With many students from vastly different backgrounds it is imperative that the groups are able work seamlessly together. The complexity of the task involved requires an excellent communication system and it is therefore evident that the Systems Engineering Design process aids in not only the quality of the work but also the success enjoyed by this project.

1.1 System Engineering Process

The goal of systems engineering is to not only help develop the end product arrive with all the requirements met and within a reasonable time frame, but also to define the scope of the project's function and its market. One of the major problems with trying to optimize a project is the triple constraint in money, time, and performance. Cornell RoboCup is no different; the project not only runs on a tight time schedule, but also must deal with the issue of the performance of the system relative to the overall cost of the system. While facing these constraints, system engineers need to be able to quickly assess the available information given and make a proper decision to best help the project. While keeping the considerations of time, money and performance the system engineer is required to establish the set goals and methods followed by the team. Luckily, throughout the past five years, the Cornell RoboCup team has been able to slowly instate several methods from a systems engineering process.

This year, the team applied a modified System Engineering process. This process has broken up the project into several distinct phases that are achieved in the process of the completion of the project. The simplified process is illustrated below.

During the project initialization, the project manager must create a set of guidelines and processes that the project will follow. The project initialization will establish the pace and the tempo the project will follow. The project then progresses to the identification of a set of goals and requirements. This is done by assessing the available information. After the requirements and goals have been defined, the project moves into the preliminary design phase. In the preliminary design phase the team members will develop structural and behavioral models. The models will then undergo a set of risk and trade-off analyses. The potential benefits are weighted against the possible risks and costs incurred. During the project implementation phase, the potential product undergoes an iterative set of tests. The product is monitored with the aim of identifying any major problems that may occur during the lifetime of the system.

1.1.1 Project Initialization

Since the RoboCup project runs on a truncated time schedule, the project needs to get started very quickly. The lab processes and team organization should be established before the team selection process. The setup and processes developed for the 2003 RoboCup team are outlined below.

1.1.2 Lab Setup and Use

Lab space has always been an issue for the RoboCup team. The proper usage of the lab is critical to the overall efficiency of the lab. This year we had the ability to move into a second room, Upson 226.

Originally this plan was meant to move the design of the robots away from the playing field. The motivation behind this idea was to prevent half completed designs and tests. It would force the tests to become more rigorously defined before they were actually run. Secondly, it was meant to clean up the lab such that it could be a showroom where only the RoboCup system would be run and tested by the Software engineering team. However the problem was that the second room was never really utilized. The mechanical team found it awkward to be so far way from the tools and the actual robots when tests and or measurements were necessary. More importantly, the primary goal of the second room was to do design and analysis away from main RoboCup lab. This never really happened because the analysis was done while the data was being taken. Moreover, the mechanical engineers actually designed the robot in Rhodes 114 the Cam/Cad design lab.

The final resultant of the lab setup was that each sub-team had their own space to work in Rhodes 153. This setup opened communication channels and lead to a better team atmosphere since many of the team members were in the same room.

1.1.3 Lab Processes and Procedures

In order to have an efficient lab a set of guideline needed to be set up. At the beginning of the year a set of lab rules was established. The lab rules provide a set of guidelines such that the lab is kept efficient and functional. A copy of the lab rules can be found on the Cornell RoboCup intranets website.

1.2 Goal Setting

In nearly all projects there needs to be a set of defined goals which are needed to be attained in order to view the endeavor as a success. RoboCup is no different. In the beginning of the year, the team leaders and experienced veterans of previous years met to establish the goals that needed to be attained in this upcoming year. The goals have been defined as follows.

- Win RoboCup 2003
- Win RoboCup 2004 and beyond
- Provide perpetuity to the Project

These goals were the most important things that needed to be attained for the current academic year. All the above goals hold equal weight and should be treated as the 2003 Cornell RoboCup mission statement.

1.2.1 Project Goals

With the established goals above, the team leaders needed to define what exactly was required to be completed be done this year. However, the three main goals need to be properly quantified into design requirements, established needs, and concerns. The first task was to develop a list of things that needed to be improved from the previous years work. This list was established with the intent of becoming the items that the team would strive to correct and of course innovate to make substantially better. The areas of needed improvement are below:

- Shorten Setup time: The system takes in exorbitant amount of time to set up and get fully functional.
- The system Latency needs to be reduced: The system exhibits a sluggishness somewhere in the that results in the loss of time in terms of frames (1/60th of a second)
- The robot has no onboard sensing: Last year, the Robot constantly missed passes from misaligned shots.

- Need a redundancy in wireless communication: Last year the team had to resort to only one kind of wireless transmission. The 2003 RoboCup team needs to have a robust communications system.
- Defense was weak: Improve the defense through new strategy or plays
- Increase the ball handling skills: Increase the speed and accuracy of the robots by improving the kicking, dribbling, and drive capabilities.
- Improve maintenance: Current design is a pain to fix when certain areas break.
- Robust Vision System: Develop a vision system that is more tolerance and is more robust.
- Manufacturability: Design parts/circuits that are still easy to manufacture but are also do not lead to overly designed system.
- Create an Adaptive System: low level in game learning.
- Learning: Robots trained with proper parameters and other plays out of a game atmosphere.
- Documentation: Establish complete and cohesive technical documentation
- Utilize a goalie: Exploit the effective use of a goalie and its function.
- Proper funding: Keep sponsors up to date and look for potentially new sources of funding.
- An efficient lab: Keep the lab clean and functional

1.2.2 Strategy Defined Goals

Though the overall team goals and objectives had been defined, the subgroups needed more refined requirements or goals that needed to be attained. These were developed again by the team leaders. The requirements have been slowly disaggregated from a general "Win 2003" to more concrete terms such as "we need a rate gyro to establish an angular position data source".

This process began with the upper level of strategy. Note this was not a discussion on plays or roles of each robot; rather it was a very high level approach to how the 2003 robots will play the game.

Initially the weaknesses of the 2002 system were examined and from there we established what was needed in terms of the 2003 system. First the offense was defined. It was determined from prior experience to multiple years of RoboCup play the primary methods of scoring goals were the following:

- Being able to outmaneuver the team
- Out pass the team
- And being able to out shoot the other team

On the defensive side, it was determined that the following were considered to be important:

- Be quicker and more maneuverable
- Be able to maintain ball possession
- Utilize a superior Goalie

The six strategy goals were then compared to the overall systems goals and objective that were listed above. The sub group goals were then established from both the strategy set of goals and the overall general system goals. The mechanical goals that were derived will be detailed below.

1.3 Project Planning and Monitoring

A very important process in Project Management is project planning and monitoring. The major planning methods use by the Cornell RoboCup team is a defined Budget and a system schedule. In addition, the major Project monitoring methods are through team Meetings and Design Reviews

1.3.1 Budgeting

The Cornell RoboCup team each year has a set amount of funds allocated from corporate and alumni sponsors. Due to the unfortunate amount of money spent by last year's team the 2003 RoboCup team had $30000 of funds in which to design build and test the next generation robots.

1.3.2 System Schedule and Milestone development

At the beginning of the year the team leaders and the Project advisors met to establish a timeline such that the team would be ready to compete for the competition. The schedule was developed from a project end to beginning approach. The first things that were developed were the system milestones. These are the dates in while the major accomplishments need to be finished. From the set milestones, generic tasks were then developed until the beginning of the year was reached. The major problem with developing a schedule in this manner would be determining the task duration and the critical path. Taking a backwards scheduling approach requires an intimate knowledge of typical task lengths and task organization.

The Current systems level schedule is explained in more detail in the Mechanical schedule section

1.3.3 Team Leader and Sub-Team Meetings

Team Leader meetings were held weekly to help facilitate open channels of communication and to help get a better understanding of the progress of each sub-team. The systems meeting provided a location for each team leader to voice their ideas and opinions about the

1.4 Mechanical System Overview

The Mechanical Design team was pleased to have 6 fulltime members and several very productive volunteers. The range of ages and experience has lead to a very productive and educational experience.

The 2003 Mechanical Design team is:

	Name	Year
Drive:	Patrick Dingle	Junior
	Leonard Evansic	M.Eng
Dribbling:	Christine Chang	Junior
	Sean Richardson	Sophomore
	Hank Law	Sophomore
Kicking	Graham Anderson	Sophomore
	David Chung	M.Eng
	Jeremy Yim	Freshman
	John Roberts	Freshman
Team Lead	Ken Sterk	M.Eng

1.4.1 2003 Mechanical Organization and Structure

The 2002 mechanical team currently follows an approximate waterfall process in which each step of the design needs to be completed before the others can continue to progress. However, the team also works very much in parallel with the other sub groups, so it is not technically an exact waterfall process. The team has been broken up into groups and has established a schedule and a budget to help organize the tasks needed to be accomplished this year.

1.4.2 Mechanical Team Structure

The mechanical team has been broken up into three distinct sub groups. Each of the sub groups is responsible for a separate area of the robot. The three major areas are the Locomotion (Drive), Ball handling (dribbling) and Kick/pass (Kicking). Each of the groups works on their own system but are in continual contact with other team members not only on the mechanical team but also in the electrical and software teams. The structure of the mechanical team can be seen below. There is also a goalie group which will be formed as the year progresses sufficiently far.

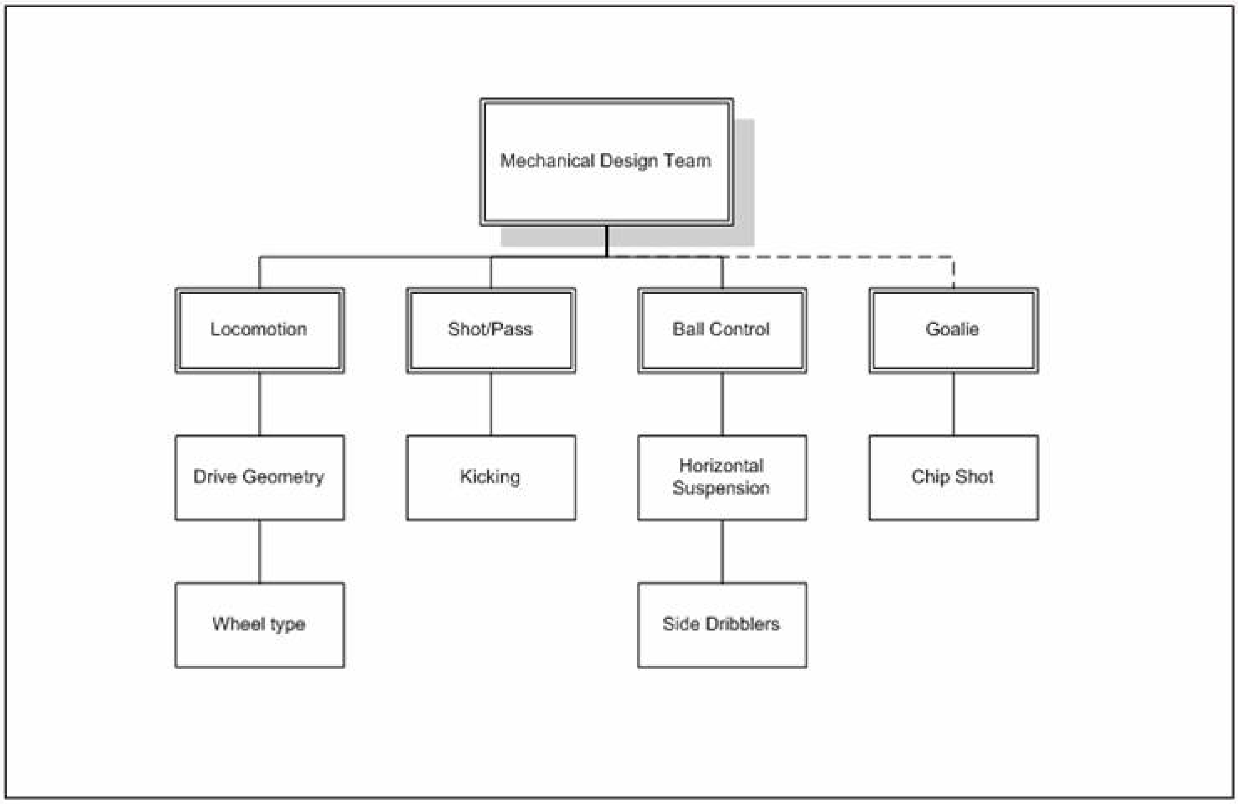


Figure 1-1 Mechanical Team Structure

1.4.3 Scheduling

In order to identify the progress and achievement of each of the teams, a systems wide schedule was made. The current schedule was developed with a very aggressive mindset. In previous years, the robots were not completed until very late in the year, thereby limiting the amount of progress the Software engineers could accomplish. This years schedule revolved completely around the goal of producing a full team of Robots to the software engineers such that they would be able to have significant amount of time to thoroughly remove the bugs in their system.

The current schedule undergoes through six distinct phases. The first phase is the team formation phase. Here the team is created and the learning of the systems has begun. The team begins to brainstorm and the set of system goals are established.
The second phase of the schedule focuses around the Optimization and Prototyping. In this phase the teams has been broken up into their subgroups and are beginning to look at potential solutions to the design goals that were given developed.

This then leads way to the new 2003 robot design. The robot is now transformed from ideas and prototypes to a completely virtual model. The next phase is the new robot prototype. A single robot of the new design is then built to validate the new design. With a prototype, flaws can be found and corrected before any major manufacturing has begun. The final stages are the mass production of the new robots and then finally delivery of the robots to the SE team. The current Mechanical and systems level schedule is illustrated in the appendix.

1.4.4 Group Meetings

In order to keep up to date with everyone's progress, the mechanical team held weekly meetings to give a simple update in the current week's progress. It is also used to develop a time to peruse new ideas and to debate other new concepts and thoughts. In addition to the weekly meeting, the Mechanical team also had working meetings on the weekends. The working meetings goals were to get all the team members in the lab such that they can do work efficiently in the lab. This enabled the team members to rely on each other for advice and ideas.

1.4.5 Mechanical Design Team Goals

From the high level strategy meeting, a set of requirements were passed to the mechanical team. From these requirements each of the mechanical sub-groups derived a subset of goals. Each of these goals are reviewed below

1.4.5.1 Omni-Directional Drive

The drive system is integral to both the defense and the offense as seen above. In addition to being quick and agile, the drive system also needs to be predictable and accurate, lest we fail to attain the goal of out passing and having better ball control. Thus the following objectives were given to the Drive group.

- Improve the control of the robot and its predictability
- Increase the robot speed and acceleration
- Institute new ideas on wheel design and traction

1.4.5.2 Dribbling System

The dribbling system also is very integral to the system. The dribblers needed to have a very large catching area and angle to facilitate the ability of ball handling. In addition a stripping mechanism should be implemented in such a fashion that the ball can be "stolen" by our robots with ease. Therefore the following objectives were given to the dribbling Group:

- Develop an effective stripping mechanism that would be able to effective strip or steal the ball away from a dribbling opponent.
- Improve the angle of reception of the robot to make it able to receive passes from different angles.
- Focus on gearing the system instead of using a belt driven system. Design for machinablility and maintainability.

1.4.5.3 Kicking System

The kicking system plays another significant role in the goals for the following year. In order to win the robots will eventually have to shoot the ball at one point in time or another. Also another key part is that the passing game is focused entirely on the kicker and robot position. The goals that were given to the kicking group were:

- Increase the reliability and accuracy of the kicker
- Increase the strength of kick

2 Omni-Directional Drive Documentation

2.1 Introduction

The omni-directional drive system is the component of the robot responsible for moving the robot about the playing field. The terminology used for our 2000, 2001, and 2002 drive systems is "omni directional," meaning the robots have three degrees of freedom in the horizontal plane: two prismatic degrees of freedom and one rotational degree of freedom. This system is perhaps the most critical system of the robot, for without it, the robots would be incapable of moving about the playing field. Further, the omni-directional design removes any kinematic restrictions on the drive system. Therefore, the trajectory generation algorithms have the freedom of accelerating the robot in any direction with any magnitude (up to a certain limit) at any time.

2.2 Preliminary Design

During the fall semester, the drive team's main objective was to come up with a preliminary design of the robot. This section documents all the analysis, testing, and design done in the process of achieving a preliminary design.

2.2.1 Design Goals

The design goals were separated into two categories: major design objectives and additional design objectives. Major design objectives were those handed down by the systems engineering group, and the additional design objectives were those that the drive subgroup desired to achieve.

2.2.1.1 Major Design Objectives

Based upon observations from 2002 performance and upon the recommendation of the systems engineering group, the goals for the 2003 drive system are:

- Fix control problems
- Increase acceleration and velocity
- Decide between three and four wheel omni system

2.2.1.2 Additional Design Objectives

Independently, the Drive subsystem group developed additional subsystem goals. These general goals were to reduce the weight of the robots, lower the center of gravity, provide more space for other subsystems, integrate the hat and wire routing into the chassis design, and most importantly provide a more maintainable design.

Reducing weight could contribute to faster acceleration. By reducing the mass that must be accelerated for motion, less power would be required to produce the same rate of acceleration. Using a drive system that produced same amount of power would give a higher acceleration to the desired velocity. However, reducing the weight also reduces traction with the ground, so the net effect of reducing weight is questionable.

Lowering the center of gravity will yield better stability of the robot, when changes in direction are required. Although the 2002 robot has a center of mass that is quite low, we believe that we can design a robot with a center of mass even lower, resulting in less mass-transfer effect and greater stability.

We want to open up space in the chassis for other subsystems. The 2002 robot design used four motors with integrated gear heads and optical encoders. This resulted in a layer of about 25 mm of vertical space that only contained drive components, which push the kicking and dribbling subsystems higher in the robot, thus complicating their design. We feel that this space could be better utilized if we were to find ways of making the drive assemblies more compact, so that, for example, the kick solenoid would be inline with the kick plate.

It was mentioned that the hat on the 2002 robot was the last part to be designed, and that our vision system would benefit if these were to be fixed more securely to the robot. Keeping in mind the goal of better control, we intend to design our chassis such that the hats will be hinged for access and be quite rigid, thus allowing the vision system to maintain a true representation of each robot's location.

We also would like to integrate the wire routing into the design of the chassis. On the 2002 robot, wires from battery packs must be tucked under the hat, and sometimes get in the way of other cables or the wheels. The ribbon cables from the drive modules, kicker, and dribbler can also get in the way. Integrating cable paths into the design of the chassis will decrease occasion the occasion of wires getting the way of maintenance or operation of the robots.

Our last goal is to make the drive and chassis more maintainable. Great strides in maintainability were made in the 2002 robot, with swappable drive module assemblies and standardization on #4-40 fasteners for all subsystem attachment. Unfortunately, some sore spots remain. The most glaring of these is the attachment and detachment of wheels to the gearbox. We intend to fix this for 2003.

2.2.2 Initial Ideas

2.2.2.1 2002 Performance Review

Since the omni-directional drive system provides three degrees of freedom – the maximum possible in a plane – we felt that our maneuverability in 2002 was excellent and that there was no reason to switch to another type of drive system. However, we noticed several improvements that could be made to the 2002 design. The first two of these observations were acceleration and velocity. Although the maximum acceleration and velocity of our 2002 design were much better than that of 2001, there was still a lot of room for improvement. For example, the Fu Fighters were able to move around the playing field at higher accelerations and velocities than our robots were able to. The other observation we made was that our robots were much more difficult to control in 2002 than they were in 2001.

2.2.2.2 Design Parameters

Assuming we continue to use an omni-directional drive system, there are a given number of parameters that we have to work with. An alteration in any one of these may significantly help or hurt achieving design objectives. These parameters include (not exhaustively):

- Motor selection
- Number of wheels

- Wheel location and geometry
- Gear ratios
- Suspension
- Wheel design and traction

2.2.2.3 Control Problems

The following ideas were suggested for improving control problems:

Suspension to reduce effect of fluctuating loads and quick changes in velocity

Switch back to three wheels. Using three wheels has two major benefits. First, minor flaws in chassis shape or slope of the ground will not cause one wheel to become airborne or with reduced contact force with the ground. For example, a tripod is much more stable than a four-legged table with one leg just off the ground. Second, control for a system with three degrees of freedom is most easily and directly obtained with an equal number of motors.

Add local feedback to determine the velocity and rotation of each robot (e.g. using optical mouse sensors)

Lower the center of the mass of the robot, reducing the effect of weight transfer

2.2.2.4 Increased Acceleration & Velocity

The following ideas were suggested for improving both the acceleration *and* velocity of the robots:

- Our robots are friction limited. Thus if we increase our effective coefficient of friction with the surface, our acceleration increases proportionally.
- Decrease the weight of the robot. The motivation for this idea arose because the Fu Fighters were very light and was able to accelerate quicker than our robots.
- Switch to brushless motors. According to the 2002 documentation, brushless motors have a better power to weight ratio.
- Lower the center of mass, reducing the effect of mass transfer and thereby allow us to accelerate more quickly without the wheels slipping. One detrimental effect of too much transfer is tipping of the robot.

2.2.2.5 Three vs. Four Wheels

The following ideas were suggested for deciding between three and four wheels:

- From the design objectives, we cannot switch back to three wheels unless we can achieve equal or better acceleration and velocity than our 2002 robots.
- An ideal solution would be to switch back to increase traction enough that we can achieve equal or better acceleration, and reduce the number of wheels to three. Since there were less control issues with three wheels in 2001, it is conceivable that this solution could both improve control and predictability, in addition to velocity and acceleration, thereby meeting all design objectives.
- For a three-wheel system, there is more room to play with the size of the wheels. Increasing the diameter of our wheels could allow us to place all our batteries *underneath* the wheel axes of rotation, thus significantly lowing the center of mass. Ideally the center of mass is as low as possible, such that the mass transfer effects become negligible.
- Assuming the robots are friction limited, a four-wheel system will always have proportionally better acceleration than a three-wheel system. See the acceleration map in section 4.1.3.3 of the 2002 mechanical design documentation.

2.2.2.6 Other Considerations

Although certain design goals are set each year, there are often other ideas for improvement that would be nice, but are not deemed as important as the major goals. The following are ideas that came up in brainstorming but did not directly contribute towards any of the main design objectives:

- Brushless motors take up much less volume and would drastically increase room for other components.
- Other types and sizes of wheels should be considered. In addition to redesigning wheels to increase traction, we can also work to make the wheels thinner or of a different radius. A good example of an alternate type of wheel is the Single Inline Roller (SIR) style wheels that the FU Fighter robots used in 2002.

2.2.3 Preliminary Analysis & Testing

Having established a list of ideas on how to meet the design objective, the next step was to determine which ideas were feasible to research in the given time, and analyzed how much each idea would help us meet the objectives.

2.2.3.1 Better Control

The drive team postulated two possible mechanical causes for poor control in 2002. The first of which was the geometrical configuration of the drive system. The second was friction in between the wheels and the rollers. This section documents the investigation into each of these possible causes.

2.2.3.1.1 Drive Configuration

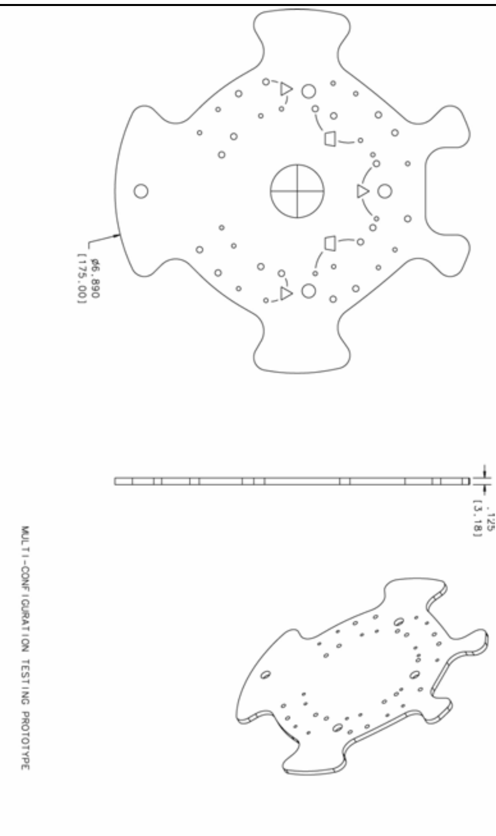


Figure 2-1 Drive Test Configuration

To address the design goal of better control, we dissected our subsystem to find out which aspects contributed to control performance. In short, we felt that drive configuration, motor/gearing selection, and wheel design would be the areas that we could improve to offer better control.

At the outset, we decided that we would proceed with an omni-directional drive design, as the benefits of simultaneous translation and orientation, gave a tremendous benefit to our player's ability to capture and control the ball. Since our wheel type functionality was defined, we examined the wheel configuration that we would use for the 2003 robot. Preliminary observations led us to suspect that the four-wheel omni-directional setup had many inherent characteristics that were detrimental to accurate control of the robot. Experienced team members commented that the 2001 robot was better able to travel in a straight line than the 2002 robot. As its four points of contact were statically indeterminate, it appeared that the robot would wiggle as three wheels would become dominant over the other. We needed to find out if it was best to keep the four wheel design for speed, or to change to another design for control.

To determine the best wheel configuration, a prototype was constructed (Figure 2-1) that would mount the 2002 drive modules in one of three configurations; perfect 3, perfect 4, and butterfly 4. These designations refer to the angles between the drive wheels. In this case, perfect means equiangular with either 120° between each of three wheels or 90° between each of four wheels. Butterfly refers to a configuration with 90° between the two rear wheels, and 110° between the front wheels. In the butterfly, the projected intersection of the front wheels lies behind the geometric center of the robot, matching the geometry employed in the 2002 robot.

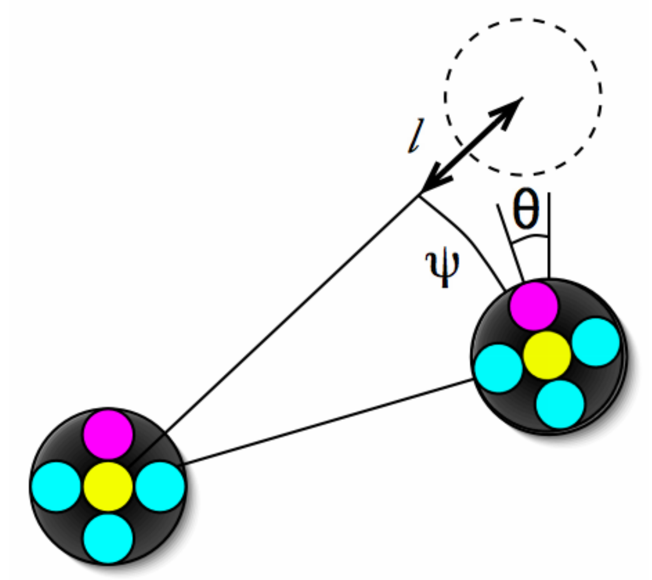


Figure 2-2 Measured Error

Based on the assumption that a robot that positions and orients reliably in open loop would perform better in closed loop control, an open loop procedure was developed to test controllability of each configuration. To quantify how well each particular configuration behaves, a map of three characteristics would be produced: linear translational accuracy, rotational translational accuracy, and rotational orientation accuracy. Linear Translational Accuracy (LTA) refers to the linear distance error of the robot from a commanded location. Rotational Translational Accuracy (RTA) refers to the angular error between the intended path to a commanded location, and the actual path that the robot takes. Rotational Orientation Accuracy (ROA) refers to how well a particular robot is able to maintain the proper orientation, while translating along a commanded trajectory. These three measurements are shown in Figure 2-2, where *l* corresponds to the measurement for LTA, ψ provides measurement for RTA, and θ gives the measure of ROA.

An additional assumption for this test is that improvements to wheel and roller design will better the results of all configurations. Also, it is assumed that a configuration that performs well in this radial linear test, will perform better when the robot is commanded to rotate while translating, than a robot that performs poorly in this test.

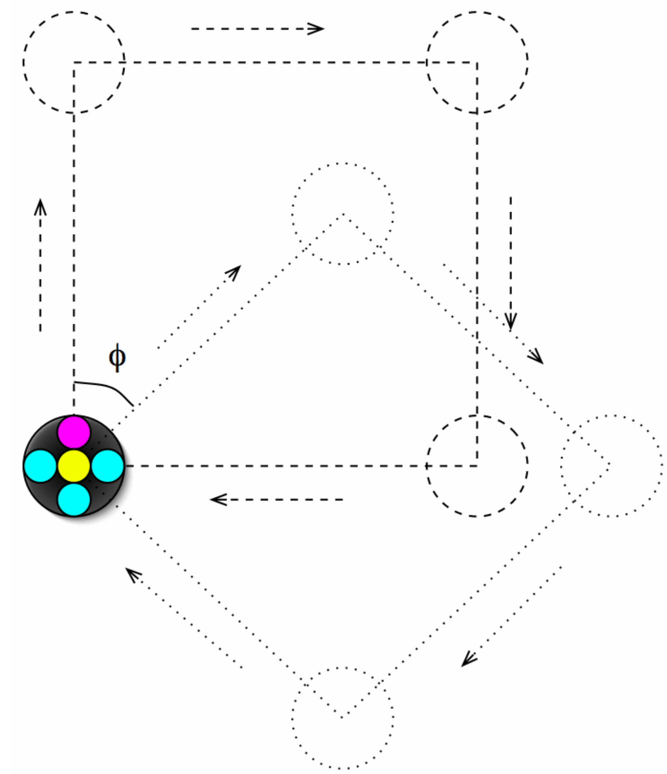


Figure 2-3 Test Pattern

Testing Procedure

A program is to be made to command the robot to traverse in a square. At the completion of each leg, the robot will pause, to assure that the next leg will commence when the robot is not moving. The vision system will record the start position, stop position, and orientation of the robot at both positions. The orientation of the robot when it stops will be used to calculate the error on the next leg of the test. This square pattern will be rotated by 5° increments, to be tested from 0° through 85°, as shown in Figure 2-3. In this manner, data will be collected to map the drive configuration's accuracy for a full 360° of commanded drive motion.

Although this test would have merits, this test was not actually performed due to time constraints. The test would not have been useful given the time constraints because the closed-loop performance has only a small correlation to open-loop performance.

2.2.3.1.2 Roller Traction

When observing the 2002 robot at slow speeds, it appeared as if the wheel rollers did not always spin freely on their axis. This caused the roller to rub on the ground rather than rolling. At driven angles greater than approximately 30° off axial of a given wheel, the rollers would bind at their ends, and prevent proper movement.

Compounding this problem is the fact that the rollers themselves are not uniform in diameter. This changes the moment arm of the ground friction reaction force, in effect varying both the normal force at the end of the rollers and the torque applied to overcome the friction between the roller and the clevis of the wheel hub that retains the roller. Also, the varying diameter of the roller requires a point contact to roll without slipping, as the roller cannot roll simultaneously across differing diameters, without different rates of rotation. By necessity then, the rollers will slip on the carpet because the carpet is compliant, and will contact a large patch of a roller at a time.

There are several ways to alleviate this problem, and several have been looked at in greater depth. The problem of differing diameters may be dealt with by flattening the rollers, which would result in a larger wheel diameter, or by decreasing the diameters by making ridges on the rollers. Likewise, the problem of roller end friction can be minimized by changing the material of the roller, minimizing both diameter and area of hub end contact, or increasing the roller diameter. Some old wheels that were found in the lab utilized thin plastic washers on the ends of the rollers, indicating that prior efforts had recognized the effects of this roller end friction. Our investigations have attempted to include all of these concepts, in the hope that a "sticky" omni-wheel could be developed that would aid in control of the robot

2.2.3.2 Increasing Acceleration

Being a major design goal for 2003, increasing acceleration was a primary area of research. This section details all the different factors that may increase acceleration, and the results of each area of research. Additionally, a section outlines the MATLAB simulation that was developed to predict accurate acceleration characteristics of any given design.

2.2.3.2.1 The Effect of Robot Weight

One of original ideas to increase our acceleration was to reduce the weight of the robot. Our reasoning was fairly simple. The 2002 FU Fighters had notably better acceleration than us, and it seemed to many team members that it might have something to do with having a lot less mass to haul around the field. From a theoretical standpoint, Newton's Laws state that the force required to accelerate a given mass at a given acceleration is equal to force times acceleration. Thus, a heavier object would take more force than a lighter object to obtain an equal acceleration. However, veteran team members pointed out that our robots may be limited in acceleration by maximum frictional force. Classical theory of static friction states that the maximum force that can be applied to a static body is proportional to the normal force. Using equations, we can express this relationship:

$$F_{\max} = \mu N \qquad [2.1.1]$$

Since we have multiple wheels on our robot, the normal force on a given wheel is equal to a fraction of the total mass of the robot times gravity. Thus we can rewrite [2.1.1] as:

$$F_{\max} = k_1 \mu m g \qquad [2.1.2]$$

Similarly we can derive an equation for the force required of any given wheel to accelerate the robot at a given acceleration from Newton's Laws:

$$F = k_2 m a \qquad [2.1.3]$$

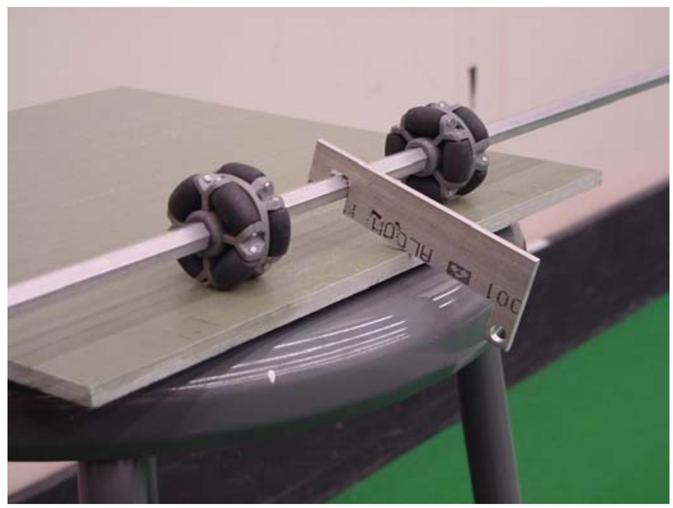
Combining equations [2.1.2] and [2.1.3], we find that the maximum acceleration of the robot is proportional to the coefficient of friction times gravity. The constant of proportionality k is related to the number of wheels, the positioning of the wheels with respect to the chassis, and the direction of acceleration.

$$a_{\max} = k \mu g \qquad [2.1.4]$$

This simple analysis tells us that if our robots are friction-limited, and coefficient of friction is actually a constant, then the mass of the robot is irrelevant. After speaking with veteran team members and reading 2002 documentation, we determined that the 2002 motors were indeed slipping, and the potential torque that could be applied by the motors was much greater than the torque at which they slipped. The second assumption, that the coefficient of friction is a constant, was not so easy to justify. College textbooks state that this assumption is only valid when the two forces are very smooth and do not dig into each other. In our situation, we have rubber wheels that can deform slightly around the fibers of the carpet, so it was not evident that this assumption is accurate. Thus, we devised a simple test using our wheels and playing field carpet to determine if the coefficient of friction is indeed a constant. If it is, then the mass of the robot is independent of maximum acceleration of the robot; but if it is not constant, then there is some relationship between mass and maximum acceleration.

Experimental Setup

Figure 2-4 Friction Test Setup



To determine if the coefficient of friction is constant, we devised a simple experimental setup that would allow us to vary the normal force on a set of wheels, and measure the amount of force required to make the wheels slip along the surface of the playing field. Two wheels were fixed to a hexagonal shaft, and in between the two wheels, a fixture connected the hexagonal shaft to a string, with the string able to apply a force at the same height as the contact point between the wheel and the surface. The entire surface was elevated on a stool, such that the string did not touch the ground, and so that equal weights could be hung at equal distances from the center of the shaft. The tension in the string before slippage occurred was measured by connecting a linear force meter in series with the string, and pulling the meter until the wheels slipped. The maximum reading of the meter during this process represents the combined frictional force of both wheels given the normal load.

Data

All data and graphs for this experiment can be found in the file *friction_test_varying_normal_force.xls* on computer *Christie* in Upson 226 under the folder "/ME2003/Preliminary Doc". A

Results

The following graph illustrates the relationship between the coefficient and normal force. From this graph, we can clearly see that the coefficient of friction appears to decay towards some asymptote as the normal force increases.

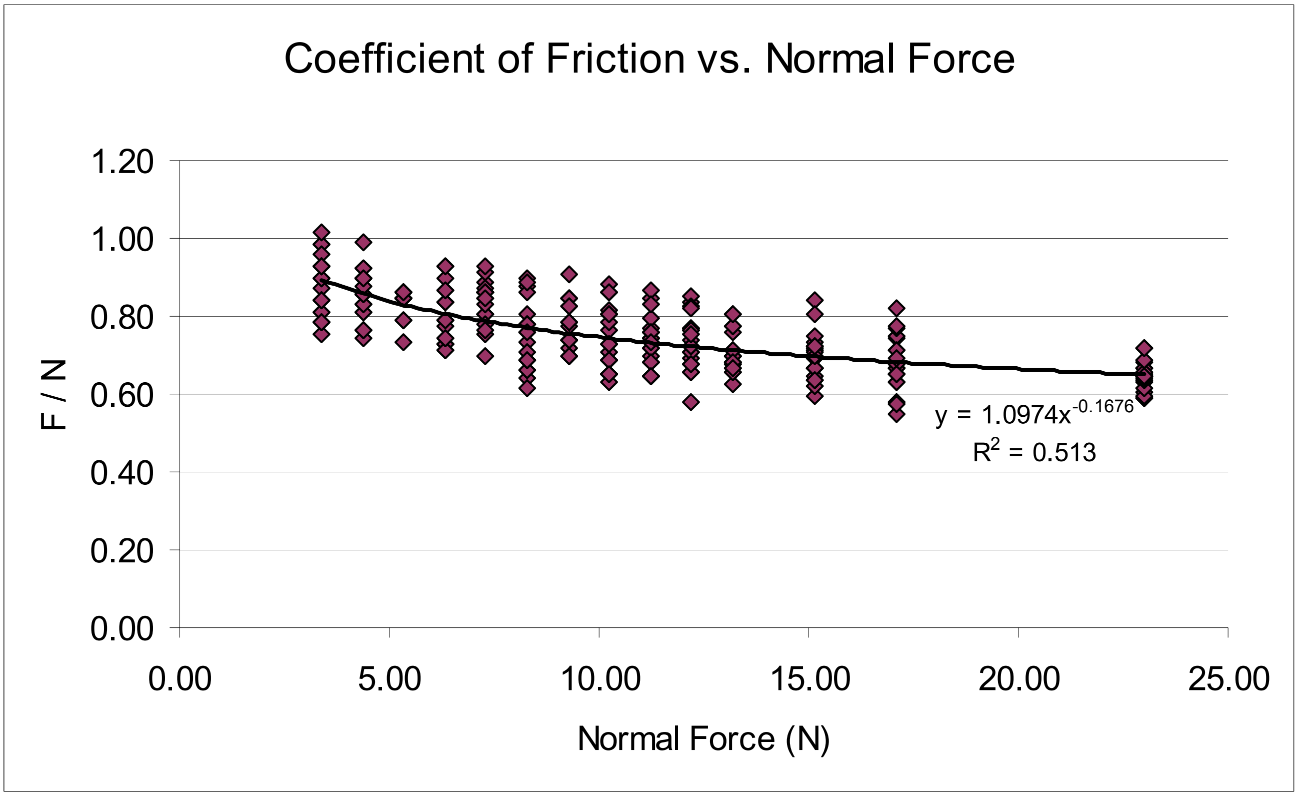


Table 2-1 Coefficient of Friction vs. Normal Force

Theoretically, these results imply that if we lower the mass of our robot, the coefficient of friction effectively becomes larger, and thus we can achieve a maximum acceleration. However, looking at the appropriate range of normal force, and assuming that at best we can achieve about a 25% reduction in robot weight from 2002, we find that the coefficient of friction only increases about 5%. Thus, with regard to acceleration, *there is no significant advantage to decreasing the weight of the robot.* Again, this is only true as long as our robots are friction limited, rather than power limited.

2.2.3.2.2 Coefficient of Friction

Regardless of what number of wheels is chosen, how they are oriented, and how mass transfer comes into the picture, the easiest way to increase acceleration is to increase the effective coefficient of friction with the ground. As long as the robots are friction limited, increasing the coefficient of friction will proportionally increase the maximum acceleration of the robots. Thus, a great deal of effort was put into redesigning wheels and rollers, and performing tests to determine which could best grip the ground.

The first step in increasing wheel-ground friction was to see what research had already been done on the subject. In 2002, some effort was made to increase the traction of the goalie robot (since the goalie required faster acceleration than other robots), but tests were never performed on these new wheel rollers, and there was no documentation on the attempt. Additionally, there was very little information found in textbooks or in the library on maximizing friction. Fortunately, Professor Andy Ruina from the Theoretical & Applied Mechanics department studied friction in detail for his PhD, and we were able to meet with him to get his advise on how to approach the problem. Professor Ruina first pointed out that the wheels we used in 2002 (with rubber rollers) only grip the ground by rubbing one surface against another. In other words, the two surfaces do not dig into each other in an attempt to become one body. Although the rollers were made of rubber and rubber is very elastic and can deform around fibers in the carpet, this effect was at most marginal. Professor Ruina's main advice was to design wheels with rollers that are able to dig as deep into the carpet as possible. This would in effect cause the wheels to grip the ground not by frictional contact, but by contact of one vertical wall (the "cleats" on the rollers) against the sides of fibers of the carpets. He also pointed out that the material probably does not matter in this case, but a more rigid material would be better so that the cleats do not give in to the carpets of the fibers. Professor Ruina claimed we could obtain an "arbitrarily high" coefficient of friction by making the cleats smaller and smaller and working on this concept.

Due to the lack of available research on the subject, the only way to test Professor Ruina's theory was to actually design different types of rollers and see how they perform. Since we already had omni wheels from previous years, it was a simple matter to remove the pins holding the rollers in, and machine new rollers to put in their place. This allowed us to easily design wheels for friction tests without redesigning an entire wheel.

Since the construction of these small rollers would need to be done on a lathe, and many would have to be produced for testing, it was necessary to learn the CNC lathe to make them. This process took some time, but after a few weeks several different types of rollers had been made. The main idea in these roller designs was to create cleats, and test how the thickness and number of cleats on the wheel affected the traction. Additionally, we wanted to know how much better each design was compared to our 2002 rubber rollers. The following photos show the finished wheels that were to be tested for coefficient of friction:

Normal 2002 wheel

2002 goalie wheel

2003 Prototype Wheel 2 thin rollers

2003 Prototype wheel 3 thin rollers

2003 Prototype wheel 2 thick rollers

Figure 2-5 Various Roller Designs

Experimental Setup

In order to find out which wheels had the greatest coefficient of friction, it was necessary to devise a testing apparatus that could accurately tell us how good one wheel is relative to another. The wheels are in static contact with the ground; only static friction was to be

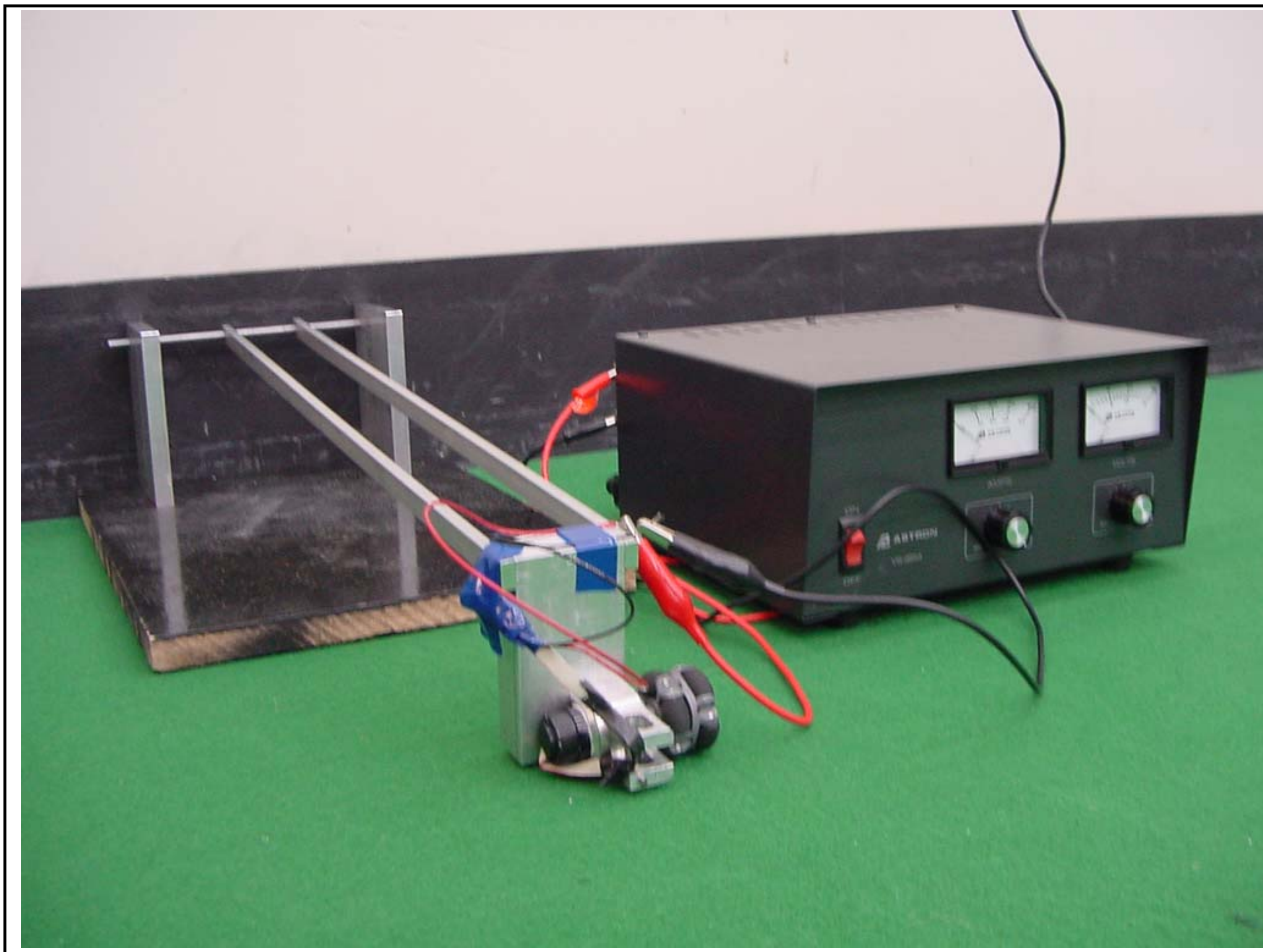


Figure 2-6 Wheel Coefficient of Friction Test Setup

measured. The following photograph illustrates the testing apparatus that was designed to measure how much torque could be applied to the wheels before slippage occurs:

As shown in the photo, a single wheel is in contact with the ground, and is powered by the 2002 motor with gearbox and mounting bracket. This is connected to a long arm, such that there is a constant normal force that closely approximates the normal force on each wheel from 2002. The normal force of this testing apparatus was measured to be 5.586 N. On the right, wires are hooked up to the terminals of the motor, and any voltage between zero and 30 volts can be applied to the motor. To make a reading, the wheel of interest was first locked to gearbox output shaft, and set up as shown in the photo. Next, the apparatus was positioned in a random spot on the carpet, to reduce the effect of possibly damaged carpet from previous observations. Then, voltage was gradually increased until the point at which the wheels slip. This voltage level was recorded, and ten observations were recorded for each wheel. Since we are using DC motors, the amount of torque applied to the wheel is proportional to the voltage. Further, all wheel radii are equal. Thus, the overall effect is that the measured readings of voltage are proportional to the coefficients of friction.

Data

The following table shows the data gathered from this experiment:

N (N)	#1: Rub Flat	#2: Rub Grooved	#3: Al 2 Thin	#4: Al 3 Thin	#5: Al 2 Thick
5.586	4.5	7.5	7.5	11.5	10.5
5.586	4.5	8	8.5	8	9.5
5.586	4	6	8	9	9
5.586	6	6	8.5	14.5	7.5
5.586	5	6.5	8.5	8	8.5
5.586	4	7	12.5	9	15
5.586	5.5	7.5	8.5	11.5	11
5.586	6	7.5	10.5	7	13
5.586	5	8.5	9	7.5	9
5.586	4	7	7.5	9	15
Mean:	4.850	7.150	8.900	9.500	10.800
Stdev:	0.784	0.818	1.524	2.321	2.679
n:	10.000	10.000	10.000	10.000	10.000
95% CI:	0.486	0.507	0.944	1.439	1.661
Min:	4.364	6.643	7.956	8.061	9.139
Max:	5.336	7.657	9.844	10.939	12.461
% of 2002:	100.000	147.423	183.505	195.876	222.680

Table 2-2 Wheel Friction Test Results

Results & Conclusion

From this table, it is easy to see that all of the alternate roller designs were significantly better than the 2002 rollers. In fact, the data for roller #5 suggests that the coefficient of friction is better by over a factor of two! However, this data does not conclusively show which of the aluminum designs are optimal. To determine this, more data points would be needed to narrow the confidence intervals. The *min* and *max* rows represent the bounds of this 95% confidence interval. What this experiment does show, however, is that *it is relatively simple to alter a wheel design to be able to better grip the carpet*, *and this can be done with small cleats*. These roller designs are most likely not the most effective at gripping the carpet, and in fact it was noticed that these designs are very good at ripping out fibers of the playing field. This damage could most likely be minimized by putting small radii on the cleats so there are no sharp edges to cut fibers. On the other hand, doing so would likely slightly reduce the effective coefficient of friction, so there will be a balancing act necessary when designing the final rollers to make sure we maximize our effective coefficient of friction but not at the expense of risking disqualification!

Once this experiment had been performed, we were able to test a robot with four wheels consisting of #5 rollers (see photographs above) on the actual playing field. Due to time constraints at the time of documentation we were not able to quantify how much better acceleration was, but it was apparent that the robot could accelerate more quickly with the "Berserker wheels" (a term coined for the wheels with #5 rollers) than with the 2002 rubber rollers. In fact, it was noticed on a couple instances the robot accelerated so quickly that one end of the robot lifted slightly off the ground! This also raises the important point that lowering center of mass will be a very important thing for our 2003 design. Additionally, we noticed after testing the robot was covered in carpet fibers, so this design would not be useable in actual competition until modified to be carpet friendly.

2.2.3.2.3 Mass Transfer and Center of Mass

Mass transfer is a dynamic phenomenon that is an unavoidable characteristic of robot acceleration. When a robot accelerates, it is no longer being acted upon solely by the force of gravity, but also by the force of frictional contact with the ground. Thus, the robot as a whole has two components of force. The first is gravity, which holds the robot to the ground. The second is due the frictional force -- or acceleration -- and is in the horizontal plane. Acceleration of a robot is achieved by a set of forces being applied to the playing field surface. These forces are equal to the output torque of the motor's gearbox acting at a constant distance (the radius of the wheel) from the motor's axis of rotation. The vector sum of these forces yields the net direction and magnitude of force. Further, the sum of the moments about the center of the robot yields the net torque to the ground. These pieces of information can be used to infer the acceleration direction, acceleration magnitude, and angular acceleration of the robot.

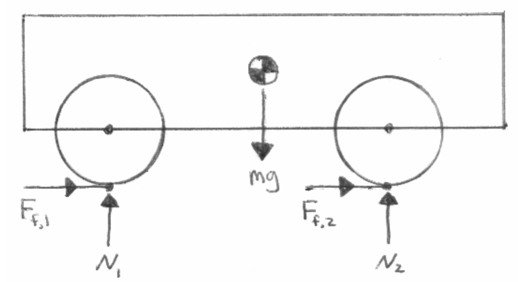


Figure 2-7 Two-Dimensional model of a Robot

If the robot – regardless of the number of wheels – is perfectly aligned and perfectly rigid, then all wheels are in contact with the ground at any given time. While this assumption can never be physically obtained, it can be assumed that we are able to machine a robot that is almost perfectly rigid and almost perfectly aligned. Further, the elastic materials on the wheel and ground can easily compensate for any imperfections in manufacturing and alignment. Given that these assumptions are valid, it can be inferred that during acceleration, the robot will tend to apply less pressure to the ground at contact points towards the front (direction of acceleration) of the robot, and apply more pressure towards the back. Figure 2-7 depicts a two-dimensional model of a robot. Clearly, if one takes a moment balance about the center of mass, more normal force is required on wheel to the left than on the right. This requirement exists because the robot is kinematically constrained to be parallel to the ground, thus the sum of the moments about the center of mass must be zero. Because the robot is assumed to be perfectly aligned and rigid, and because the ground and wheels are assumed to be elastic, each wheel can be modeled with a small spring under each wheel. This model demonstrates quite clearly that the normal force must be proportional to the distance from the center of mass. In a three dimensional model (see figure 2-8), the normal force must be proportional to the distance from the wheel to the axis that goes through the center of mass and is perpendicular to the direction of acceleration.

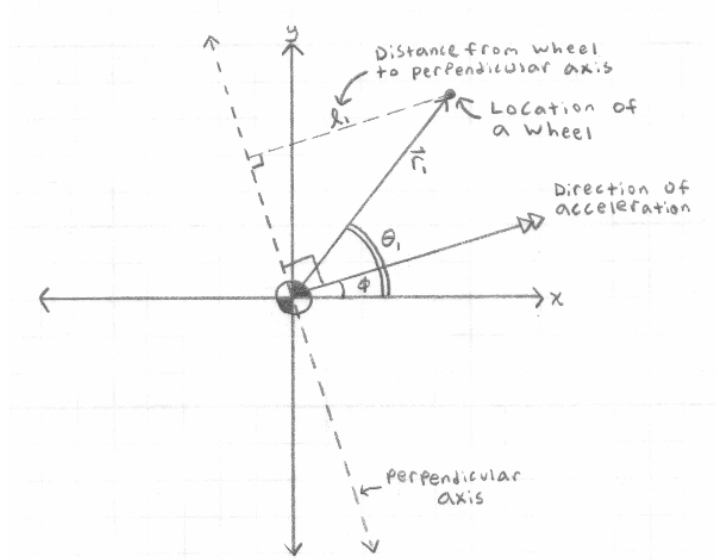


Figure 2-8 Variable definitions for wheel location (birds-eye view)

Given the robot's direction and magnitude of acceleration, the amount of normal force between each wheel and the ground can be found. Since deciding between three and four wheels was one of the major design objectives, mass transfer effects for both a three-wheel robot and a four-wheel robot were considered. The actual derivations of the mass-transfer formulas were too complex to carry out by hand, thus Maple was used to find the formulas. The full derivation for both the three and four-wheel robot can be found in the Appendix or the Maple file *mass_transfer.mws* on the computer *Christie* under *D:\ME2003\Preliminary Documentation*. The derivation process of the mass transfer equations for a three-wheel robot is detailed below. Derivation for the four-wheel robot is extremely similar and is thus omitted.

First, assuming the robot is perfectly rigid, perfectly aligned, and that the wheels have elastic contact with the ground, the normal force on each wheel is a linear function of distance from the perpendicular axis (see Figure 2-8 for variable definitions). Defining unknown constants A and B, the linear relationship can be expressed as:

$$\begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} = A \begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix} + B \Rightarrow \begin{matrix} N_1 = Al_1 + B \\ N_2 = Al_2 + B \\ N_3 = Al_3 + B \end{matrix} \quad [2.2.1]$$

Next, applying force balance in the vertical direction, the sum of the normal forces must equal the weight of the robot:

$$N_1 + N_2 + N_3 = mg \; [2.2.2]$$

Plugging in the linear relationships from equation [2.2.1] yields:

$$Al_1 + Al_2 + Al_3 + 3B = mg \; [2.2.3]$$

Solving for the unknown constant B yields:

$$B = -\frac{1}{3}Al_1 - \frac{1}{3}Al_2 - \frac{1}{3}Al_3 + \frac{1}{3}mg \quad [2.2.4]$$

Next, moment balance about the axis perpendicular to the direction of acceleration can be used to get a second equation:

$$-maH = l_1 N_1 + l_2 N_2 + l_3 N_3 \; [2.2.5]$$

In these equations, *H* is defined as the height of the center of mass and *a* is the magnitude of acceleration, and *m* is the mass of the robot. Plugging in the linear relationships from equation [2.5] and solving for the unknown constant A yields:

$$A = -\frac{m(3aH + l_1 g + l_2 g + l_3 g)}{2(l_1^2 + l_2^2 + l_3^2 - l_1 l_2 - l_1 l_3 - l_2 l_3)} \qquad [2.2.6]$$

Since both unknowns *A* and *B* have been found, equation [2.2.1] yields the desired mass transfer equations for the three-wheel robot. However, it is desirable to have these equations in terms of distance from center of mass (l), location of wheel with respect to front of robot (θ), and the direction of acceleration (ϕ). This relationship is a simple trigonometric relationship, and can be expressed as:

$$l_n = r_n \cos(\theta_n - \phi) \qquad [2.2.7]$$

The final mass transfer formulas for the three-wheel robot can be found by plugging in the constants *A* and *B* into equation [2.2.1], plugging [2.2.7] into the result, and simplifying. The mass transfer formulas for a four-wheel robot can be derived using the same methods outlined above. The final formulas are too complex to list in the text portion of this report, but can be found in the maple derivation, which is included in the Appendix.

These mass transfer formulas yield the normal force on each wheel as functions of the wheel geometry, number of wheels, and the direction and magnitude of acceleration. These relationships become especially important when looking at the location of the center of mass of the robot. If the center of mass is too high, then a small acceleration can in fact cause so much mass transfer that the robot tips over! Further, if the center of mass is not at the geometric center of the robot, then the robot will have undesirable mass transfer effects in certain directions. Since one limitation of acceleration is traction, it is desirable to have equal weight on each wheel. Thus, mass-transfer effects are generally undesirable. As a rule of thumb, the center of mass of the robot should be as low and towards the geometric center of the robot as possible.

2.2.3.2.4 MATLAB Acceleration Analysis

The previous sections have outlined different types of design decisions that can affect drive characteristics of a robot. Several of these properties, such as mass transfer, traction, and wheel layout have proven to be non-trivial. Thus, developing simple formulas to quantify a robot's ability to accelerate is not feasible. However, computer algorithms can be developed to look at all these different factors and to quantify how fast a given robot can accelerate in any given direction with any rotational velocity. MATLAB scripts were developed to do precisely this, and construct a graph depicting the maximum acceleration as a function of angle, robot and field properties, and rotational velocity. This section outlines what the tool is, how it works, and how to use it. This tool is intended to aid research and analysis on various design issues, including three vs. four wheels and increasing acceleration. All acceleration profiles used in this report were generated using these MATLAB tools.

2.2.3.2.4.1 Important Assumptions

The MATLAB functions were developed under the assumption that a robot is friction-limited. In other words, a robot can accelerate in a given direction with a given magnitude only if all four of its wheels maintain static friction with the ground. Therefore, the acceleration profiles developed using this script are not quite complete. The other possible limitation of acceleration is the capabilities of the motors. The profiles generated by this program are accurate only if the motor and gearbox can actually output the necessary torque to achieve these accelerations.

2.2.3.2.4.2 Detailed Description

While the MATLAB acceleration profile is generated under the assumption that motors are not limited in torque output, it is also important to understand what factors are accounted for in the program that creates these profiles. The following list outlines characteristics that are taken into consideration when generating acceleration profiles:

Mass Transfer: Perhaps most importantly, the program takes into consideration the mass transfer effects that occur during acceleration. When the robot is accelerating quickly, much of the weight of the robot becomes concentrated on a couple wheels, and less on the other wheels. The program will determine that maximum acceleration in a given direction has been obtained when any given wheel slips with the ground. Decreased normal force due to mass transfer is accounted for.

Coefficient of friction: The program assumes a constant coefficient of friction, however any coefficient of friction can be set as a parameter.

Wheel Layout: The program accepts any wheel layout. Functions to generate standard wheel layouts are provided, however these functions need not be used. Thus, nonstandard layouts (such as pointing the wheels in random directions) can be set as well.

Center of Mass: The program accepts any location of the center of mass

Torque Distribution: Given a direction and magnitude of acceleration, the program determines the optimal amount of torque to apply to each motor to achieve the desired acceleration. For three wheel systems, this is a one-to-one correlation; however, a four-wheel system must be optimized, as different combinations of torques can achieve the same acceleration.

2.2.3.2.4.3 Required Files

There are eight files included, many of which are required to generate an acceleration profile. These files are listed below, with a brief description of what each file does. Usage instructions and comments are provided in the files, thus are omitted from this documentation. These files are available in the appendix.

PlotAccelerationEnvelope.m: This function is the file that actually calls the necessary functions to generate an acceleration profile, and generates the plot.

Accel.m: This function takes a direction magnitude of acceleration, and determines how much torque is necessary to apply to each wheel to achieve that acceleration. For four-wheel systems, this is done using a least-squares optimization.

AccelerationEnvelope.m: This function generates the data used to plot the acceleration envelope. However, it does not plot the data.

GetSymmetricGeometry.m: This is an optional function that can be used to quickly generate a “standard” omni-wheel layout. This function accepts wheels located at any angle. However, it assumes that all the wheels are tangent to a circle centered at the geometric center of the robot.

GetVirtualRobotParameter.m: This function outputs any desired parameter of a virtual robot. A virtual robot is a data structure used to store all the information about a robot.

MakeVirtualRobot.m: This function takes all the different properties of a robot, such as friction, wheel location & geometry, mass, and moment of inertia, and outputs a single "virtual robot" data structure that stores all the information. This data structure is required as in input by most other functions.

MassTransfer.m: This function calculates how much weight (normal force) exists between each wheel and the ground, given robot parameters and desired acceleration.

Aetemplate.m: This file is a template that is essentially a tutorial. It walks a user through all the necessary steps to create an acceleration profile, and plots the profile at the end.

2.2.3.2.5 Number of Wheels

Altering the number of wheels in an omni-drive system can significantly change factors that affect acceleration. The 2002 documentation, section 4.1.3.3, outlines acceleration capability for a four-wheel system versus a three-wheel system. However, this analysis is incomplete since it ignores the effect of different weight distribution of the two systems. With fewer wheels, more weight is distributed to each wheel. Thus, if both three-wheel and four-wheel robots are friction-limited, the three-wheel robot has more frictional force per wheel. Perfect omni-geometry and center of mass location is assumed for this analysis. The effect of wheel geometries is discussed in the next section. If n is defined to represent the number of wheels, these ideas can be expressed as formulas. The normal force of each wheel can be expressed as:

$$N = \frac{mg}{n} \quad [2.3.1]$$

Since the maximum frictional force a wheel can provide is proportional to this normal force, the maximum force a wheel can apply to the ground can be found:

$$F_{\max} = \mu \frac{mg}{n} \quad [2.3.2]$$

This simple analysis shows that as the number of the wheels increases, the frictional force that can be obtained with the ground decreases. Thus, while adding more wheels yields more motors to apply torque, less torque can be applied before the wheels slip. Thus, the relationship between the number of wheels and acceleration characteristics is not trivial.

Comparison of Acceleration Profiles

In order to compare acceleration characteristics of a three-system and four-wheel system, the MATLAB simulation was utilized to generate acceleration profiles of each system. The primary question of interest was to determine which system could accelerate faster. To make this comparison, we ran two simulations, one for each system. All physical properties of the robot, including mass (2.5 kg), coefficient of friction (1.0), and center of mass (4cm high, geometrically centered) were set equal for each system. Figure 2-9 shows the two acceleration profiles superimposed. This profile can be regenerated by running the MATLAB file *perfect3vs4_4cmup.m.*

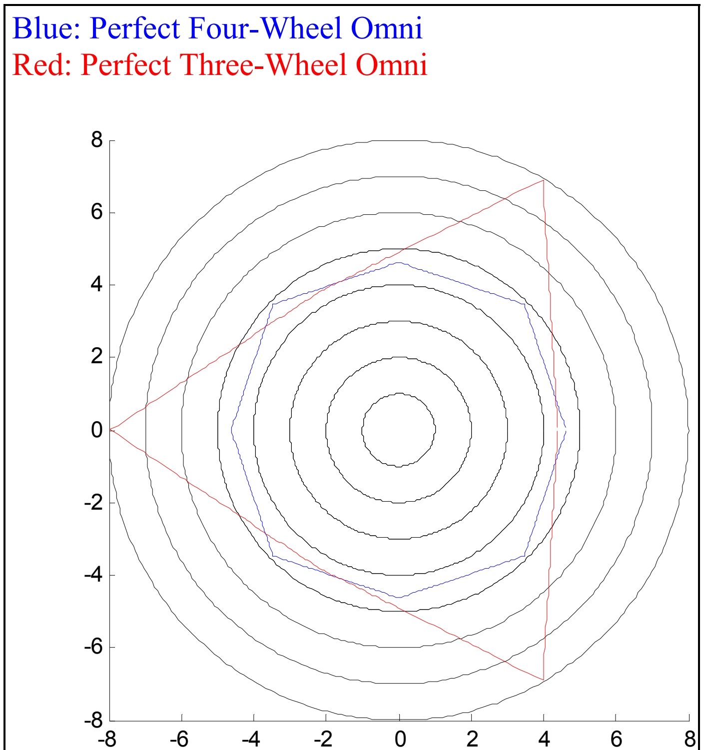


Figure 2-9Acceleration Profile

Figure 2-9 clearly shows that in certain directions the three-wheel system is able to accelerate much faster than the four-wheel system. Acceleration straight backwards, for example, is much better with the three-wheel robot because the weight shifts onto the wheels accelerating the robot backwards, allowing the wheels to grip the carpet with more normal force than usual. However, the three-wheel system is slightly worse than the four-wheel robot in certain directions.

Testing

As stated earlier, we are primarily interested in increasing the maximum acceleration that the robot can achieve. After much theoretical discussion on the merits of three-wheel vs. four-wheel configurations, testing would have to be done to determine which configuration would provide the best results.

Total System Test: Properties

Closed-loop test

Testing at multiple drive angles. 0°, 45°, 90°, 120°, 180°

Three configurations

9:1 gear ratio

High-traction DSR wheels

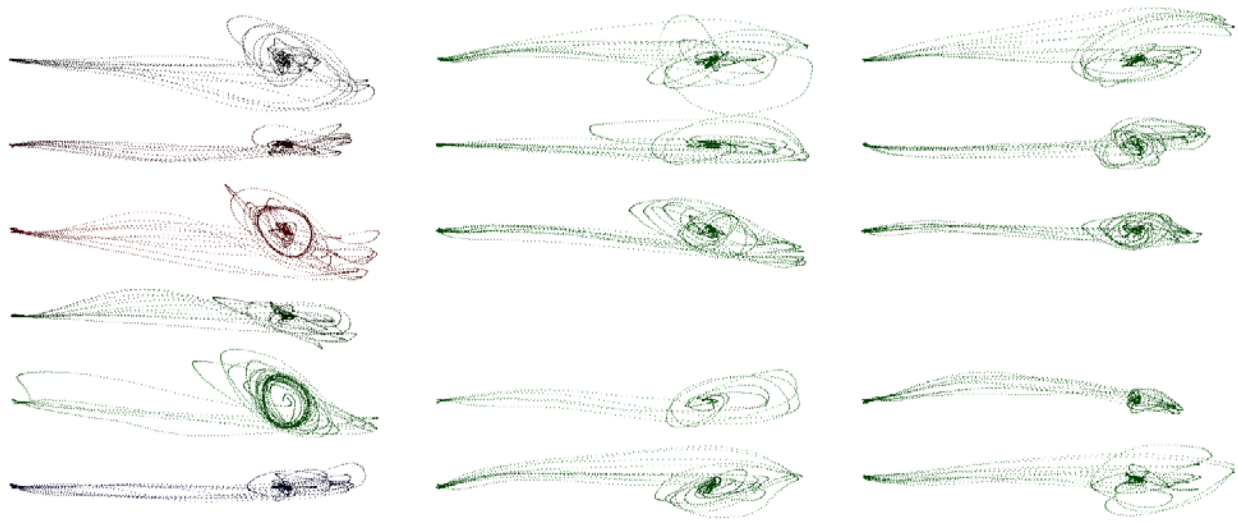


Figure 2-10 Time-Trajectory plot of Drive Geometry test

3 Wheel 4 Wheel 4 Wheel Butterfly

This figure (2-10)displays a time history of the location of the robot. Subjectively, it appears that any improvement in traction will greatly help both three and four wheel configurations. It is important to note that accuracy of the hat placement contributed more to the accuracy of control than traction or wheel configuration. It should be noted that the traces showing ovals were taken after battery changes where the hat was not oriented with the target aligned to the drive system.

Both the "perfect four" and "butterfly four" could be accurately controlled in almost any direction, contrary to the behavior seen in the 2002 robots. This test was for acceleration, not control, but it showed weakness in the butterfly when moving forward.

The location plots captured by the vision system showed that the three wheel configuration was not as accurate as the four wheel configurations, contrary to observations made of the 2002 and 2001 robots. The most likely reasons that our subjective evaluation doesn't match this objective test are improvements in traction and vision latency. Perhaps the greater acceleration of the four-wheel system combined with relatively large latency of the vision system, caused greater overshoot, with less perceived control in the four wheel system.

2.2.3.2.6 Wheel Layout

Once the number of wheels has been chosen, it may become necessary or desired to change the location or direction of wheels out of the ideal omni direction. The location of wheels can affect robot acceleration in a couple different ways. First, the geometry dictates what direction each wheel can apply a force in. If all the wheels point in the same direction, for example, then the robot is incapable of accelerating in any other direction. Ideally, a robot would be mechanically capable of accelerating in any direction, thus it is desirable to lay out the wheels such that there are no directions with poor acceleration capability. Second, mass transfer is a function of wheel layout. If the wheels are located close to the center of the robot, the robot will easily tip over during acceleration. However, if the wheels are as far out from the center and equally spaced along the perimeter of the robot, the effect of mass transfer will be much less significant.

One of the major design problems that is typically encountered every year is how to locate the front wheels such that they do not interfere with the dribbling module. Due to this consideration, past teams have opted to flare the front wheels out and back – a configuration that has been termed the "butterfly configuration." In order to understand how these different configurations affect acceleration, we used the aforementioned MATLAB acceleration profile generators to compare perfect-omni profiles to butterfly profiles. Figure2-11 shows the comparison for a three-wheeled robot (left), and the four wheel robot (right). Each butterfly configuration flares the front wheels outward by ten degrees, thus increasing the angle between the front wheels by twenty degrees. These profiles can be generated with the MATLAB file *perfectvsbutterfly_3wheel.m* and *perfectvsbutterfly_4wheel.m*.

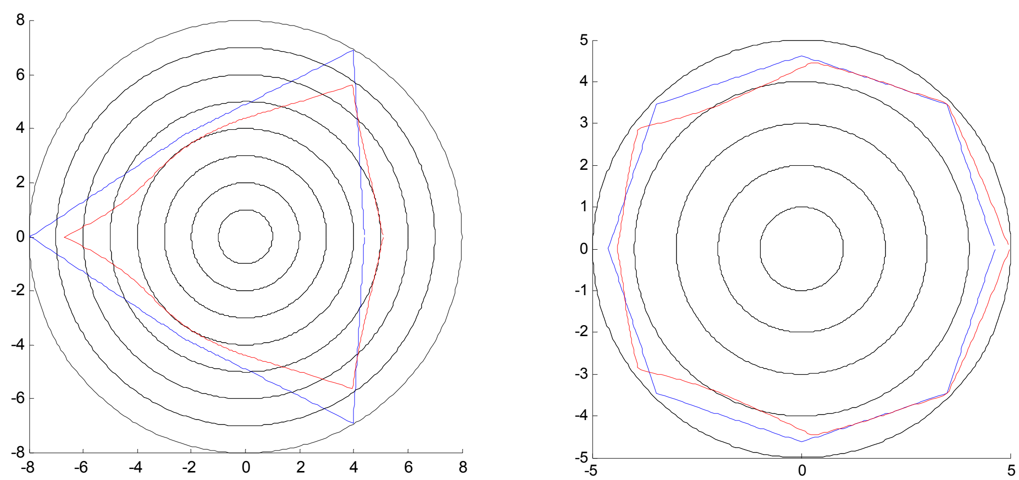


Figure 2-11 10-Degree Flare Acceleration Envelope

Figure 2-11 shows that a ten degree flare does affect the acceleration profile. The change clearly is more dramatic for the three-wheel system, and less dramatic for the four-wheel system. For both systems, however, the flaring allows the robot to accelerate faster in the forward direction, and less fast in the backwards direction.

2.2.3.3 Wheel Size & Style

One of the topics that was addressed while doing preliminary design was wheel design and size. One option was trivial, which was to use the same wheels as previous years. However, with new wheels, it would be possible to achieve better traction, take up less space, and be less of a maintenance hassle than previous years. We had two styles of wheels in mind: *dual staggered roller (DSR) wheels* and *single inline rollers (SIR) wheels*.

2.2.3.3.1 Single Inline Roller "SIR" Wheels

The first type of wheel we looked at was inspired from two places. First, Patrick had experience with these types of wheels in the F.I.R.S.T. Robotics Competition. Second, similar wheels were used in 2002 by the FU Fighters, and their robots had very impressive acceleration. Although the FU Fighters have already demonstrated that these types of wheels are both feasible and effective, we decided to design a prototype wheel to determine the machinability of the wheel. The following picture shows the finished prototype:

Figure 2-12 SIR roller

With regard to friction, these wheels are very similar to aluminum rollers machined for the 2002 wheels. The similarity exists because the concept is the exact same, having small cleats dig into the carpet. With these wheels, several team members felt that this design can be slightly modified to have rollers with rubber inserts or O-rings around the perimeter, so that we do not risk being disqualified for damaging the carpet. Additionally, it is possible that small rubber cleats could in fact have a larger coefficient of friction than the aluminum cleats.

2.2.3.3.2 Dual Staggered Roller "DSR" Wheels

The dual staggered omni wheels used in 2001 and 2002 have served well, but it is our assessment that we should and could do better. To achieve better performance and handling, we have designed several variants and alternatives. With the goal of lowering the center of gravity of the robot, all of our proposed wheels have larger overall diameters. The increased clearance affords

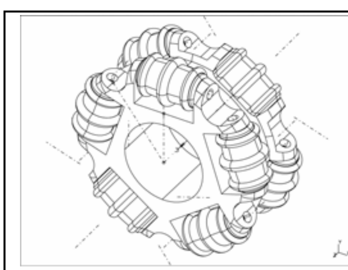


Figure 2-13 63.5mm Wheel with Composite Rollers

space below the drive components that can be used for battery storage, which will help to lower the CG of the robot.

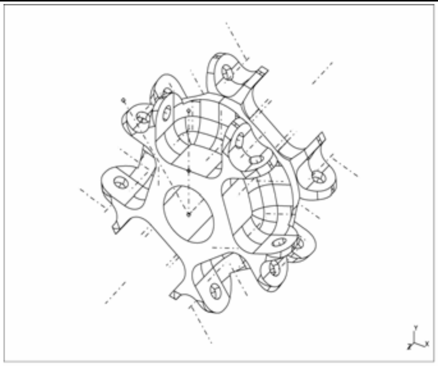


Figure 2-14 48mm Wheel Hub

A larger, 63.5mm version of the Dual Staggered Roller (DSR) wheel was designed to accommodate the gearbox of the 2002 motor assembly within its hub (Figure 2-13). Utilizing flatter, larger diameter composite rollers, it was designed to overcome many of the 2002 wheel's shortcomings. The hub is to be machined out of aluminum or Delrin. Fabrication would involve the CNC lathe and the Okuma VMC with a manual indexing divider head.

With the discovery of the Maxon EC45 brushless motor, a follow-on 48mm DSR wheel was designed, for direct drive. This wheel gives 150mm of linear motion per revolution. Differing from the 63.5mm wheel, it does not accommodate the gearbox of the 2002 motor assembly. The hub, shown in Figure 2-14, is simpler than the 63.5mm wheel to fabricate, requiring the CNC lathe, and a multi-setup fixture in the Okuma VMC.

2.2.3.3.3 Wheel Bouncing Effect

Since much research was done into new types of rollers and wheels, and most all of these new designs introduced non-continuous radius along the circumference of the wheels, there is some bouncing effect as the wheels rotate. Thus, an equation was derived for quickly determining how much a given wheel design will bounce up and down as it rotates. Since the derivation is a relatively straightforward use of trigonometry, only the resulting formula is shown:

$$\Delta R = R\left[1-\cos\left(\frac{180^\circ}{n}\right)\right]$$

As a simple example, the amount the prototyped SIR wheel is shown below:

$$\Delta R = (3.04cm)(1-\cos(180^\circ/16)) = 0.058cm = 0.58mm$$

Given that the playing field is a carpeted material and that these rollers may contain rubber in the future, this type of bouncing distance is not expected to significantly affect the performance of the robot. However, it should be kept in mind when examining control problems, especially if we use accelerometers or optical mice sensors.

2.2.3.4 Motor Selection

At the beginning of the semester, it was a forgone conclusion that the 2002 motor assembly would be used for the 2003 robot. The 2002 design utilized the most compact assembly of motor, gearbox, and encoder that we could find. Along the way though, a team veteran mentioned that they had purchased several Maxon EC 45 brushless DC "Pancake" motors, but had not had time to sufficiently test them.

Perusal of 2002 and 2001 documentation had made mention of investigations into DC brushless motors, but dismissed the possibility of their use for reasons beyond control of the ME team. It became apparent that the reason that the 2002 team had not pursued this motor was that the diameter of the motor exceeded the diameter of the DSR wheels used, and that a suitable gearbox was not found in time.

Before proceeding, it is important to note the reasons why we feel compelled to use the EC 45 motor, and the reasons why it may not be better than the 2002 motor assembly. The main reason that we want to use this motor is space utilization, but performance characteristics are comparable.

While the EC 45's pancake design has a much larger diameter, its axial depth is many times shorter than the 2002 assembly. In the 2002 design, the length of the motors forced the shift of the axial drive intersection points to the rear of the geometric center of the robot, and as mentioned before provides a vertical 25mm thick layer that cannot be used by any other subsystem.

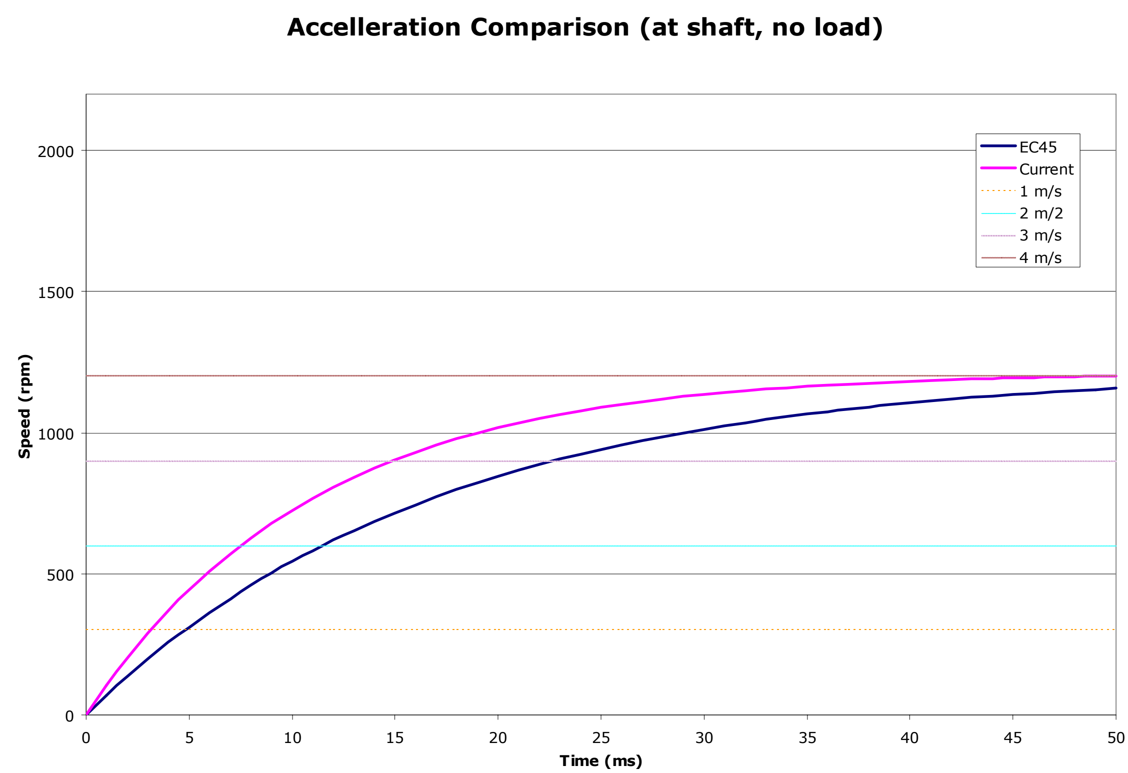


Figure 2-15 Acceleration Comparison

The EC 45 provides ten times the specified torque of the Faulhaber motor of the 2002 drive. In this way, an non-geared EC 45 will outperform the torque output of the 2002 unit after the 9:1 gear reduction. It may be possible to even use the Hall Effect sensors of the brushless motor, to replace the need of an optical encoder. Also, the Hall Effect sensors may be ignored, and commutation may be set independently, since the motor will lock phase like a stepper motor. This will have to be investigated more fully in the future.

The brushless motor does have some drawbacks. It is not as efficient as the brushed motor, with a peak efficiency of 77.6% vs. 82%. A completely different electronic control scheme has to be used, as the EC 45 requires half H-bridges to drive three phases, with circuitry deciphering the Hall effect sensor outputs into commutations. The brushless DC motor requires a bipolar supply, or a unipolar supply of twice the voltage. Even with the differing drive circuitry, the motor would still be controlled by Pulse Width Modulation (PWM) signals, so the EE redesign would be kept to the periphery.

After discussions with other team members and a dissection of an EC 45 motor we have decided to develop a gearbox to use with the EC 45 motor. This motor does have a set of pre-loaded ball bearings, but they are not sufficient to take the abuse of having the wheels directly mounted on the motor shaft. The proposed gearbox would have a ratio of 2.7:1, and would incorporate a reflective optical encoder on the motor mounted pinion gear.

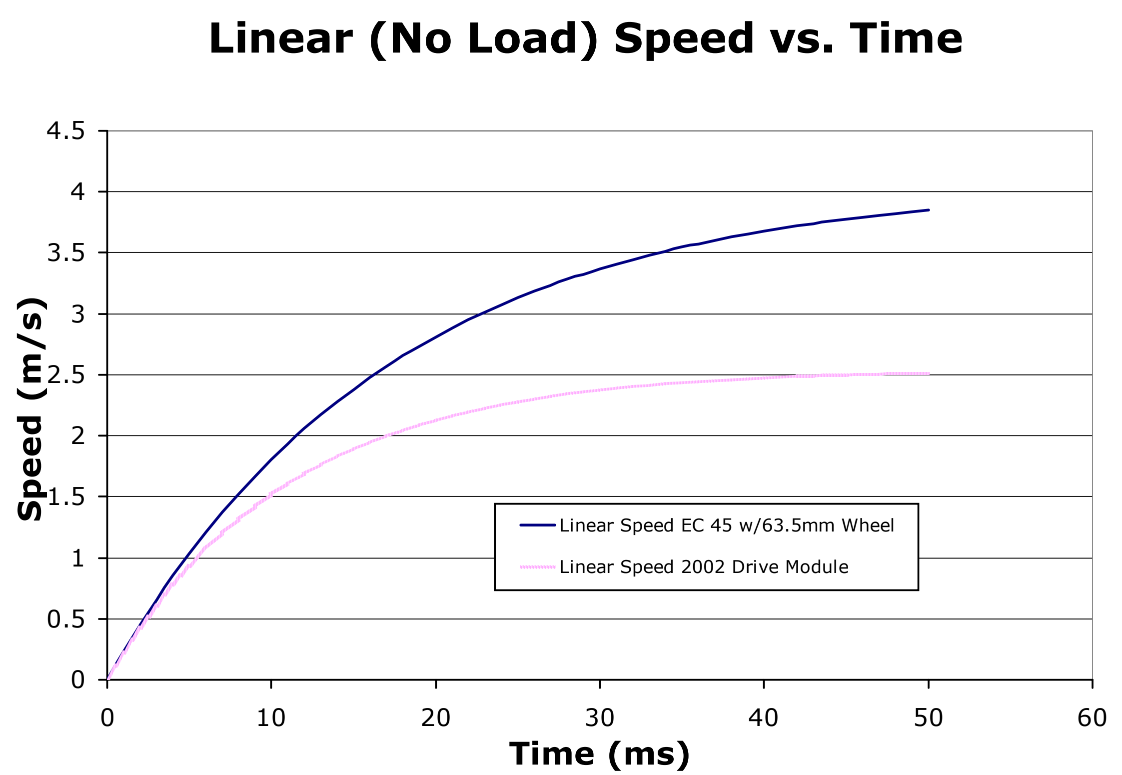


Figure 2-16 Linear Speed Comparison

Figure 2-16 shows a graph of theoretical no-load linear speed vs. time of the 2002 drive module, plotted against the EC 45 motor with a 2.7:1 gearbox and the proposed 63.5mm wheel. It should be noted that the supply voltages are not the same, with the Faulhaber motor being driven over voltage with a supply of 12V, and the Maxon motor being driven under voltage with a supply of ±9V. Still, the brushless motor would deliver an almost identical amount of torque and power to the wheel, as shown in Figure 2-15. Because of the difference in wheel diameter, less wheel slippage and higher velocities should result.

The gearbox that will have to be constructed, will serve as a drive mount, the basis of a drive module. Since the motor would not be encased, it should be much easier to construct this gearbox compared to the drive mounting module used in the 2002 design.

In summary, we feel that the benefits of moving to a pancake brushless DC motor outweigh the hurdles that we will have to overcome. Unfortunately, the control circuitry and testing was not completed in sufficient time to use the DC brushless motors. Concerns about power-consumption are unresolved, and further research will have to be done.

2.2.4 Major Design Decisions

2.2.4.1 Three vs. Four Wheels

The decision between three and four wheels was a long and hard decision. In 2001, when a three-wheel robot was used, the control was very good. However, the acceleration was lacking. In 2002, the control was relatively poor, but the acceleration was much better. Prior experience therefore yielded no clear solution. In the end, we decided to take a look at all the analysis that had been done, in addition to conducting performance tests to determine which system would better achieve the design objectives.

The first thing that we looked at was performance tests. These tests, outlined in an earlier section of this document, compared the trajectories of a three-wheel perfect omni, a four-wheel perfect omni, and a four-wheel butterfly configuration. The purpose of these tests was to see how closely each configuration could move from one point to another without going far off course. To the surprise of much of the team, the tests showed that the three-wheel configuration did not perform any better than four. In fact, the three-wheel configuration was somewhat worse. Since the same motors were used in all the configurations, along with the same trajectory generation and vision system, this test provided as accurately as possible a measure of how well each system could be controlled. While experience from 2001 and 2002 suggested that a three-wheel system might have better control, this test was more conclusive, because it eliminated all the other system-level and design differences between 2001 and 2002. The testing used the same motors, the same vision system, the same accelerations and velocities, and the same trajectory generation. Thus, the conclusion from the testing was that the four-wheel system is not more difficult to control than the three-wheel system.

The second source of information that we used to make a decision was the acceleration profiles generated using the MATLAB scripts. The comparison between perfect-omni configurations for three wheels and four wheels showed quite clearly that in general, a three-wheel system can accelerate faster than a four-wheel system. However, the three-wheel system had drastically different acceleration limitation depending on what direction it was accelerating in, while the four-wheel system had a fairly constant acceleration limit.
Again, these results were very surprising because a comparison between the 2001 and 2002 robots would suggest that a four-wheel robot has much better acceleration ability. Once again, the discrepancy was explainable. In 2001, the controls on board the robot limited acceleration to a relatively small amount. Further, less powerful motors were used in 2001, in addition to less efficient gearboxes with different gear ratios. The wheels on the 2001 robots did not slip with the ground, thus the assumption that the robots were friction limited was also invalid. Thus, it made no sense to infer that a four-wheel robot is faster than a three, based solely from comparing 2001 to 2002.

After careful consideration, we decided that the four-wheel system would be a much wiser choice than a three-wheel system. This decision was made for several reasons. First, the testing demonstrated that at equal accelerations, a three-wheel robot was equally hard to control (if not harder) than a four-wheel robot. Second, the maximum velocities that AI sends to the robots are set as constants. This implies that in order to have robots that will not slip and lose controllability, the maximum acceleration constant must be set to the minimum possible acceleration before the robot slips *at any acceleration angle*. In other words, the acceleration constant must be set to the radius of the largest possible circle in the acceleration envelope that does not pass through any plotted lines. Looking at the acceleration envelopes for the three vs. four-wheel designs, it is evident that this constant will be about the same for both systems. Thus, the acceleration envelopes suggest that the acceleration characteristics for each system would be about the same. Finally, the third factor we considered was the amount of torque each motor would be required to provide.

Since either system (assumed to be friction limited and that as there is no cap on voltage to be delivered to the motors) would have similar maximum accelerations, a three-wheel system would be required to provide more torque from each motor, on average, to achieve the same acceleration. This average is simply inversely proportional to the number of wheels. Less wheels would imply that there would be more torque required by each wheel to achieve the desired acceleration. Thus, it can be inferred that for a three-wheel robot, each motor would have an average voltage approximately 33% larger than with a four-wheel robot. To decrease the number of batteries necessary and to lessen the risk of burning out the drive motors, the clear choice is a four-wheel robot. In the end, we decided on four-wheels because it was successful in 2002, and we had no evidence at all that a three-wheel system would perform better than a four-wheel system, either with acceleration or control performance.

2.2.4.2 Motor Selection

A decision made was to continue using the Faulhaber 2224 motors from the 2002 robot. Despite hopes that testing could be completed in time to use the brushless DC motor, the unknowns of power consumption, and the ability of the EE team to make an adequate controller forced a retreat to the proven drive components. Contributing to this decision was the added manufacturing and design burden of creating a matching gearbox with an integral high-resolution encoder. This was a task that time was not budgeted for.

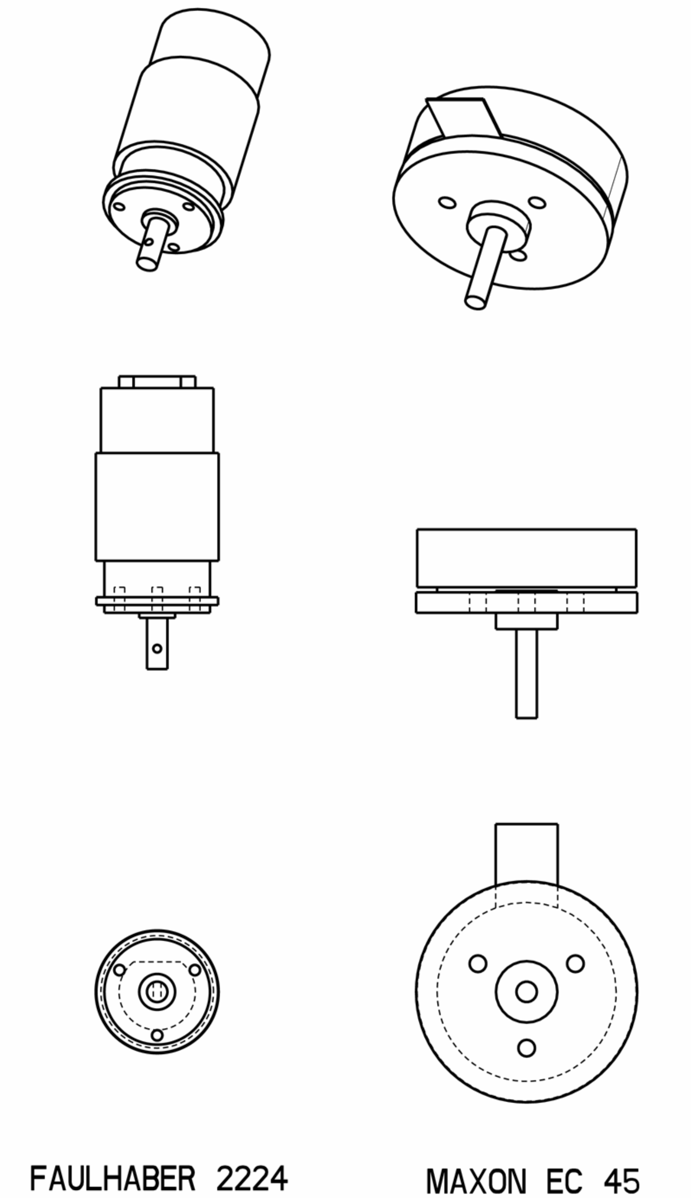


Figure 2-17 Motor Comparison

2.2.4.3 Gearbox Selection

After deciding between three and four wheels, we immediately proceeded to select the appropriate gearbox for the drive system. The two gearboxes available for our selected motor were 13.5 and 9.0 (used in 2002). Gearboxes with ratios larger than 13.5 were available for use; however, these were not considered because they were too large and would severely decrease space available for the kicking system. Using 2002 as a reference, it was quickly realized that it was necessary to increase the gear ratio. First, the SIR wheels were slightly larger in diameter than the 2002 wheels, so we would need to be able to provide more torque to obtain equal accelerations. Second, the new wheels had a much larger coefficient of friction; so much quicker acceleration was possible. Thus, increasing the gear ratio of the motors would guarantee that the wheels indeed would be able to provide the necessary torque to achieve the acceleration.

2.2.4.4 Wheel Type

At about the same time that the number of wheels was determined, a decision was made on the type of wheel that would be used. The larger 63.5mm DSR style wheel was designed to recess the Faulhaber motor and gearbox within its hub, which gave it a radial space advantage. Unfortunately its manufacture was complex, requiring exotic machining setups. The SIR wheel could not recess the gearbox in its hub, but was half as wide as the any of the DSR wheels and much easier to fabricate. The commercially sourced DSR wheels used on the 2002 robot were determined to be too space inefficient compared to the newer designs, and were thus considered unacceptable.

The loss of availability of a CNC mill with a fourth axis made the fabrication of the DSR wheel near impossible. Likewise, the code to cut the rollers designed for this wheel proved overwhelming to the aged CNC lathe available for use. These manufacturing problems were a contrast to the simplicity of the SIR style wheel, and this was the primary reason this style was chosen. It was also observed that the SIR wheels did not make the robot “shimmy”, as the DSR wheels did at low speed.

After designing and building a prototype SIR wheel, its advantages quickly became apparent. First, the wheel was much smaller in thickness. This would allow the drive motors each to move out a half inch. As a result, the kicking subsystem would have much more space at the bottom of the robot, making an inline kick possible. Almost entirely for this reason, the SIR wheel clearly became the preferred wheel. As explained in the preliminary analysis section, equal traction can be obtained with either design, so traction was not a factor considered when deciding between the two types of wheels.

2.2.4.5 Wheel Location

After deciding between three and four wheels, it became necessary to decide where the wheels would be placed. For simplicity and for possible performance advantages, it was desired to put all the wheels at a constant radius from a single geometric center. Further, the drive team felt that angles used in 2002 was a good compromise between drive performance and room for the dribbling system. Thus, it was desired, if possible, to use the same angles used in 2002.

2.3 Design Documentation

2.3.1 Motivation & Goals

Although the 2002 robots were much improved from 2001, there was much motivation to improve the design further for 2003. First, a more compact drive system would have several positive effects for the entire robot. For example, the dribbler system would have more room, and the kick system might be able to utilize an in-line kick, eliminating several design problems in that system. Second, reliability was desired. The robots should not require much maintenance, and if maintenance is required, it should not take long. For example, the drive wheels should be easy to remove in case a wheel is damaged. Finally, and most importantly, the design objectives must be met.

2.3.2 Design Approach

It would be nice to think that after preliminary work was done, a design congealed in the near final form, but that did not happen. In actuality, a successive string of decisions were made that forced other aspects and problems to materialize. Because of this, the drive and chassis design did not materialize in any logical order. In general, the design was made from the bottom up. In other words, the wheels were first designed, then the motor mounts, then the chassis. Once a preliminary design had been made, many revisions (and even complete redesigns) of parts were necessary to eliminate arising problems. After a number of iterative steps, the design slowly morphed into a final design, with less and less problems arising and changes needing to be made.

2.3.3 Initial Design

2.3.3.1 SIR Omni-Wheels

A prototype of the SIR omni-wheel was machined by hand. The wheel consisted of 16 aluminum rollers, with cleats to dig into the carpet. The wheel has a diameter of 2.5", which much larger than the 2002 omni-wheels.

Shortly after making the prototype wheel, however, it was determined that the aluminum cleats should not be used because they tear up the playing field carpet and therefore risk disqualification. Thus, the team pursued the idea of using rubber o-rings to act as the contact material between the roller and the ground. This motivated a different design of the roller. Instead of having a small cleat to dig into the carpet, a roller was designed with a recess such that the rubber o-ring could securely snap onto the roller.

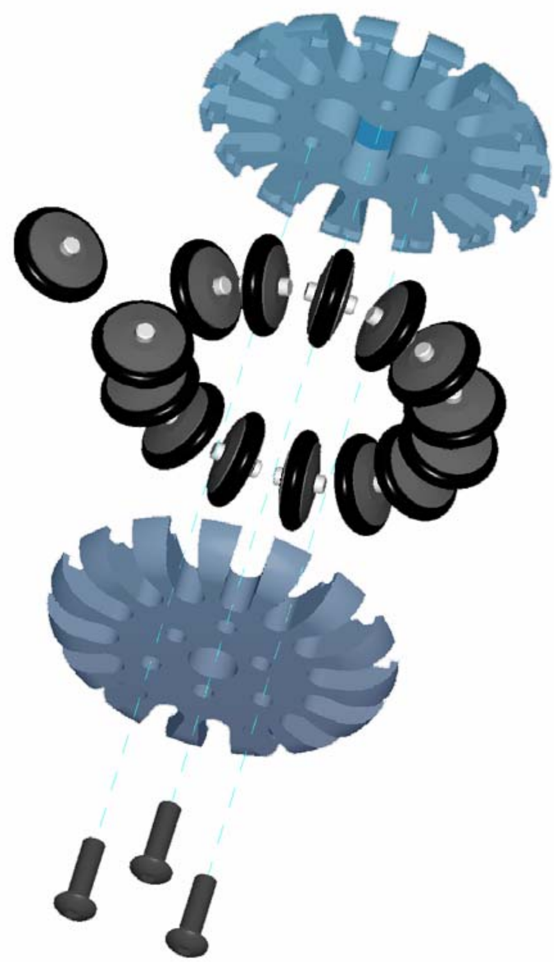


Figure 2-18 SIR Omni-Wheel Assembly

Two different materials for the o-rings were tested. The first was Buna-N, the standard o-ring material that can be found in most any hardware store. The second was silicone, a softer type of rubber. After assembling a wheel with each type of o-ring, it was casually determined that the silicone o-ring would be unsuitable, and that the Buna-N would likely work quite well. When rubbing the wheel against the playing field carpet, it was easy to tell that the Buna-N o-ring had much better traction. Additionally, it was not very difficult to destroy the silicone o-ring by hand, while it was very difficult to destroy the Buna-N o-ring. Thus, the Buna-N o-ring was chosen for the final roller design.

After choosing an o-ring type, the proper material for the roller itself had to be selected. All prototyping had been done using aluminum, but two other materials were also considered. The first was Delrin plastic, and the second was brass. These materials were considered because aluminum tends to deposit residue when in constant contact with another metal. Thus, over time, the quality of the contact surface between the roller and the axle may degrade. As a result, friction between the roller and the axle may increase. Both plastic and brass do not have this tendency to deposit any sort of residue. Thus, Delrin was initially chosen as the material to be used for the roller. Delrin was chosen over brass because brass is much heavier than Delrin.

A second design issue with the wheel was the number of rollers and diameter of the wheel. A large number would reduce the amount of "jitter" of the robot. However, if there were too many rollers, the amount of material supporting the rollers would yield. After communication with the rest of the mechanical team, a wheel diameter of two inches was chosen. This was the smallest size wheel that was feasible (in the opinions of the drive team) to manufacture. In order to maximize the room available to other components, we thus chose a wheel diameter of two inches. Correspondingly, the number of rollers was reduced to fifteen.

2.3.3.1.1 Wheel/Hub Integration

The SIR design used an external hub flange, which lengthened the overall drive module. This flange had stability and fastening issues, as guaranteeing an orthogonal mounting on the gearbox output shaft would be difficult, if not impossible. A cloverleaf-shaped internal hub was designed, and the SIR wheel modified to accommodate this hub, so that no unnecessary extra length would be added to the drive module. This hub is held onto the drive shaft by a solid pin, which is in turn retained by the wheel hub.

2.3.3.2 Chassis Design

With the number of wheels and wheel style selected, details of configuration and wheel size were yet to be determined. As acceleration testing progressed, three separate solid models were constructed to match the wheel configurations that were being tested. These corresponded to the three-wheel (120° equiangular), and four-wheel (90° equiangular and 110° butterfly) configurations. Two proposed wheel diameters were also modeled: 63.5mm and 51mm.

Configuration	Wheel Size (mm)	DribblerSpan (mm)
2002 Actual	40 (DSR)	107.3
3 Wheel	50.8	106.3
	63.5	97.2
4 Wheel	50.8	73.3
	63.5	62.1
4 Wheel Butterfly	50.8	96.1
	63.5	86.2

Table 2-3 Summary of Drive Configuration and Dribbler Size

The solid models were initially assessed for fitness by comparing the linear span between the front wheels, as a dribbler mechanism would have to fit. The 2002 dribbler was used as an acceptable baseline, with some allowance made for the fact that the SIR wheel had a drastically different footprint than the DSR wheels previously used. It was apparent that the "perfect four" model would not work with either wheel size, and the "butterfly four" would not work with the 63.5mm wheels, as any of these combinations would not leave enough room for the dribbler mechanism.

It should be noted that with the overall drive module length reductions, it is now possible to have the intersections of the drive-axes for all modules to be coincident at the center of the 180mm containment cylinder. Mechanical interferences in the 2002 robot caused the front motors to have drive-axes intersection to the rear of this point and the rear motors' intersection slightly forward of the front axis intersection, but still to the rear of the geometric center of the robot. The attempt to make common intersections through this geometric center point is to make drive trajectory more accurate.

At this point, select components from other subsystems were inserted into the model. It was apparent that the shortening of the drive modules had other benefits, as now it was possible to put the kick solenoid inline with the ball. The benefit to the kicking subsystem of putting the solenoid inline were deemed to be great enough that configurations that could not accommodate this were deemed unfit. This reduced the options for design consideration, by eliminating the 51mm wheeled version of the three-wheel configuration, as the rear drive motor would then intersect with the kicking solenoid. The remaining contenders were the 63.5mm three-wheel and 51mm butterfly four-wheel designs.

2.3.3.3 Motor Mounts & Heat Sinks

One important aspect of the drive system design is how to mount the motors to the wheels and chassis. From 2002, we found that the wheels were extremely difficult to separate from the robots. In order to separate the wheels, a pin needed to be hammered out. Several times, this removal process resulted in a broken piece. One of the design goals for 2003 was to make the wheels easier to remove. Further, with a new wheel design being implemented (the SIR wheel), wheel replacement should be as simple as possible should the designs require replacement over time.

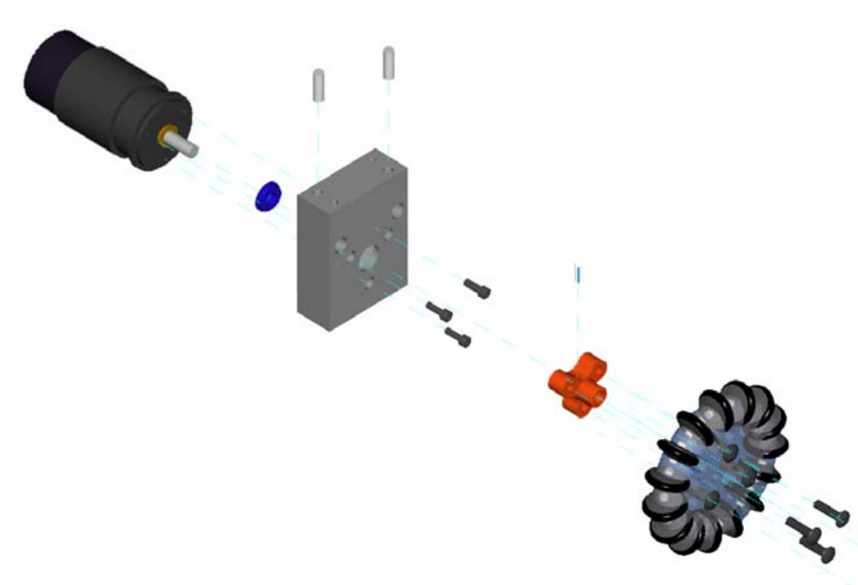


Figure 2-19 Motor mount assembly

A simple way to make a detachable wheel is by utilization of a hub. With a hub, the wheel can be removed from the hub, while the hub remains permanently attached to the motor shaft. For the 2003 design, we decided to use a three-leaf clover shape. As previously mentioned, the shape of the hub is machined out of the wheel, so the wheel attaches to the hub simply by insertion, and using three standard screws to fasten the wheel to the hub.

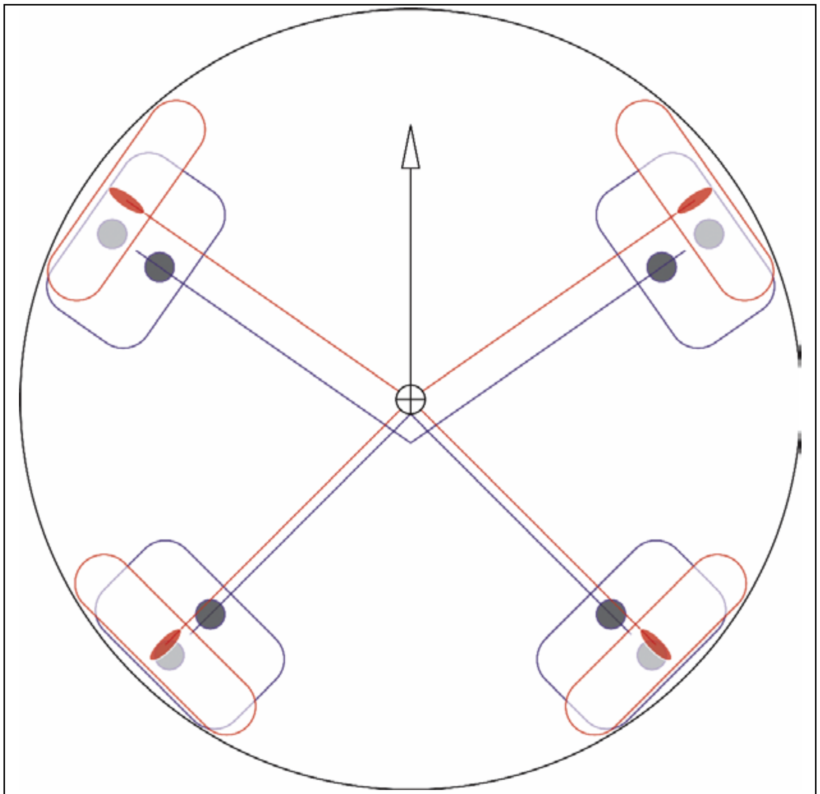


Figure 2-20 2002 vs. 2003 Wheel Layout

The motor mounts were designed to serve two primary purposes. First, they were designed to secure the motor. Second, they functioned as a means to connect the top chassis plate to the bottom chassis plate. One of the important functions of this design is to protect the motor shaft. The motor shaft is directly connected to the wheels without gearing, thus is subject to withstanding all the impulses and forces on the wheels. To support forces perpendicular to the drive axis, a ball bearing was added to the motor mounts. Without this bearing, the motors are not capable (within specifications) of supporting the weight of the robot.

Additionally, the team decided to add heat sinks to the 2003 design. These were added after observations that the motors on the 2002 robots got warm after use. With an increased voltage in 2003, there is greater risk that the motors will burn out. Therefore, heat sinks were added about the back circumference of the motor. These heat sinks are designed to allow conduction out of the motor, up the heat sinks, and into the chassis. It is recommended that thermal paste be used to minimize the contact resistance between the motor surface and heat sink surface.

2.3.3.4 Battery Selection

Batteries had to be fit into the design. The original idea was to have the batteries attached to a removable bottom plate, effectively creating an easily swappable battery pack. Quick-release fasteners would allow the pack to be locked onto the robot, while rigidly mounted electrical connectors would enable the pack to be plugged and unplugged without having to route wires.

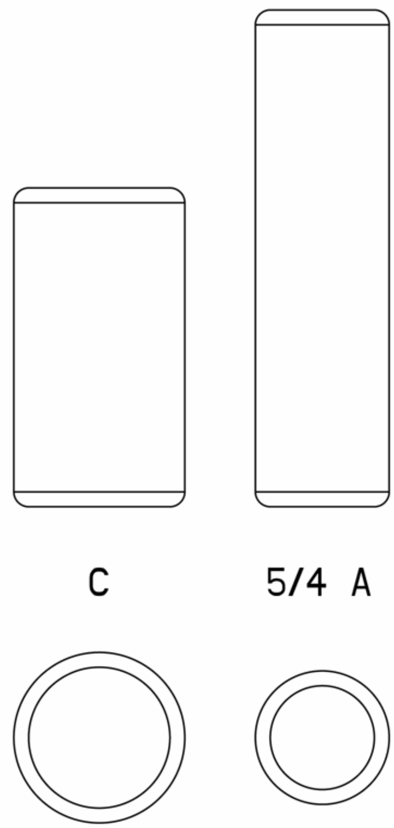


Figure 2-21 Battery Comparison (C vs. 5/4 A)

Figure 2-22 Eating One Battery

In the past, size C Nickel Metal Hydride (NiMH) batteries were used for primary cells. These cells provide adequate power, but their large 23 mm diameter meant inefficient packaging and use of space. In either the three-wheel or four-wheel designs, only ten cells could be fit. It was determined that twelve cells would be necessary to achieve the desired performance.

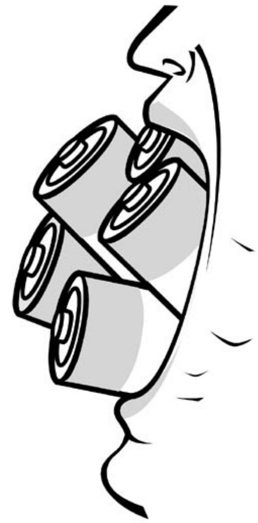


Figure 2-23 Eating Five Batteries

Instead of using size C cells, 5/4 A size batteries were explored. The 5/4 A cells have a smaller diameter of 17-18 mm, but a longer length of 67 mm, vs. 43 mm for C. Fourteen of these cells would fit in the four-wheel design, while it was possible to only fit twelve in the three-wheel. The new cells were longer than the prior size C, jutting above the top chassis plate. Fortunately, both of the proposed chassis designs were more compact than the 2002 design, and still left room for the electronics to be packaged above the batteries.

2.3.3.5 Wheel Configuration

Upon completion of the acceleration testing, it was decided that the four-wheel butterfly design would be used. Twelve cells were settled on, arranged in triangular packs of six on each side of the robot. It became apparent that the rigid battery pack would not work for this design, so a rigid bottom plate with pass-through holes for the batteries was developed.

The area between the two rear drive motors was re-purposed to house the new kicking circuit, particularly the DC-DC converter and the storage capacitors. The space between the battery packs on the top plate was reserved as a location for the new rate gyroscope.

With refinement of the design through integration with other subsystems, it became apparent that interferences with the dribbling system would cause problems. To accommodate he new belt-less gear drive system for the horizontal dribbling bar, a notch had to be cut into the chassis top plate, and the size of the drive motor mounts had to be greatly reduced.

The newly integrated dribbler IR sensor holders posed other problems. They interfered with the wheels, when set to the same height above ground as the 2002 sensors. To alleviate this problem, the drive group lowered the sensor pair on the swing and narrowed the horizontal dribbling bar.

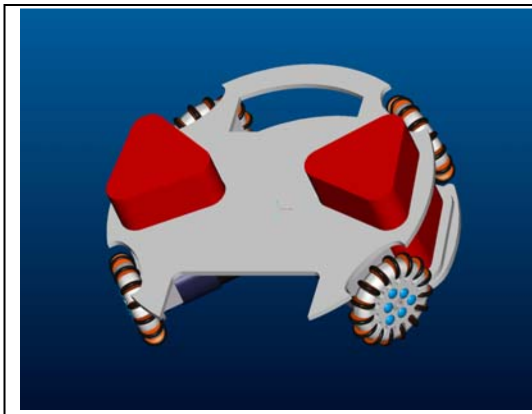


Figure 2-24 Battery Configuration

The narrowing of the dribbler caused much concern within the system group, as it was felt that a loss of dribbler width would compromise the ability of the robot to adequately capture the ball. As such, a wider dribbler was facilitated by the change in front wheel angle from 55° off-axis to 57°. The battery packs were also rotated rearward from their 95° off-axis position to 96°, maintaining their bisecting position between the front and rear drive axes on each side of the robot. Any further rearward movement of the drive motors would make it impossible to carry twelve batteries, preclude the solenoid from being mounted inline with the kick, or move the intersection of the drive axes from the geometric center of the robot.

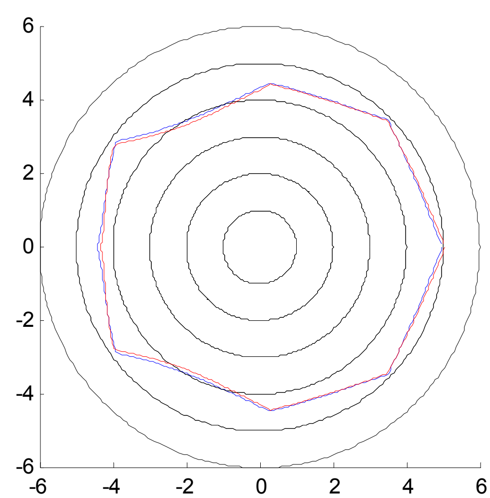


Figure 2-25 Normalized acceleration profile for 2002 (blue) vs. 2003 (red)

The drive team was also asked to investigate whether the front wheels could be flared a little bit more to give dribbling more room. Some simple calculations showed that a two-degree increase on each of the front wheels would be sufficient for the dribbling group. To be sure there would be no detrimental effects to the drive system, acceleration envelopes were generated to compare the 2002 and proposed 2003 drive geometries. Figure 2-16 shows this comparison. The acceleration profile showed no significant change, thus the final decision was to flare the wheels an additional 2 degrees, yielding wheel angles of 57º, 135º, 225º, and 303º.

2.3.3.6 Battery Placement & Accessibility

Although the 2002 batteries were easy to remove without the need for any tools, there were still nuisances about the 2002 batteries. For example, there were three pieces. Each piece needed to be stored in its own door, making it cumbersome to install and remove a full set of batteries. Thankfully, the team was able to locate batteries that were smaller in diameter (albeit longer in length), so we were able to design a battery pack with two packs of six. The smaller number of pieces reduces the amount of time it takes to swap batteries.

During the CAD design portion of the project, the team realized that it would not be possible to use a similar method of securing the batteries to the robot. As mentioned, the batteries were much longer, thus it was required that they protrude through the top chassis plate. Thus, we were forced to mill out the shape of the batteries from the top plate. This had a major advantage, however. By using this type of design, five of six degrees of freedom are removed from the battery: X-translation, Y-translation, XY-rotation, XZ-rotation, and YZ-rotation. The only other restriction needed is Z-translation. In order to restrict this last degree of freedom, we decided to restrict vertical travel by letting the batteries rest on top of the bottom plate. Such a design, however, would make it impossible to remove or install the batteries! Thus, holes for the batteries were also designed into the bottom plate such that the batteries could translate in and out through the bottom of the robot. Once installed, a "shelf" slides under the battery to restrict Z-translation. The shelf is secured to the robot via a pin (similar to 2002 battery pins) and a recess milled out of the bottom plate.

While the 2003 battery accessibility may prove less cumbersome than 2002, it may also prove not to be cumbersome. With the design of the drive system (namely the larger diameter of the wheels), the number of possible ways to secure the batteries on the robot was very limited. There was no longer room to slide batteries in from the side, because the wheels got in the way. Thus, the only simple option would be to insert from the bottom.

2.3.3.7 Hat Design

Early in the design process, there was a discussion about designing the hat with the rest of the robot. In recent years, little thought was given to the hat, until the rest of the robot was designed and built. This would lead to cumbersome schemes for hat attachment, and sometimes hats that would jiggle on the robots, causing minor problems with the vision system.

During the acceleration tests, it became very apparent that variations in hat attachment could cause large errors in closed loop control, as an incorrect angular orientation would be recorded by the vision system. The control system would attempt to correct this orientation problem by adding a rotation to the translation. This in turn would cause the robot to veer off course. Instead of having the robot translate in a straight line, it would fade to one side, and then spiral in closer and closer until it would hit the desired target.

Using this information, a decision was made to make the hat rigidly anchor to the robot in a manner that would produce identical, repeatable, aligned vision targets. Two methods were proposed. The first was to hinge off of the top of the tower, while the second would extend posts vertically from the tower, and through the EE boards to secure the top.

In 2002, clear polycarbonate was used for the hats. It was hand formable, but not very reproducible, requiring hand tuning for fitting the final shape. The 2001 team used carbon fiber, which is difficult to tool (when dry) and messy to work with when wet. Quite by accident, we stumbled upon a material that is lighter than carbon fiber, easier to work with than the polycarbonate, and resistant to impact. For the hat this year, we are machining and fabricating out of High Impact PolyStyrene (HIPS).

2.3.4 Final Design Specifications

2.3.4.1 Drive Motor and Gearbox

The motor selected for the drive system was the **Faulhaber 2224**. This was the same motor used in 2002, and was chosen because the 2002 team research appropriate motors in depth, and no superior brushed motor could be found. The gearbox selected was the integrated **13.5:1 gearbox**.

2.3.4.2 Number of Wheels & Wheel Layout

The 2003 robots have **four wheels**. Each wheel is located at a constant distance from the geometric center of the robot, and aligned tangent to the circle passing through all four of the wheels. Figure 2-17 depicts the wheel geometry for the robot. The wheels are located (in degrees from the positive forward axis) at **57º, 135º, 225º, and 303º**. The wheel directions (in degrees from the positive forward axis) are **147º, 225º, 315º, and 33º**. All wheels are equidistant from the geometric center of the robot.

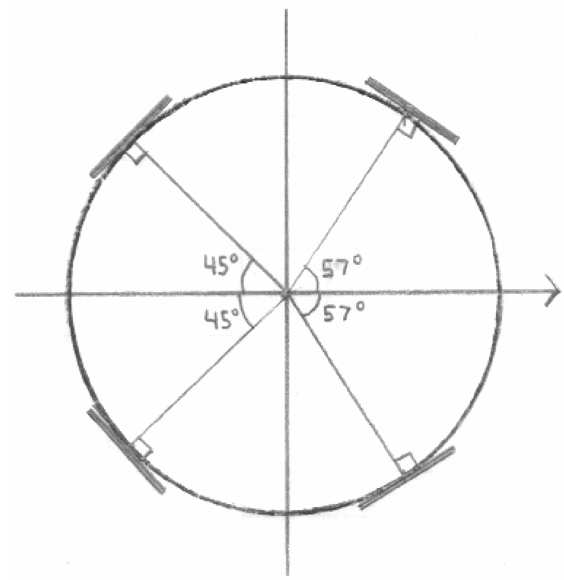
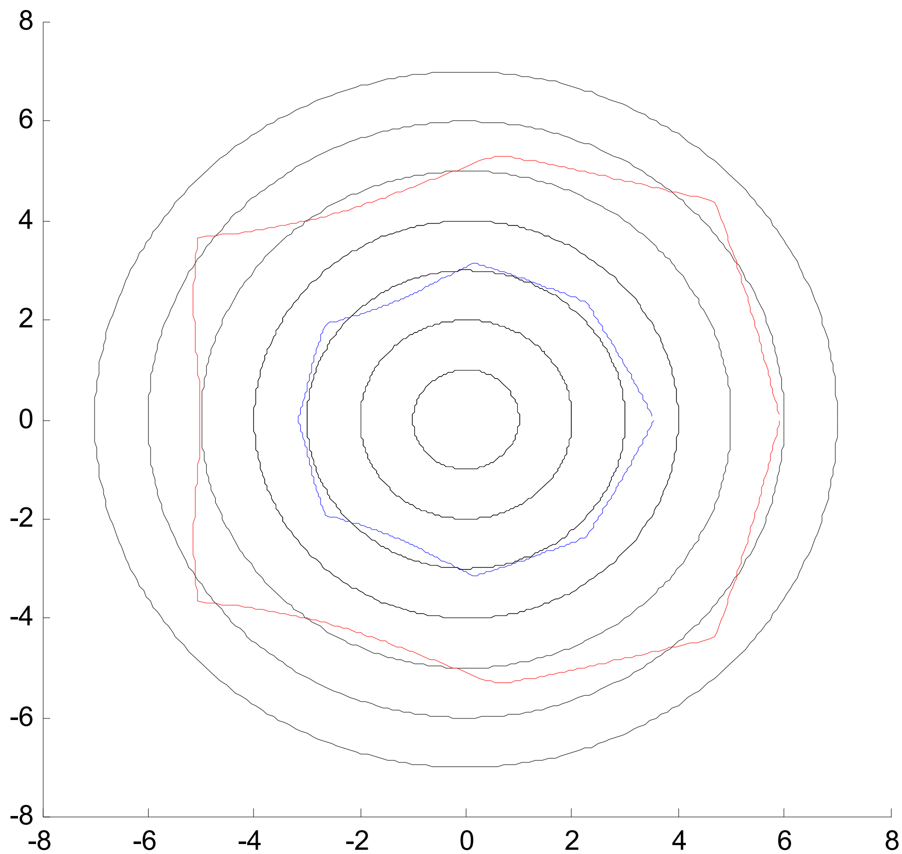


Figure 2-26 Wheel Geometry

2.3.4.3 Theoretical Acceleration Envelope

A theoretical acceleration envelope for the 2003 robot was generated using the MATLAB scripts documented earlier in this report. For comparison, the theoretical acceleration envelope for 2002 is included as well. Figure 2-18 shows the 2003 vs. 2002 theoretical acceleration envelopes. This plot (and all the constants used) can be found in the MATLAB file *theoretical2002vs2003.m.*



Red: 2003
Blue: 2002

Figure 2-27 Theoretical Acceleration Envelopes (m/s^2)

2.4 *Initial Testing & Revision*

2.4.1 Motivation for Testing

After completing the 2003 prototype robot, it was the desire of the entire team to see if it worked, and if so, how well. The drive group, in particular, was eager to see how the new robot compared to those of previous years. More importantly, however, the robot needed to be tested in order to determine what needed to be redesigned and remanufactured. If any portions of the robot failed during testing, it is reasonable to assume they will fail during competition. Testing of the prototype is the proper time to find these problems and fix them before final robots are machined.

2.4.2 Prototype Drive System Test

Since the drive system has only one function – to move the robot about the playing field – only one function exists to be tested. Since the purpose of the testing is to determine mechanical problems with the robot (and not determine final performance specifications of the robot), the robot was simply driven around the playing field manually. Using a Sidewinder Game Pad for control, the robot was driven around the playing field. Translation, rotation, and various combinations were performed non-stop for durations up to twenty minutes. Additionally, since the robots accelerated so quickly, the robots inadvertently sustained several extremely hard impacts during testing.

2.4.2.1 Problems Encountered and Solutions

2.4.2.1.1 Wheel Roller Material

After a couple hours of drive time, it became apparent that the rollers on the wheels would not be durable enough to last throughout an entire season. Many of the rollers (Delrin at the time) had cracked or damaged portions, and several were missing chunks of material that hold the o-rings in place. It became evident that these fractures were caused during impacts, particularly when the robot hits the side of the playing field at high velocities.

Figure 2-28 Fractured Delrin Roller

After noting these fractures, new wheels were manufactured with aluminum rollers of the same dimensions. Aluminum is much less susceptible to impact, and also has a much higher yield strength than Delrin. Although the aluminum design should prove much more durable than the Delrin, it should be noted that during prototyping with aluminum rollers in the fall, we noticed that some residue built up on the steel axles supporting the rollers. Over time, this may degrade the performance of the wheels. Several brass rollers were also machined, but the idea of brass rollers was tested or pursued. Should aluminum rollers hamper performance of the robot, brass rollers should be investigated because they have better surface-to-surface contact properties, and should not bind or leave residue on the steel axles. On the other hand, the density of brass is much larger than that of aluminum, thus more torque will be required to overcome the increased polar inertia of the wheel.

2.4.2.2 Battery Retention

During initial testing, we noticed that the long steel pins designed to secure the battery shelf in place were coming loose. When the pins came loose, the battery shelf could slide out, eventually allowing the battery to drop down and rub against the surface of the playing field. Although a solution had not been manufactured at the time of this documentation, a simple piece can be added to the design to keep the pin from coming loose. Since the handle of the pin can be rotated at any angle, it a simple matter machining a piece that will restrict the pin from vertical motion. The pin can be dropped in, then rotated into the piece that restricts vertical motion.

2.5 Future Consideration & Goals for 2004

During the design process, many ideas are dismissed and goals are altered for various reasons. These actions are not always due to poor or unreasonable ideas, but sometimes to things such as time constraints or other priorities. Below is a list of ideas that were dismissed but merit future research, and other goals that the 2003 team recommends to the 2004 team.

- ***DC Brushless Motors***

As documented in this report, brushless motors may have some advantages over the brushed DC motors used in past years. One of the key merits is space efficiency. The motors require less volume than brushed motors. Further, the free speed and stall torque for brushless motors are such that they might not require gearboxes for our usage. However, successful testing of these motors was not completed, and it has not been demonstrated that they will meet the demands of the robot. Additionally, the Maxon brushless models available do not include integrated encoders, thus cannot be used for feedback loops without adding on an encoder manually.

- ***Wheel Design***

Being the first year of use, the SIR wheel design can likely be optimized in future years. The o-ring sizes were chosen arbitrarily based upon intuition, and all the different o-ring materials have not been tested for traction and durability. A material may exist that would both increase traction and prove more robust than the Buna-N material used this year. Additionally, the performance of the roller material (aluminum) should be examined and alternate materials should be considered.

- ***Batteries***

After the prototype had been manufactured, further analysis by the electrical team yielded another type of battery that could possibly be used on the robot. These batteries were lithium-ion batteries, and were rectangular in shape, very thin, and could easily fit under the drive motors. These batteries would be able to be stored extremely close to the bottom of the robot. Having the batteries (the heaviest part of the robot) so close to the ground would greatly lower the center of mass, allowing significantly higher acceleration and room for other components.

3 Dribbling Design Documentation

Figure 3-1 Dribbling Face

3.1 Introduction

The ball control system for the robots includes the horizontal dribbler, side dribbler, suspension system, and stripper. The dribbling system helps the robot maintain ball control while moving, while the stripper serves to prevent the opponent from maintaining such ball control. The dribblers and suspension system mount on the swing as the dribbling system, and the stripper mounts on the hat as its own system. (The swing is the large frame of the dribbling system to which all dribbling components are mounted.)

3.2 Performance Review of 2002

The 2002 dribbling system shows many improvements from 2001 dribbling system. The 2002 horizontal and side dribblers allow the robot to maintain ball control while rotating or translating faster. The vertical dribblers from 2001 were nearly ineffective, but the angled side dribblers added force components that worked to keep the ball on the dribbling face. The dribblers work well during translational motion, but their performance tends to decrease during rotational motion, as the ball tends to slip out to the side. The suspension in the 2002 dribbling system also allows the dribblers to catch the ball at higher speeds. Thus, the major improvements of the 2002 dribbling system over previous years were its ability to maintain ball control during fast rotation and sideways translation and its ability to capture high speed passes. The major drawback of the 2002 dribbling system is that it is made out of many small components that make manufacturing and maintenance very time consuming.

3.3 Design Objectives

3.3.1 Increase performance

When a 2002 robot was rotating quickly during a game, the dribbling system could not retain the control of the ball. Sometimes the ball would even spin off the dribbling face and travel back toward our own goal. Increasing the dribbling system's ability to maintain control of the ball by increasing the dribbler rotational speeds, optimizing the dribbling geometry, and optimizing the damping will allow the drive system to accelerate more quickly with ball control. Since the horizontal dribbler height, dribbler radii and dribbler materials were optimized in past years, we can gain no further performance from redesigning these characteristics.

3.3.2 Reduce maintenance time

One major problem during games is robot maintenance. Robot failure during a game can cost goals and cause the team to lose, and robots sitting in the maintenance pit for long periods can slow the pace of a game and incur penalties. Also, testing by the software engineers, electrical engineers, and mechanical engineers in the lab is often hindered by broken robots that await maintenance and repairs by mechanical engineers. Thus, if we can reduce the number of failure modes and reduce the time it takes to fix problems that do occur by planning better for screw locations and necessary dismantling, we can decrease robot downtime, increase available testing time, and aid in smoother game play.

3.3.3 Stripper motivation

In the 2002 competition, the most effective strategy for our robot was to dribble the ball across the field to score while the other robots picked the opponents. (Picking is when a robot positions itself to block an opponent from traveling in a direction we believe would be detrimental to our strategy.) One of the main reasons this strategy was effective was because we had the best dribbling system at the competition. The horizontal dribbler induces backspin on the ball, which allows our robot to maintain ball control. The side dribblers give the robots more control by preventing the ball from slipping off the dribbling face during rotation. Therefore, the dribbling system makes it hard for the opponents to strip the ball away from our robots. From exposure during this competition, we must assume that most of the teams in 2003 will have dribbling systems that work as well as our 2002 dribbling system. In order to regain ball control during the games, we need a stripping mechanism for our robots to strip the ball from the opponents.

3.4 Initial Ideas

Having defined our objectives, we brainstorm ideas for the new 2003 dribbling system that could increase our performance while reducing maintenance time. We examine each component individually for the improvements it offers the system. We also come up with ideas for the new stripping mechanism that we are going to include in the new dribbling system.

3.4.1 Dribbling

3.4.1.1 Wafer dribbler

The wafer dribbler is essentially a very thin 2001 vertical dribbler that contacts the ball above its center point. The concept of the wafer dribbler is to vastly improve manufacturability by reverting to a vertical dribbler that provides the same force vector on the ball. Vertical dribblers maintain orthogonality throughout the dribbling system, making machining much easier.

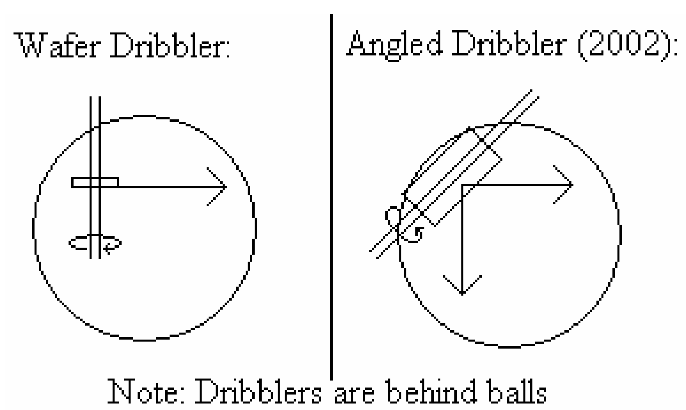


Figure 3-2 Wafer vs Angled Dribbler

3.4.1.2 Bevel gears

Bevel gears allow us to angle the motors away from each other and drive the dribblers with minimal space. (Bevel gears are gears with angled teeth such that when two are mounted in contact with each other, their shafts are orthogonal or at some angle other than parallel.) Using bevel gears reduces maintenance time since the belts used in 2002 needed to be maintained at the right tension.

Figure 3-3 Bevel Gears

3.4.1.3 Spur gears

Spur gears allow us to reliably, and within little space, power the horizontal dribbler. Spur gears are the most common gear one sees, one where when two are mounted in contact with each other, their shafts are parallel and the direction of rotation opposite each other. Like bevel gears, the spur gears reduce the maintenance time.

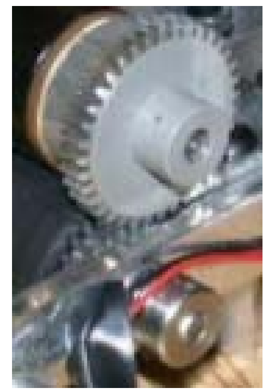


Figure 3-4 Spur Gear

3.4.1.4 Cross mount

We want to simplify the angled dribbler mounts (incase the wafer idea fails). We decide we can either screw the mounts directly to a back plate in the vertical plane (thus eliminating the angled pyramid) or retain the 2002 mounting design (screwing the mounts to the angled pyramid, then the pyramid to the swing). (The pyramid is a mounting bracket screwed to the 2002 swing that has two planes not orthogonal to the rest of the pyramid such that when the side dribbler mounts are screwed into them, the side dribblers are at an angle instead of vertical.)

Figure 3-5 Cross Mount

Figure 3-6 2002 Pyramid

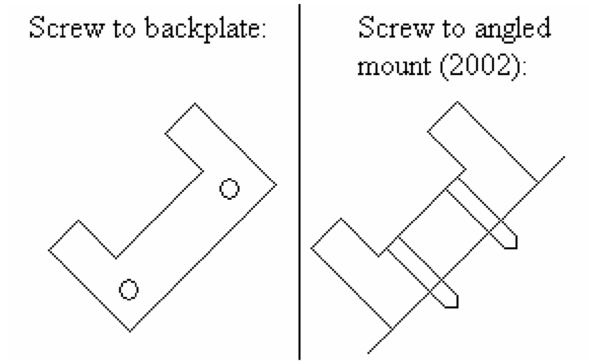


Figure 3-7 Methods for Motor Mount Fastening

Noting that screwing the mounts directly to a back plate is much simpler and has no drawbacks compared to screwing the mounts into an angled mount, we brainstorm how to accurately align the mounts. A metal cross cut into the back of the mounts that presses onto a cross protruding from the back plate allows us to align the mount rotationally and in both translational directions. Thus, we can keep the dribblers from vibrating or moving during collusions, making them more robust increasing performance of the dribbling system over the course of a game.

3.4.2 Adjustable Suspension

3.4.2.1 Spring and damper

The spring and damper idea allows us to precisely set a spring constant and damping coefficient based on analysis rather than relying on the spring constant and damping coefficient of a given material like those of the ear plugs. After finding the desired spring constant, we can simply order such a spring. After finding the desired damping coefficient, we can either attempt to find one for order or machine one.

3.4.3 Stripper

3.4.3.1 Active stripper

The first idea for an active stripping mechanism is similar to our existing side dribblers but spins in the direction opposite the side dribbler rotation. This opposite spin induces side spin on the opponent's ball and drives the ball to the side, out of the opponent's dribblers.

3.4.3.2 Passive stripper

A second idea is to design a passive stripping mechanism. High fiction material can be mounted on both sides of the robots. By brushing the material against the ball while our robots rotate, there would be enough force generated to pull the ball away from the opponent.

3.5 Preliminary Analysis

3.5.1 Dribbling

3.5.1.1 Force Analysis

From the diagram on the previous page, we find that the wafer dribbler is not feasible. The 2002 dribbler provides an inward, downward, and backward force vector, and the wafer dribbler can only provide an inward and backward force vector. The downward force vector provides a normal force with the carpet and a strong frictional force as the ball spins so that the ball is forced back into the robot. Because the wafer dribbler does not create this backward frictional force with the carpet, but ball will not remain with the robot, negating the effect of a dribbler. Thus, the wafer dribbler idea failed.

3.5.1.2 Geometry calculation

The dribbler geometry consists of the dribbler heights, dribbler diameters, dribbling face width. The horizontal dribbler height remains fixed at the optimized height from preceding years.

The 2003 side dribbler height is lower than that of 2002 based on observations that the ball contacted the side dribbler near its bottom in 2002. When a robot has possession of the ball and is turning or otherwise using the side dribblers, we want the ball to maintain contact with the center of the side dribblers and the horizontal dribbler so the robot maintains control of the ball even when the ball bounces or the robots jumped slightly. Thus, the height of the side dribblers has been adjusted so that the ball contacts the center of the side dribblers when on the side of the dribbling face in a neutral dribbling condition.

The dribbling face width is dictated by the space left from the drive system geometry, though the drive system has its front wheels angled out slightly to provide as wide of a dribbling face as possible.

3.5.1.3 Angle Analysis

Analysis done last year for the side dribbler mounting angle shows that there are two different optimal angles for either pushing or pulling the ball on the side dribblers. (Pushing is when the side dribbler in contact with the ball during rotation or sideways translation is behind the ball along its path, and pulling is when the side dribbler in contact with the ball during rotation or sideways translation is in front of the ball along its path.) As noticed during test and competition games, however, the ball is very rarely pulled because the moment the robot begins to turn and needs the side dribblers to keep the ball against the dribbling face, the ball's inertia carries it across the face to be pushed by the other side dribbler. Therefore, the mounting angle is set at the optimal pushing angle because the optimal pulling angle deserves no consideration.

3.5.1.4 Horizontal Motor and Gear selection

The horizontal motors used in 2002 are overdriven to around 16V maximum. Due to constraints dictated by the EE team, our main battery has a maximum output of 12V. Therefore, we have to optimize the motors so they perform at the same or higher RPM during different dribbling situations as the motors in 2002 with a higher voltage.

In order to optimize the motors, we find the currents that run through the motor during a game. We use an ammeter to measure the currents flowing through the motor while it is running in different dribbling situations like freely rotating, neutral dribbling, and a dribbling battle. (Freely rotating is when the dribbler is not in contact with the ball; neutral dribbling is when the dribbler is dribbling the ball with no resistance from opponents; and a dribbling battle is when the dribbler is dribbling or attempting to dribble the ball while against an opponent dribbler trying to do the same with opposite rotation.) The currents range from

0.4A without the ball to 1.8A during a dribbling battle. From this data and the characteristic of the motor, we calculate the maximum torque the motor must generate. This torque data allows us to find the motor that suits our needs best, as motor catalogues provide torque and power curves and other data.

Table 3-1 2002 Motor Summary

	Current (A)	**2002 motor** torque(mNm)	**(Nominal Voltage, 7.2V)** Total torque require (mNm)
without ball	0.40	1.96	10.61
with ball	0.60	2.95	15.91
during battle	1.80	8.84	47.73

The motor that matched our needs best was the Maxon 6V motor # 11827 (we are planning to overdrive it to 12V) with either a 4.4:1 or 5.4:1 gear head ratio.

Table 3-2 2002 Motor Gearing Summary

2002 Motor (Nominal Voltage, 7.2V)				
Voltage (V)	Gear head Ratio	Gear head efficiency	torque (mNm)	speed (rpm)
16.00	5.40	0.90	205.20	0.00
16.00	5.40	0.90	0.00	5074.07

Table 3-3 2003 Motor Selection Information

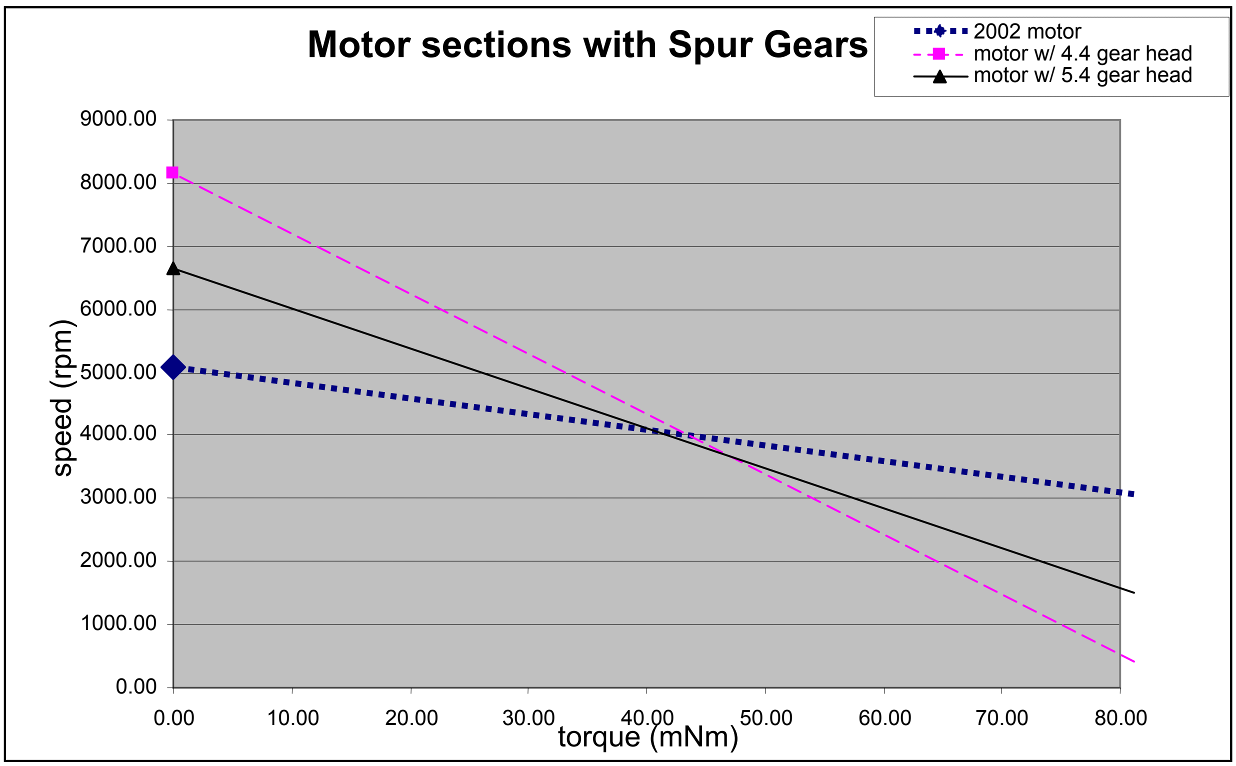
2003 motor consideration (Nominal Voltage, 6V)				
Voltage (V)	Gear head Ratio	Gear head efficiency	torque (mNm)	speed (rpm)
12.00	4.40	0.90	128.30	0.00
12.00	4.40	0.90	0.00	5440.91
12.00	5.40	0.90	157.46	0.00
12.00	5.40	0.90	0.00	4433.33

Since both gear head ratios provide much larger torque that needed, we may gear them up to a higher speed, spinning the dribbler faster and providing better control of the ball. We disregard the 5.4:1 gear head because the extra torque it provides compared to the 4.4:1 gear head is not necessary. Remembering that we wish to match or beat the RPM of the 2002 dribbling system under all dribbling situations, and knowing that the range of dribbling situations takes us from 10mNm to 48mNm, we must choose a spur gear ratio that makes the 2002 and 4.4:1 gear head lines intersect at a point around 48mNm. The spur gear ratio we find that matches our needs is 1:1.5.

Table 3-4 2003 Motor Summary - 1.5 Gear Ratio

2003 motor consideration with 1.5 gear ratio				
Voltage (V)	Gear head Ratio	Gear head efficiency	torque (mNm)	speed (rpm)
12.00	4.40	0.90	85.54	0.00
12.00	4.40	0.90	0.00	8161.36
12.00	5.40	0.90	104.98	0.00
12.00	5.40	0.90	0.00	6650.00

Table 3-5 Motor Sections with Spur Gears



To calculate the maximum power used by the motor, we divide the speed of the motor by its torque at maximum torque (48mNm). For the 2002 motor, the power is 22.27W. The 2003 motor with 4.4 gear head and 1:1.5 spur gear ratio requires 23.18W. Although the 2003 maximum power is slightly higher than the 2002 maximum power, power consumption will not be continuous. Therefore, the 2003 motor should not burn out when running with 9V.

3.5.2 Suspension

3.5.2.1 Spring and damper analysis

To begin the analysis, we went to the 2002 final documentation. There we found many derivations for various necessary constants. But after careful attempts to regenerate the formulas that were in the documentation, we found some errors that needed to be corrected in order to proceed. Our first analysis was derived from energy conservation. We assumed that the ball began with a certain amount of kinetic energy, from both its translational and rotational velocities:

$$K = \frac{1}{2}mv_0^{\ 2} + \frac{1}{2}I\omega_o^{\ 2}$$

And with the following substitutions:

$$I = \frac{2}{5}mr^2$$
$$v = \omega_0 r$$

the expression for kinetic energy is:

$$K = \frac{7}{10}mv_0^{\ 2}$$

Knowing that the force provided by the damper and the spring is

$$F_{kb} = bv + kx$$

The integral of this force over the distance the ball travels (δ) is the energy that the suspension system can dissipate:

$$W_{kb} = \frac{1}{2}\left(bv_0\delta + k\delta^2\right)$$

By setting the work done by the system equal to the energy of the ball, the following expression is obtained:

$$\frac{7}{5}\frac{m}{\delta}v_0^{\ 2} = bv_0 + k\delta$$

Then, by using basic kinematics equations and Newton's Law, and assuming a value t_p, the desired time for the swing to decompress from its damped position, we can solve for the spring stiffness constant, k:

$$F_k = kx = ma$$

$$x = \frac{1}{2}at^2$$

lead to the expression:

$$k = \frac{2m}{t_p^{\ 2}}$$

(The m value in this equation is the equivalent mass of the swing module.)

Using this expression to find a suitable k value, the process of finding a value for the damping constant can then continue. By plugging the expression for k into the previous equation of energies:

$$b = \frac{7}{5}\frac{m}{\delta}v_0 - \frac{k\delta}{v_0}$$

Once an expression for the damping constant was found, the search began for the actual meaning of this constant. First we attempted to use general force laws to give dimensions for a dashpot. Using the following equations:

$$F_d = bv = PA \text{ (P = pressure, A = area)}$$

$$F = m_{ball}a_{ball} + m_{swing}a_{swing}$$

$$x = \frac{1}{2}at^2$$

$$x = (\Delta v)t$$

We wrote a Matlab program to solve for areas of a damper for balls of varying incoming velocities (see appendix). Choosing an optimal velocity for which to damp will be a key decision, as this variable tends to change drastically from one opponent to another. There are various errors in the program due to certain misunderstandings and miscalculations. But the general idea of the program should produce a usable result when certain equations are modified. The inclusion of the file is meant to be a template for later research on this subject.

The values chosen for the above variables are as follows:

$$t_p = 0.5s$$

$$k = 0.1598 lb / in$$

A second method of analysis made use of the ideal gas law, in addition to kinetic energy equations. Keeping in mind that there are separate variables for velocity (v) and volume (V), the following derivation is conducted:

the distance x is the compression distance

l is the total compression length of the damper

$$\gamma = A / A_H$$

$$F = -kx - bv + F_{backspin}$$

$$at\, x_f : \quad kx = F_{backspin}$$

$$PA = bv$$

$$v = PA / b = PA_H \gamma / b$$

$$PV = nRT$$

$$V = A(\iota - x)$$

$$A = V / (\iota - x)$$

$$v = \frac{nRT}{B(\iota - x)}$$

$$\frac{dm}{dt} = PA_H \sqrt{\frac{N}{RT}}$$

$$n = n_i - A_H \sqrt{\frac{1}{NRT}} \int P dt$$

$$W = -kx^2 - b\int v dx + \int F_{backspin} dx = -\frac{1}{2} m v_i^2 + \frac{1}{2} m v^2$$

$$\frac{1}{2} m (v_i^2 - v^2) = kx^2 + b\int v dx - \int F_{backspin} dx$$

$$\frac{1}{2} m \left(v_i^2 - v^2\right) = kx^2 + RT \int \frac{n}{\iota - x} dx - \int F_{backspin} dx$$

These equations could theoretically then be solved to give us the constants and values we need. But there are various flaws in this process as well. We then resolved to simply try to prototype different sizes of dashpots and test them with the spring stiffness constant that the first way of analysis gave.

Most of the results that came from this semester were given in the analysis. In attempts to prototype, not much progress was made due to the pending receipt of a spring with which to test. We came to a tentative conclusion that due to the small scale of the system, a dashpot may be too large and over engineered. When rethinking the dashpot, we thought that further testing of various materials that act like the foam currently in place might be productive.

The analysis done to find an optimal size for the dashpot is definitely useful in terms of future research and continuing research for next semester. The current prototyping of a dashpot with a Delrin plunger and aluminum pot will continue for next semester once the right materials have arrived.

Most of the results that came from this semester were given in the analysis. In attempts to prototype, not much progress was made due to the pending receipt of a spring with which to test. We came to a tentative conclusion that due to the small scale of the system, a dashpot may be too large and over engineered. We feel that further testing of various materials like foam or rubber may provide a simpler and mechanically equivalent spring and damping system.

The analysis done to find an optimal size for the dashpot is definitely useful in terms of future research and continuing research for next semester. The current prototyping of a dashpot with a Delrin plunger and aluminum pot will continue for next semester once the right materials have arrived.

3.5.3 Stripper

3.5.3.1 Geometry limitations

In order to maximize the performance of the strippers, they need to be mounted on the outside surface of the robot about 21mm above the ground (radius of the ball). The regulation for the RoboCup competition also states that the top projection of the robots cannot be greater than a circle of diameter 18cm. Since our robots have a radius of 17.5cm without the stripper, the stripper can be up to .25cm thick.

3.5.4 Strategy usefulness

The stripping mechanism needs to be useful for the strategy of the robots. In the event one of our robots encounters an opponent dribbling the ball, we want to provide as many strategic choices as possible. A robot with a stripper may either enter a dribbling battle or attempt to strip the ball with the stripper.

3.5.5 Material research

Any stripping material needs to have a high coefficient of friction or unique shape advantageous to stripping so it can pull the ball away from the opponents more easily. With a high coefficient of friction or properly shaped material, the stripper is able to generate more force to pull the ball away from the opponent, which increases the chance it will strip the ball. The materials tested were rubber fingers, Vinyl, surgical tubing, latex, and floor mat. Vinyl, surgical tubing, and latex were selected because of their high coefficients of friction. The floor mat was selected because of its shape; the tiny fingers on the mat might provide more frictional force with the bumpy ball surface. For more detailed results, see the material testing section.

3.6 Prototype build and test

3.6.1 Gears

3.6.1.1 Bevel gears for side dribblers

We manufactured a motor mounting bracket to mount a 2002 side dribbler motor on the 2002 swing such that the motor's rotational axis was front-to-back. We mounted a bevel gear on the dribbler shaft and powered it at right angles with a bevel gear on the motor shaft. To test the system, we turned on power to the side dribbler motor and stalled the motor numerous times to assure the bevel gear teeth would not slip or the bevel gears would not loosen on their shafts. We also ran the system with occasional dribbling resistance (provided by pushing a ball against the dribbler) for a few minutes, monitoring the motor and gear heat to assure the system would not destroy itself in-game.

3.6.1.2 Spur gear for horizontal dribbler

We manufactured a motor mounting bracket to mount a 2001 horizontal dribbler motor on the 2001 chassis plate such that the motor's rotational axis was parallel to the horizontal dribbler. We mounted a spur gear on the horizontal dribbler shaft and powered it with a spur gear on the motor shaft. To test the system, we turned on power to the horizontal motor and stalled the motor numerous times to assure the spur gear teeth would not slip or the spur gears would not loosen on their shafts. We also ran the system with occasional dribbling resistance (provided by pushing a ball against the dribbler) for a few minutes, monitoring the motor and gear hear to assure the system would not destroy itself in-game.

3.6.2 Stripper

3.6.3 Material testing

Because the rubber finger was made out of a very hard rubber, it provided little friction, and the long length of each finger would violate the robot size regulation. Therefore, it was dropped from the test.

The material test required a program that gave a robot a rotational velocity parameter ranging from -10 to 10 (AI rotational Gain). The best material would be the one that requires the lowest rotational velocity parameter to perform a successful strip (defined as stripping the ball away from the opponent after roughly 180 degrees rotation on the first try).

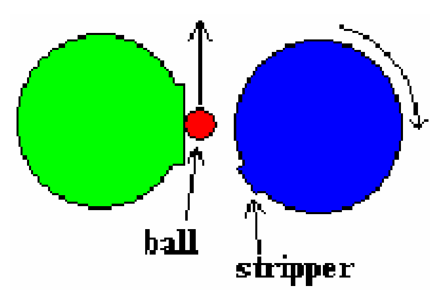


Figure 3-8 Method of Passive Stripping

The test used two of the 2002 robots. One robot acted as the opponent who had control of the ball, and the other robot would try to strip the ball away. We first checked the opponent's horizontal and side dribblers to make sure they worked well, then mounted the material on one side of the other robot. We placed a ball in front of the first robot's horizontal dribbler and set the robot on dribbling mode. Next, we placed the other robot about 5cm in front of the first robot and set its rotational velocity to 1 to see if the material was able to make contact with the ball when it was rotating. We repositioned the robots until the contact could be made, then increased the rotational velocity until the robot successfully stripped. We recorded the data and repeated the procedure with the other materials.

3.7 Idea Selection

3.7.1 Dribbling Assembly

Based on the above idea generation and analysis, we plan to optimize the current angled dribblers, mount them against a back plate with no angled metal at the optimal pushing angle, and drive them with bevel gears. The optimization will improve the dribbling performance. The bevel gears will improve the packaging because they take much less space than belts; they will require much less maintenance, as we will not have to adjust their tension or check for extreme wear before every match; and they are more efficient than belts. The new mounting style will eliminate the most difficult part of machining last year: the pyramid. We will use less fasteners and parts, thus improving the reliability and manufacturability of the dribbling system.

3.7.2 Stripping Mechanism

After comparing the two ideas with the limitations and restrictions, the passive stripping mechanism suits our robots better. The main problems for the active stripping mechanism are small contact area and the size of the mechanism. Because of the small contact area in the active system, it requires very precise positioning of the stripper relative to the location of the ball. This is very hard to accomplish since the ball will move randomly along the horizontal dribbler. The small space decreases the efficiency of the stripping mechanism since the ball would have a low probability of hitting the small stripper. Since the passive stripping mechanism requires less space and has a much larger contact area, it makes the stripper more reliable. The high friction material has a higher chance of applying sufficient force on the ball to strip it away. Although an active mechanism may generate a stronger spin on the ball, we can spin the robot to effectively make the passive stripping mechanism an active one. It is also useful with our current strategy; the robot can spin in front of the opponent and strip its ball away.

3.7.3 Suspension

Because of the complexity of mounting a spring and machining and mounting a damper, we retain the ear plug suspension system. The ear plugs are easy to mount and proved to be effective in 2002 at receiving and retaining the ball at very high speeds and various angles, so we feel there is no need to change the spring and damper material.

3.8 Results/Conclusion

3.8.1 Gear performance

The bevel gears performed flawlessly in both the stall and endurance tests. Since the plastic molder gear teeth do not perfectly mesh, the bevel gears bind slightly or have severe backlash when running. This binding or backlash causes an increase in fiction and a decrease in performance. We have recently ordered metal bevel gears that we hope will mesh more precisely and increase our performance for the final 2003 robot.

The spur gears also performed flawlessly in both the stall and endurance tests. We noted that to improve performance, we must manufacture a snug shim to mount the English inner diameter bevel gears on the tiny metric motor shaft to ensure the gear is not eccentric and will loosen over time. The gear teeth bind slightly if one or both gears are eccentric, and such binding applies uneven force over the rotation of the gear, thus loosening it over time.

3.8.2 Passive stripper performance

For the Vinyl, the rotational velocity parameter needed to achieve a successful strip was 9 AI rotational gain, while the surgical tubing never achieved a successful strip. One of the main problems during the test was that when the robot had the dribblers on and carrying the ball, the robot tended to move backward due to the force generated on the ball, thus decreasing the force between the tested material and the ball. Therefore, the data might not be very accurate for a real game, since the opponent would more likely to move forward rather than backward.

3.9 *Final subsystem*

3.9.1 Horizontal dribbler

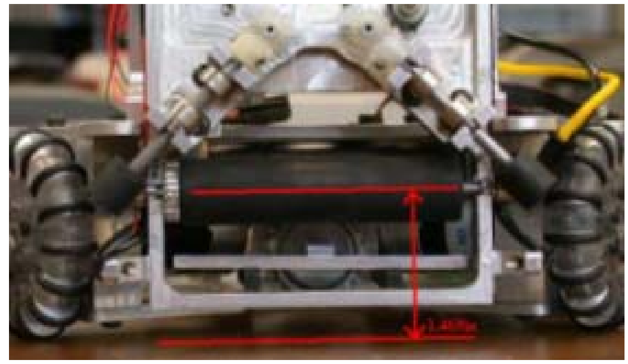


Figure 3-9 Horizontal Dribbling Height

The height of the horizontal dribbler axis from the playing field is 1.469in, which was the same as 2002. The dribbler diameter was designed to match the dimension from 2002. The width of the dribbler was set at a maximum given the restraint of interfering with the wheels. The greater the dribbling face width, the higher the chance the robot will intercept passes on its dribbler and retain control of the ball.

3.9.2 Side dribblers

From the analysis before, the side dribblers are set at 45 degrees to maximum the performance. The height was set so it could be contact at the center when controlling the ball. The side dribblers are placed relative to the horizontal dribbler such that the ball maintains contact with the edge of the horizontal dribbler when the ball is in contact with a side dribbler.

3.9.3 Dribbling motors

As discussed in the horizontal motor and gear selection section, the 2003 horizontal dribbler is a 6V Maxon motor #11827 with a 4.4:1 gear head. The gear head output is then geared up by a 1:1.5 spur gear pair to increase the speed of the dribbler.

Since we run the side dribbler motors at the same voltage as that of 2002, the side dribbler motors are the same model as those of 2002. The only change to the side dribbler motor system is that their output is fed to the side dribblers by bevel gears rather than belts because gears offer higher efficiency and reduced maintenance.

3.9.4 Material selection for stripper

The results show that Vinyl is a better material to use for the stripping mechanism than surgical tubing. The rotational velocity needed to perform a successful strip (9 AI rotational gain) is lower in a real game than in the tests since the force acting between the material and the ball will be higher (in a real game, the opponent robot will most likely be pushing against us than shying away). Thus, we plan to mount Vinyl on the sides of the robot and notify the Software Engineering team that they need to write code to utilize the new stripping mechanism.

3.10 Design Documentation

After deciding what mechanism to use for the 2003 dribbling system, we integrate all of the components to create the entire dribbling system. This integration took place in many stages on Pro-Engineer so that we could view the entire system, note and fix maintenance problems before the prototype was manufactured, and eliminate all part interferences.

3.10.1 Motivation and Goals

3.10.1.1 Simplicity

Looking at the 2002 dribbling system, we notice that there are many small parts and fasteners. These parts make manufacturing and maintenance more difficult and time consuming. Thus, one goal for the 2003 dribbler system is to have as few parts as possible.

3.10.1.2 Reduce maintenance time

Reducing maintenance time does not mean only designing a simpler dribbling system. Such improvements like changing the components used, in addition to reducing their numbers, may eliminate or reduce maintenance in some areas. Planning screw locations such that they are easier to access with less dismantling makes fixing problems much faster. Reducing the maintenance time means we can decrease robot downtime, increase available testing time, and aid in smoother game play.

3.10.2 Initial Design

3.10.2.1 Horizontal Dribbler

The dimensions for the horizontal dribbler were based on the dimensions from 2003 (see Final Subsystem section). The only differences from 2002 are that the dribbling face width was reduced to accommodate the larger 2003 wheels and that the dribbler will be powered by spur gears rather than a belt and pulleys.

3.10.2.2 Side dribbler mounts

The pyramid used in the 2003 dribbling system to attach the side dribbler mounts was difficult to machine because of the 45 degree planes and did not mount rigidly, causing severe maintenance problems. To eliminate these machining and mounting problems, the 2003 side dribbler mounts are attached directly to the swing. Because the CNC machine must cut a swing out of an aluminum blank, we can program it to cut the holes to attach the side dribbler mounts in nearly the same amount of time.

3.10.2.3 Dribbling motors

As discussed in the horizontal motor and gear selection section, the 2003 horizontal dribbler is a 6V Maxon motor #11827 with a 4.4:1 gear head. The gear head output is then geared up by a 1:1.5 spur gear pair to increase the speed of the dribbler.

Since we run the side dribbler motors at the same voltage as that of 2002, the side dribbler motors are the same model as those of 2002. The only change to the side dribbler motor system is that their output is fed to the side dribblers by bevel gears rather than belts because gears offer higher efficiency and reduced maintenance.

3.10.2.4 Integrated IR mounts

One of the main problems for the 2002 robot is that the IR sensor is not aligned correctly, causing the kicker to kick continuously. Because the 2002 IR mount is a separate piece from the swing, mounting it introduces the possibility of misalignment. To solve this problem, we integrate the IR mounts with the swing, as was done to attach the side dribbler mounts.

3.10.2.5 Passive stripper

The tests and limitations discussed above dictate using a passive Vinyl stripper. Vinyl is mounted on both sides of the robot 21.25mm from the ground (ball radius).

3.10.3 Initial Design Problems/Limitations

3.10.3.1 Reduced dribbling face

Because of the increased wheel size this year, the dribbling face width had to be reduced slightly more than expected to keep the IR sensors from interfering with the wheels at any point in the swing distance.

3.10.3.2 Circuit board slots

To help mount the circuit boards, we had to make part of the towers wider front-to-back to cut slots in them.

3.10.3.3 IR sensor mounts

Regardless of whether the IR sensor mount is integrated with the swing or is a separate piece, it protrudes significantly from the side of the swing and tends to interfere with the wheel at least some point in the swing distance unless the swing is not as wide. Thus, this protrusion contributes to the reduced dribbler face width mentioned above.

3.10.4 Final design

After considering the problems and limitations noted above the final design is the initial design with wider front-to-back towers and a reduced dribbling face width. The dribbling face is reduced from roughly 80mm in 2002 to 72mm in 2003 because of the larger 2003 wheels (see Mechanical Interferences section). The side dribbler mount attachment and IR mounts are integrated with the swing as one piece. The dimensions for the horizontal dribbler, except the face width, are the same as in 2002. The 2003 stripper is mounted on the sides of the hat at the ball radius height.

3.10.5 Part description

3.10.5.1 Swing

The swing serves as the mount for most other dribbler parts. The side dribbler mounts, side dribbler motor mount, horizontal motor mount, horizontal dribbler, and IR sensors mount directly to the swing.

3.10.5.2 Towers

The towers screw directly to the chassis plate and hold the swing above the floor. A connecting piece screws between the towers to hold the ear plugs and catches.

3.10.6 Initial Testing

After assembling the prototype for the new dribbling system, we tested our prototype to see if it would meet the RoboCup rules.

3.10.6.1 Static test

The static test was to be sure the dribbling system did not violate the 180mm rule or 20% rule. The 180mm rule was tested with the U-shaped measurement tool in the lab, and the dribbling system stayed within the 180mm maximum diameter. Secondly, the 20% was tested with the 20% tester, and we found that the side dribbler mounts and bevel gear teeth crossed the 20%. We missed this 20% violation in the design process because the side dribbler position relative to the horizontal dribbler was physically measured with calipers on the 2002 dribbling system; the measuring process was inaccurate enough to position the side dribblers too far forward.

3.10.6.2 Dynamic test

The dynamic test was to see how well the gears remained attached to the motor shafts under repeated stress and to assure that the motors and gears did not heat up or get destroyed. We found that the horizontal motor spur gear came loose quite easily, but the rest of the system was robust. The horizontal motor also heated up significantly, but that was a coding problem that was fixed (the pulse count was set too high). We also noted that, while the side dribblers maintained good ball control, the bevel gear teeth seemed to not engage well, so the gear-to-gear connection remained loose with a lot of backlash. This backlash also made the bevel gears very noisy, which means we were losing efficiency by converting some energy into sound.

(Backlash is the opposite of binding; the gear teeth do not fully engage each other because of pour tooth shape or the gears are too far apart, and the driven gear is free to jiggle within a small rotational slop range. Severe backlash may result in the teeth on one gear striking the teeth on the other gear nearly perpendicularly, immediately stopping rotation. Binding is when the tips of the gear teeth on each gear are forced into the grooves between teeth on the other gear because of pour tooth shape or the gears are too close together; this causes a lot of friction and rotational resistance.)

As an unexpected consequence of the dynamic test, we noticed that the side dribbler rubber rides up onto the shaft after a couple minutes of dribbling, which exposes the hard, slick Delrin core to the ball and destroys the dribbling capabilities if the side dribbler.

3.10.6.3 Suspension test

The suspension test tested how well the robots are able to catch the ball. First, a ball was placed on a ramp 3ft high. A robot with its horizontal and side dribblers turned was placed underneath. When the ball was released, potential energy was converted to kinetic energy, and the ball slammed into the dribbler. Based on the height, we could compute the potential energy before release, all of which was converted to kinetic energy. Based on that kinetic energy just before impact, we know the speed of the ball. The test measures if the robot catches the ball (maintains control of the ball after impact) at given speeds.

When we placed the ball at the maximum height (3ft), the robot was able to catch the ball nearly every time. From energy conservation, this catch speed was about 4.2m/s. The actual maximum catch speed is most likely much higher than 4.2m/s, as the 2002 dribbling system could usually catch a pass at such a speed and the 2003 dribbling system has an increased damping range; the actual maximum capture speed cannot be determined until the final robot is produced with the updated dribbling dimensions.

3.10.7 Revision

The static test showed that the dribbling system was violating some of the rules for the RoboCup competition.

3.10.7.1 Spur gear flat

To keep the horizontal motor spur gear from loosening, we plan to grind the motor shaft flat further down and possibly add a second flat rotated 90 degrees. In addition, we may Lock-Tite the spur gear set screw.

3.10.7.2 Metal bevel gears

To improve the fit between the teeth of the bevel gears, we are switching to metal bevel gears. This precision fit should drastically reduce the backlash and binding and make the bevel gears much quieter, thus making them more efficient and less irritating to listen to.

3.10.7.3 Reposition side dribblers

To fix the 20% violation, we first considered adding thin blocks behind the ear plugs to change the angle of the neutral position of the swing and push out the bottom of the swing. However, we discovered that this significantly changes the horizontal dribbler height, may cause an interference with the kicking system, causes a violation of the 180mm rule, and takes much longer to machine due to the drastically increased thickness of the part connecting the towers. Thus, we decided to move the mounting plane of the side dribbler mounts back into the robot. This solves the 20% violation because the ball position into or out of the robot is set only by the location of the horizontal dribbler; moving the side dribbler assembly relative to the horizontal dribbler moves the side dribbler mounts and bevel gear teeth back into the 20% zone.

3.10.7.4 Side dribbler rubber mounting

To keep the side dribbler rubber from riding up onto the shaft, we will epoxy the rubber onto the Delrin core. We considered adding a rib to the top of the Delrin core during machining to act as a stop for the rubber, but we decided against that because of the added uniform-diameter Delrin core. Both ideas accomplish the same goals, but the epoxy solution sounds slightly easier.

3.10.8 Future Considerations

3.10.9 Side dribbler suspension

When the robot is dribbling the ball and suddenly rotates, the ball moves rapidly across the dribbling face away from the robot rotation and smacks into the side dribbler. Because the side dribbler contacts the ball on the back half, not along the centerline front-to-back, it knocks the ball away from the robot and into the open field. In an attempt to dampen the blow from the side dribbler coming around and hitting the ball, one may want to consider a side dribbler suspension system. One such system may be rotary suspension about the motor axis, possibly using the motor itself as a shaft to mount a bearing to the swing.

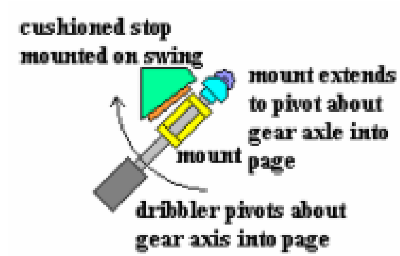


Figure 3-10 Side Dribbling Suspension

3.10.10 Four bar linkage swing

A four bar linkage swing accomplishes a similar motion as the swing but with less vertical space that the swing's towers require. However, the four-bar linkage also has an increased height displacement for a given compression distance proportional to the decreased vertical height of the mounting system, and it may require a more complex mount since it is effectively made up of two swings mounted in parallel with one in front of the other. The only difference between a four bar linkage and a short swing is that the four bar linkage keeps the side dribbler assemblies vertical under any displacement.

3.10.11 Single side dribbler motor

To conserve weight and power, one may want to consider powering two side dribblers with one motor and a simple gearing system. Because only one side dribbler is used at a time during dribbling, there is no power loss if both dribblers are powered by the same motor (other than slight losses from a gearing system). Though the power saved from running half as many motors is minimal at high RPM, having just one side dribbler motor is simpler and cheaper than two. One simple gearing system would be to imagine the 2003 side dribbler assembly; remove one side dribbler motor; and mount two equal sized spur gears, one on the remaining motor shaft behind the bevel gear, and the other on a new shaft where the old motor shaft was behind that side's bevel gear. This system maintains the same gear ratio (and thus final speed) of each side dribbler, reverses the direction of rotation of one side dribbler as needed, and uses the minimum possible amount of gears needed to change the direction of rotation of one side dribbler, thus decreasing system friction and increasing system efficiency.

4 Kicking Design Documentation

4.1 Introduction

The third mechanical subsystem is the kicking system. Even though it is the simplest subsystem from a mechanical standpoint, its contribution to the overall functionality of the entire robot is equally important. The kicking system's main function is to propel a captured ball from the robot to another point. This is utilized mostly in three tasks: shots at the goal during a game, passes to another team member, and also the required free kicks added this year. Without this system, scoring points and ball manipulation between robots will be quite difficult.

4.2 Preliminary Design

The process of preliminary design is similar to other design processes. The kicking team started by establishing goals for the subsystem. Then, we analyzed the different aspects and performed tests to verify them.

4.2.1 Design Goals/Objectives

To determine the design goals and objectives, we realized that we had to first evaluate the performance of the 2002 kicking system. Then, using the 2002 system as a baseline reference, we would determine the improvements needed for 2003 and create our goals accordingly.

4.2.2 Summary of 2002

Although the 2002 robot performed well in competition, close observation of the kick system showed that there were some weaknesses that needed improvement. Speaking to some of the members who went to the 2002 competition and observing the kicking module in game situations, we came up with some key points of concern about the 2002 kicking system.

First of all, last year was the first year in which the team implemented a kicker made of plastic. In previous years, the kicker was made of Aluminum. The motivation behind this switch to plastic was that plastic is less dense than Aluminum. This meant that the kicker would be lighter, which should result in a faster kick speed. This objective was achieved last year as the kick speed was improved over 2001's. Unfortunately, this increase came at the cost of kick accuracy. Because the kicker was optimized for energy consumption based on the constraints imposed by the other mechanical sub-teams, the accuracy flaw was not realized until the design was finalized and the robots manufactured. At that point, it was too late, and too close to the competition to alter the design. During a kicking sequence, we were able to observe that kicks performed by the robot were never accurate to a point in which two consecutive kicks had the same velocity (speed and direction). Many of those kicks were off-center, highly unpredictable, and sometimes even in a curved path. Upon closer observation, we determined that the plastic kicker was experiencing significant deflection. Since the kicker is shaped as a T, there is no support to the left and right side of the T. It was obvious that the two sides were bending back upon impact. Furthermore, the vertical portion of the kicker, the kick leg, showed twisting along its vertical extent when there was a load on the kick plate. Both deformations were evident when loads of finger pressure were applied to various parts of the kicker, as shown in Fig. 3-1.

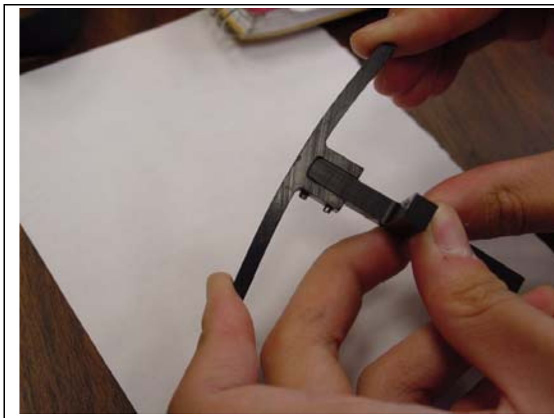


Figure 4-1 Deflection of the kicker face under load

In addition to the deformation of the kicker, we noticed flaws at the connection point between the plunger and the kicker that would decrease the accuracy of the kick system. Sometimes, the plunger shaft might not be correctly threaded, with threads skewed off-axis, causing the kicker to lean one way or the other. Other times, the kicker itself might not be tapped correctly, and a similar misalignment results.

Next, another aspect first innovated in 2001 was the use of extra kick batteries. Extra cells were connected to the kicking circuit so that its voltage was higher (27 volts instead of 12). As predicted, the increased voltage resulted in a higher voltage and thus current flow to the solenoid. Because of this, the kick was stronger, leading to a higher kick speed.

Similar to previous years, the kicker was powered by a tubular solenoid. When current is run through it, a magnetic field is generated. This in turn creates a magnetic force along the axis of the solenoid, pulling the iron core forward. The result is work done by the kicker on the ball – a kick.

Even with the kick system design oriented towards optimizing energy consumption efficiency, the 2002 kick system was only mediocre. When compared to other teams in the Skill Competition at RoboCup, our kick strength was still inadequate.

Finally, although the 2002 team improved access to the kicking system compared to 2001, maintenance of the 2002 kick system was still tricky. To gain access to the solenoid mount, the entire bottom plate of the robot had to be removed. Furthermore, with a locknut holding the kicker, removing it without taking the entire module out was very difficult. In addition, locknuts could not be removed and refastened too many times, because that degrades the plastic inside it, causing it to lose its "locking" ability. Lock nuts are single-use hardware, and should only be used once.

4.2.3 Improvements Needed for 2003

Looking at the weaknesses in the 2002 kick system, we needed to improve upon three main areas. Our kicks will have to be more precise and accurate because the kicks seldom went where they were intended. Next, a higher kick speed is needed to be on par with some of the other competitors at RoboCup. Furthermore, a faster kick will cause the ball to deviate less due to inertia. Finally, a simpler process of removal of the subsystem is necessary for quick maintenance.

4.2.4 Initial Ideas and Brainstorming

The first step in the design process is to come up with goals for the 2003 kicking system. After that, the team brainstorms ideas that would accomplish those goals.

4.2.4.1 2003 Kicking Goals

With the needed improvements in mind, goals were established for the 2003 kicking system. Since accuracy was the biggest problem from last year, that became the primary goal. More accurate kicks will ensure more effective goal shots and also, better passing. Next, to surpass the other competitors at RoboCup in terms of kick speed, we will need to increase our current speed drastically. These two goals tie together to form one of the system goals to outshoot the other teams.

In 2002, the team had a prototype goalie robot that was capable of a chip shot – a shot with a ballistic arc used to clear the ball over the opponents. However, the chip kick system was not completely reliable. Given enough time this year, the kicking sub-team will try to achieve a much more robust chip kick.

Finally, the last goal is to research the possibility of a one-time kick that would be valuable during penalty kicks. This kick would be substantially more powerful than normal kicks, employed when we absolutely have to get a goal.

To help achieve the above objectives, the kicking sub-team further sub-divided into groups for more specific focuses. The subgroups became: 1) kicking actuation and 2) kicking method. One group of the kicking team would aim to optimize the actuator to improve power; the other group will strive to create a more accurate kicker.

4.2.4.2 Ideas & Brainstorming

Since there were multiple methods to achieving the same goal, we chose to divide the brainstorming by goals, instead of by components within the subsystem.

4.2.4.3 Accuracy

The main solution to increase the accuracy of the kick system was to eliminate the deformation of the kicker during a kick. One way to accomplish this was to design a truss system that would provide support to the ends of the kick face. With the supports, there should be minimal bending of the kick face. Another idea was to return to an aluminum kicker. Aluminum was used in previous years and proved to be stiff enough to resist deflection. A third idea was to implement linear bearings into the design. Linear bearings have extremely low friction and travel along a track with minor play about the axis. This would help to prevent torsion in the kick leg, but more significantly, if the solenoid mount was brought in line with the kick face, the linear bearings could play an important role in guiding the kicker. However, for the solenoid mount to be in line, there would have to be more space in between the drive motors to fit the solenoid.

4.2.4.4 Speed

To increase the kicking speed of the system, there were ideas to improve different components of the system. Experimentation from previous years had suggested that the kicker would be in contact with the ball for a relatively long period of time, accelerating it – a push. This was in contrast to an impact in which the kicker only came into contact with the ball for a very short time – an impact. Because the kick was a push rather than an impact, the speed will be determined by the work done on the ball. $W = Fd$. Also, $F = ma$. To increase the resultant ball speed of the kicker, its mass could be reduced. This would result in a higher acceleration of the kicker. Another method was to modify the surface of the kick face to increase the energy transferred from the kicker to the ball. Research in this area was done in 2002 and could be found in the 2002 documentation. In addition to designing the kicker to increase the speed of the system, increasing the power output of the solenoid would also lead to a faster kick. One idea was to use different batteries that have a higher voltage for the solenoid. This would be similar to the 2002 implementation in which there were "super kick" batteries to increase the kick speed. Another idea was to incorporate capacitors to store higher voltage in the kicking circuit. This would produce a much larger current to supply to the solenoid, considerably increasing the force of our kick. With a different current flowing through the solenoid, the stroke length would have to be optimized to generate the best result, since solenoid pull force and inductance was based on core position.

4.2.4.5 Goalie Chip Kick

Because the goalie chip kick was a relatively low priority, there was not much as much thought put into it. However, there were two main ideas. One was to improve upon the 2002 spring-loaded design. Since there was not much time to completely develop and prove the design, it was still a viable option. The other idea was to look into rotary solenoids. Unlike conventional solenoids, rotary solenoids have an output shaft that produces a torque around its central axis. This is similar to electric motors, but with limited shaft rotation.

4.2.4.6 One-Time Kick

Since a 1-time kick will be extremely powerful, three completely different methods of actuation were brainstormed: a smokeless chemical propellant, compressed carbon dioxide and also a crossbow-style kick.

4.2.5 Ideas Selection

Once we had a list of ideas, it was time to decide which ones to pursue, and which ones to discard. This was determined mostly by the idea's feasibility, and also how much impact it would have toward our goals.

4.2.5.1 Pursued

These are the ideas that the kicking team pursued, organized under the aforementioned goals:

4.2.5.1.1 Accuracy:

4.2.5.1.1.1 Truss system

Truss structured kicking leg is theoretically stronger thus provide a more accurate kick as compared to our current simple design of plastic kicking leg.

4.2.5.1.1.2 Aluminum kicker

Theoretically on a weight basis, aluminum is much stronger than most polymeric material, thus it would not deflect as much on impact. This idea was implemented in the 2003 prototype kick leg as well as the final kicker design.

4.2.5.1.1.3 Inline solenoid mount

This is heavily dependent on wheel geometry and available volume determined by the drive motor location. We toyed with the idea for some time, but then decided that there would not be enough space. However, towards the end, there was just enough room to fit the solenoid inline. This led to a redesign, which will be discussed later in the documentation.

4.2.5.1.2 Speed:

4.2.5.1.2.1 Lower mass

Before it was decided that the solenoid could be mounted in line, having a kicker with lower mass yet improved accuracy was out of the question. The prototyped combination aluminum/ABS kicker was heavier than 2002, but lighter than 2001. However, once the solenoid was brought in line, the kick leg was completely eliminated form the design. This resulted in less material being usage thus, a lower mass than 2002.

4.2.5.1.2.2 Different stroke length

It seemed that optimizing the stroke length for the solenoid would be a quick and easy way to improve our kicking speed. Although we looked into this idea as an option, it was ultimately not implemented.

4.2.5.1.2.3 Capacitors

The capacitors were a good idea because they could store charge from the battery, increasing the voltage circuit greatly without adding too much weight to the robot. With capacitors, we no longer needed extra kick batteries, a volumetric and weight concern for the chassis and drive team.

4.2.5.2 Goalie Pursued

4.2.5.2.1 Rotary solenoid

From the information gathered from the manufacturer of rotary solenoids, it would make a very simple design of catapult, thus allowing us to make a chip shot. However since we have limited experience with rotary solenoids, additional research and testing is required.

Spring-loaded

We felt that this system is very complicated and during actuation a backward momentum may be induced. A reaction force is exerted on to the robot, causing it to move backwards.

Thus, we felt the system is inefficient. However since last year's chip shot goalie was our first implementation of chip shot, we would like to further perform research into this setup.

4.2.5.3 Discarded

The following are ideas that were discarded due to impracticality. They are also organized by the previously mentioned goals.

4.2.5.3.1 Linear bearings

While linear bearings looked promising because of its low friction and guiding track, it was decided that the additional mass and difficulty of implementation was not worth the time and effort for the marginal improvement.

4.2.5.3.2 Extra batteries

In general, adding extra batteries would dramatically increase the weight of the whole robot, thereby lowering its acceleration.

Lithium-Ion: Even though they contain higher voltage per cell, it was known that Lithium-Ion has high impedance thus not efficient for our design.

Lithium-Polymer: Relatively new technology. Would have similar properties compared to Lithium-Ion battery, and expected to be very costly.

4.2.5.3.3 Chemical propellant

Even though a chemical propelled kick can be potent in power from knowledge of firearms, we rejected this idea since we feel this design is dangerous and it will most likely be banned by rules. Thus the idea has been discarded.

4.2.5.3.4 Carbon Dioxide

While a CO_2 powered kick is a very interesting option, we rejected this idea due to the amount of space required to incorporate a reservoir and valve design. Also, we feel that a CO_2 tank could be dangerous and transportation to the competition may be difficult. As a result, the idea has been abandoned.

4.2.6 Preliminary Analysis and Testing

To examine the different ideas, analyses and tests were conducted to determine the effect it would have on the system and whether or not the idea is worth implementation.

4.2.6.1 70% height

In a dynamics class, it is a common problem to analyze the maximum efficiency of energy transfer. We were inspired to determine an optimal height at which to kick the ball. When a ball moves along a surface, it is either rolling or sliding. In an ideal situation, the ball would only be rolling, because there is a smaller friction force compared to sliding. In order to achieve the highest efficiency in energy transfer, we believed that the energy transfer would have to be totally rotational instead of translational. To find the height at which this situation exists, we did the following analysis:

Kinematics:

$$\dot{X} = \dot{\theta}R$$

$$\ddot{X} = \ddot{\theta}R \quad [1]$$

$$\ddot{X} = \frac{F}{m} \quad [2]$$

$$\ddot{\theta} = \frac{Fl}{I} = \frac{Fl}{\frac{2}{5}mR^2} \quad [3]$$

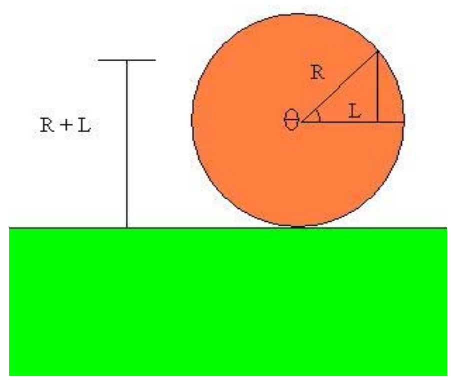


Figure 4-2 Diagram showing what the different variables

Plug [2] & [3] into [1]:

$$\frac{F}{m} = \frac{Fl}{\frac{2}{5}mR^2}R$$

$$\Rightarrow \quad l = \frac{2}{5}R \quad \therefore \quad l + R = \frac{7}{5}R = 70\% \text{ of diameter}$$

Thus, in theory, if we kicked the ball at 70% of its height, we would be able to achieve the highest rotational energy transfer, making our kick most efficient.

4.2.6.2 Truss Analysis

To solve the bending problem, our team thought of and actively pursued several different methods. We initially thought that a truss would solve the bending problem. A segment of plastic that spanned from the backside of the kicking surface to the kicking leg would transfer some of the load of a kicked ball to the leg, decreasing the bending in the kicking surface.

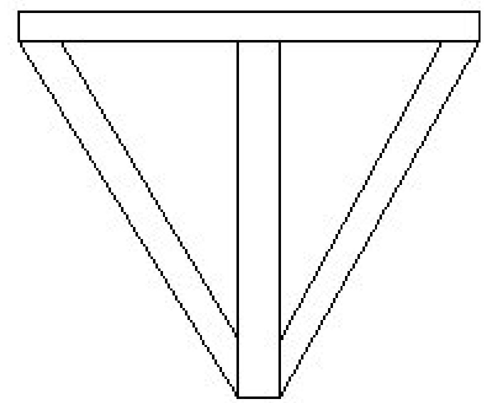


Figure 4-3 Initial idea

We initially assumed that a single truss running from somewhere on the kicking leg to the far side of the face would create a situation similar to a beam supported at both ends. When the kicker kicks the ball, the beam becomes loaded. Dynamic loading of beams can be quite complex, especially if the object causing the load—the ball in our case—bounces away as a result of the impact. In order to make any conclusions as a result of our analysis, we assumed that the load of the impacting ball was a static load. The maximum deflection under these assumptions is

$$\delta_{\max} = \frac{PL^3}{48EI}$$

where P is the load, L is the length of the kicker under consideration (one half its total length) E is the elastic modulus and I is the area moment of inertia of the face. We measured the deflection of our current kicker by hand and found it to be .839 cm. We entered this into the deflection equation for a cantilever beam

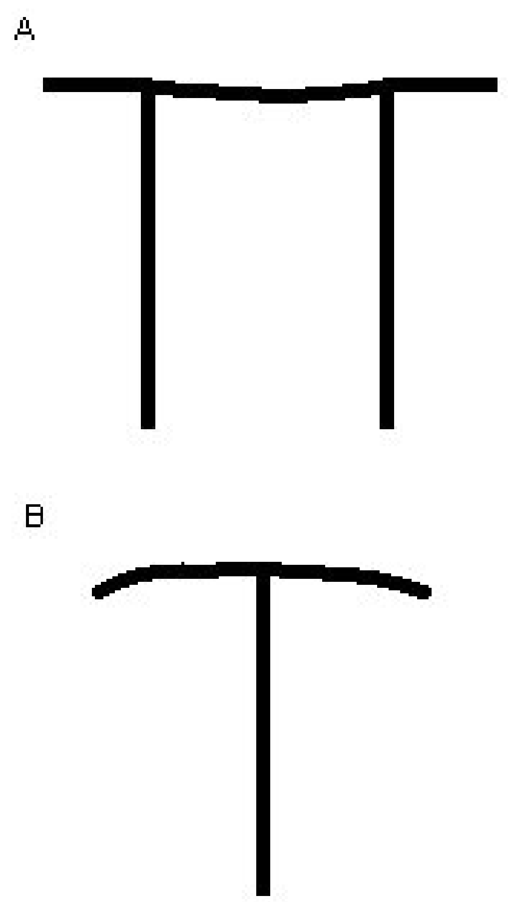


Figure 4-4 A) Positive bending, B) Negative bending

$$\delta_{\max} = \frac{PL^3}{3EI}.$$

Where with E = 3.2 GPa, I = .0018, and L = 3 cm. The resulting load was 38 N. Because we have assumed that the load is static instead of dynamic, and we have ignored the fact that the ball bounces away from the kicker, this load does not have any real world significance. This doesn't mean that the kicker is actually acting on the golf ball with a force of 38 N. 38 N is a value that we can use in the deflection equation to predict the deflection of other kickers relative to our current one. For our purposes, we used the value to predict the deflection of a kicker with a truss on either side. Using bending moment diagrams, we showed that to minimize the total bending moment, a truss should be placed in the center of each side of the kicker. However, upon further inspection, we realized that we want to eliminate all negative bending. Negative bending occurs when a load is applied to the end of a cantilever beam (the beam frowns if load is applied from above) and positive bending occurs when a load is applied between supports of a beam (the beam smiles). Negative bending will always result in the ball being pushed away from the center of the kicker, while positive bending only pushes the ball away from the center if the ball is already near the center (between the centerline and the point of maximum bending). In positive bending if the ball hits the kicker near the outside edge, (between the point of maximum bending and the edge of the kicker), the ball will actually be pushed back toward the center of the kicker.

Our analysis shows that for an ABS kicker with two struts that extend to the ends of the kicking surface and causing all bending to be positive, the max deflection would be .05 cm, or .02 in. This compares to the maximum predicted deflection of a basic aluminum kicker with no trusses: .029 cm. While the aluminum kicker still resists bending to a greater degree, the plastic kicker with trusses appears to be strong enough to withstand deflection.

4.2.6.3 Web Analysis

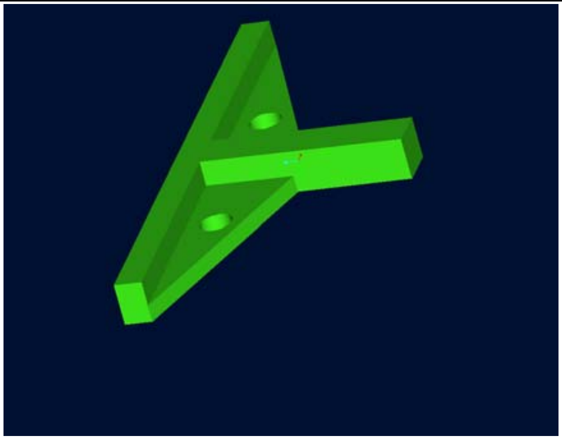


Figure 4-5 The first webbed design drawn on Pro Engineering

We showed with this analysis that making trusses would indeed improve the resistance to bending and decrease weight. We realized, however, that making many kickers with trusses would be difficult to machine. It would be easier just to cut a triangle web shape behind the kicking surface. This design would provide at least as much resistance to bending as a standard truss design.

The only worry with this design is the weight of the kicker. Assuming a triangular webbing that runs along the entire length of the kicking surface and runs up the entire kicking leg, and is .1 inches thick, an ABS kicker with webbing would weigh 8.08 grams, lighter than an aluminum kicker with no support, 13.7 grams.

We have shown with analysis that a webbed kicker will meet our functional goal of reducing motion parallel to the kicking surface to less than 1" in 55" of perpendicular motion, and we have shown that it will be lighter than our next alternative which is bending resistant, an unsupported aluminum kicker.

In further analysis, it will be useful to analyze the webbing as part of the bending face of the kicker, rather than an extended truss. This method of analysis incorporates the webbing and face together as a T-beam, a more accurate description of the kicker. This new analysis will allow us to examine the effects of altering the thickness of the web in optimization studies.


Figure 4-6 2003 prototype kicker

To prove this design, we created a prototype webbed kicker to confirm our analyses. Unfortunately, the results were not as good as we hoped. The improvement in accuracy was only marginal. We made the mistake of assuming that if a full web eliminated bending, that a web that extended halfway up the kicking leg would reduce bending to almost the same degree and would be lighter. We found that the ball traveled 3.85 in. parallel to the kicker for every 36 in. perpendicular. This means the face was still deflecting .32 inches. This is much greater than the predicted .02 in. We inspected the kicker to determine the cause of the bending, and found that we had indeed eliminated significant bending in the face of the kicker. The load of the ball was now being reacted in the leg of the kicker. Negligible bending occurred in the leg that was attached to webbing. However, kick vertical kick leg exhibited torsion (a twisting deformation) along its vertical axis. Because it is quite difficult to eliminate the torsion given our size constraint – external supports would require too much space, we decided to go back to aluminum for the vertical kick leg. Aluminum is heavier than plastic, but it is also stiffer and has a higher modulus (Al: 69GPa; ABS: 1.79-3.2GPa). With this in mind, we redesigned our kicker to be a combination of aluminum and abs. The kick leg made of aluminum, and the horizontal portion of abs. We believed that this would give us a more accurate kicker without too much increase in mass. The next step is to compare this new 2003 prototype kicker (see figure to the right) with the 2002 and 2001 kicker.

4.2.6.4 Accuracy Test

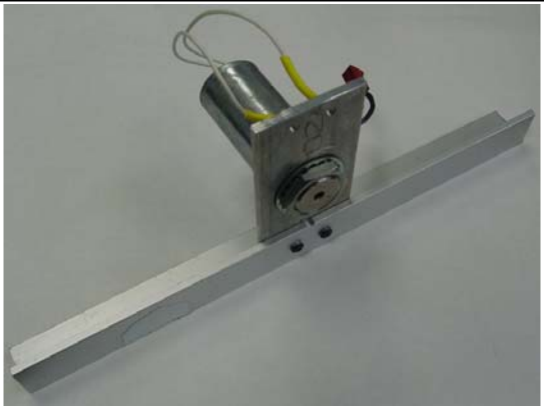


Figure 4-7 Testing kick stand

To perform the accuracy test, we created a kick stand that allowed us to interchange parts very quickly. The stand was easily made out of an aluminum angle and a 1/8" plate. A hole was drilled in the 1/8" plate to hold the solenoid, and a vertical slot cut beneath it to constrain the leg of the kicker. Also, we created the stand to have the same kick height as the 2002 robot. This was meant to keep a variable constant for comparisons. While doing the tests, it was necessary for us to clamp additional weights to it so that the stand would not move from the reaction force.

The kick stand was set up 3 feet away from the wall and 15 kicks were performed with the extreme left and right of the kick face. To get the positions of the ball when it hits the wall, we taped a piece of paper over it. When the ball hits the wall, it leaves a scuff mark on the paper. The extreme left and right deviation from the center is recorded, and then an angle of deflection is calculated. Below is the data obtained from the tests:

	Mass	Left	Right	Total	Angle
2003 (Trial 1) Al + ABS	10 g	2.375"	6.25"	8.625"	9.28
2003 (Trial 2) Al + ABS	10 g	2.5"	4.625"	7.125"	6.82
2002 Delrin + ABS	6 g	7.0"	6.5"	13.6"	17.24
2001 Al only	14 g	3.875"	4.25"	8.126"	9.22

Table 4-1 Data from accuracy test

Based on these results, we conclude that the 2003 prototype kicker is almost twice as accurate as the 2002. Although its accuracy is comparable to that of the 2001 kicker, when we look at mass, the 2003 prototype kicker is decently lighter than the 2001.

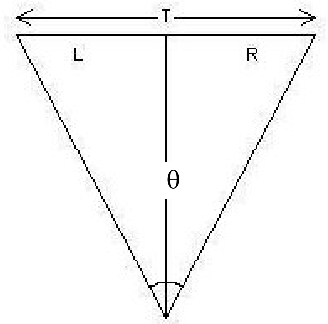


Figure 4-8 Accuracy test diagram

4.2.6.5 Mass Test

According to the equation $F = ma$, it is almost assumed that a lighter kicker will produce a more energetic kick. But it is possible that more energy would be transferred by a kicker with more momentum according to the equation $P = mv$.

To be sure that the first relation dominates in this situation, we conducted tests to try to prove it. The relation of the acceleration of the kicker to the energy it delivers to the ball is complex. It depends on a position-varying force supplied by the kicker and a collision with the ball that has not been thoroughly researched. The consensus from returning team members and previous documentation is that the kick is a push rather than an elastic impact, and it is possible to delve into the interaction of the kicker with the ball. This is currently unnecessary since we can directly measure the final product of the kick, the energy imparted to the ball, and we can examine how it changes as we vary the mass of the kicker.

To conduct this test, we used the previously mentioned kick stand. We started with the mass of a bare 2002 kicker and kicked the ball 10 times up a ramp made with 1" aluminum angle rotated 45 degrees. The average height was measured and the energy calculated according to the equation $U = mgh$. We then repeated the process, each time adding about 10 grams to the kicker by attaching weights to it.

Our test showed that we were correct in assuming a lighter kicker would produce a more energetic kick. A big surprise came in our evidence that the relationship is not entirely linear. This could be a result of a wide variety of factors, ranging from a poorly understood interaction between the kicker and the ball to frictional forces between the ball and the ramp. However, the details of our result are not as important as the solid conclusion that a lighter kicker will transfer more energy to the ball.

The 2002 team did tests to determine what material delivered the most energy to the ball. They tested these materials while holding the mass of the kicker nearly constant. Their tests showed that Surlyn plastic, the same material as the surface of the ball, produced a more energetic kick. They also found that a lighter kicker resulted in a more energetic kick, a fact that we have confirmed this year. It was the 2002 team's conclusion that the mass of the kicker was more important in determining the performance of the kicker than the material of which the kicker was constructed. In other words, to optimize the kick speed, the most important variable to consider is the mass of the kicker.

Continuing with this reasoning, we checked to be sure that a plastic kicker with trusses would be lighter than a regular aluminum kicker with no trusses. Both kickers would significantly eliminate bending. Based on the Pro E drawings, the aluminum kicker weighs 13.7 g and an ABS kicker with two trusses weighs 6.27g.

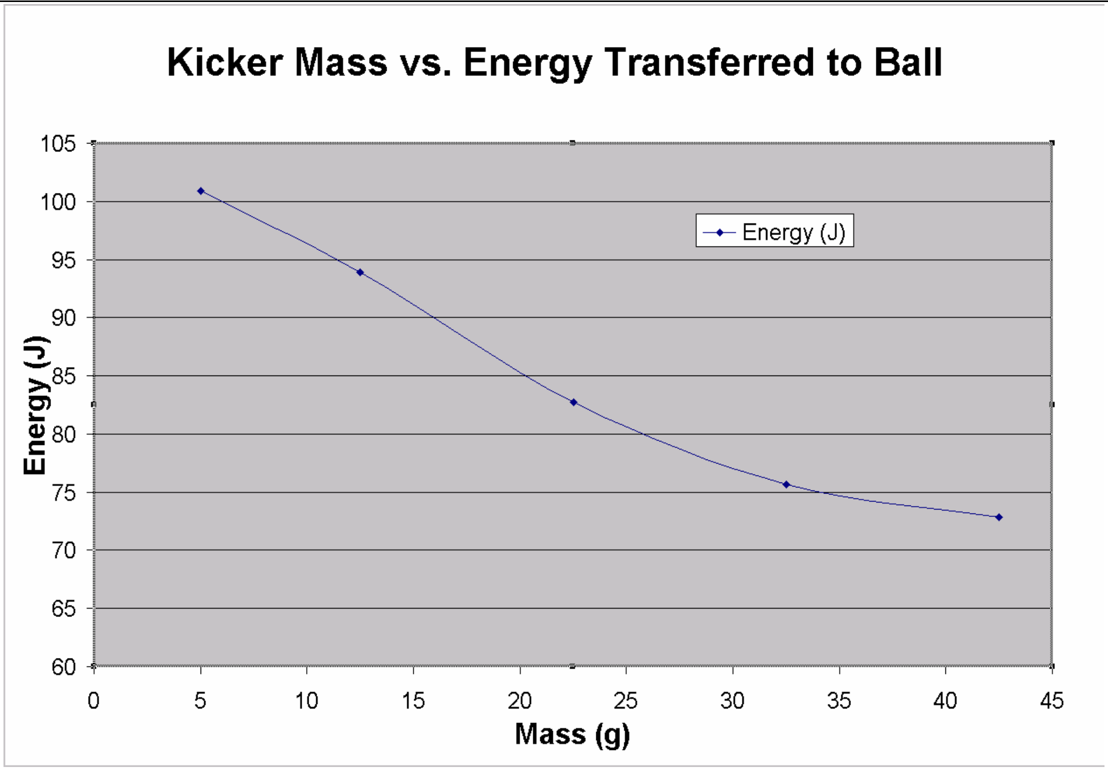


Table 4-2 Graph of results from mass test

Our group initially tried to incorporate matching the material of the kicker with the material of the ball into our analysis. We were unable to find any theory on the subject of matching materials and our only information came from the 2002 test results. In order to critically take the effect of matching the materials into our analysis, we would have had to perform more testing to determine why the act of matching materials creates a more energetic kick. Does this matching effect come from similar moduli of elasticity between the two materials, or does it come from molecular interactions, or some other unknown cause? The knowledge that 'Surlyn works best' is not enough information to base an analysis upon. After running down multiple paths of thought in which we did not have enough information to go forward, our group abandoned this theory and concentrated on creating a light, rigid kicker.

4.2.6.6 Stroke Length Test

Use LaGrange Equations of Motion

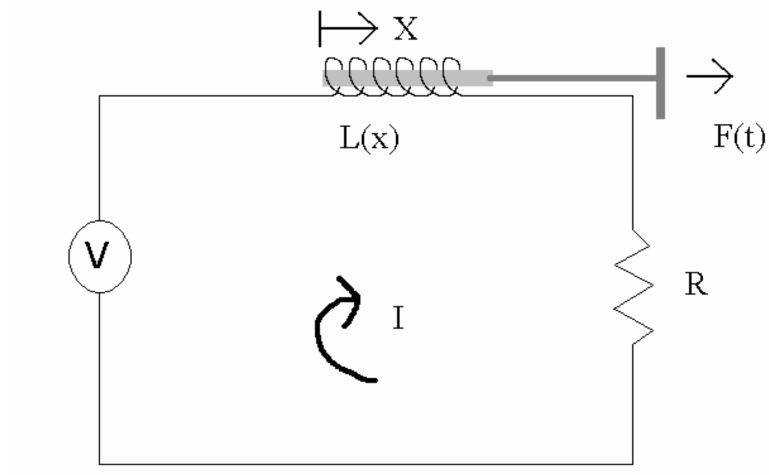


Figure 4-9 Kicking Circuit

KE $T = \frac{1}{2} m\dot{x}^2$

PE $V = 0$

$W_{electrical} = 0$

$W_{magnetic} = \frac{1}{2}(L(x))I^2$

$Q_1 = F(t) \qquad Q_2 = V(t)$

Linear approximation for change of inductance: $L(x) = L_0 x + L_1$

Dissipation through resistor:

$$R_e = \frac{1}{2} R I^2 = \frac{\partial R}{\partial I} = RI$$

LaGrange:

$$L = T - V + W_m - W_e$$

$$L = \frac{1}{2} m_{sys}\dot{x}^2 + \frac{1}{2} L(x) I^2 = \frac{1}{2} m\dot{x}^2 + \frac{1}{2} L_0 x I^2 + \frac{1}{2} L_1 I^2$$

$$\frac{\partial L}{\partial \dot{x}} = m\dot{x} \qquad \frac{\partial L}{\partial I} = L(x) I \qquad \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = m\ddot{x}$$

$$\frac{d}{dt}\left(\frac{\partial I}{\partial I}\right) = \dot{L}(x) I + \dot{I} L(x) = L_0 I + (L_0 x + L_1)\dot{I}$$

$$\frac{\partial L}{\partial x} = \frac{1}{2} L_0 I^2 \qquad \frac{\partial L}{\partial q} = 0$$

Build Equations of Motion:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i + \frac{\partial \Re}{\partial q_i}$$

From Previous:

1) $m_{sys} - \frac{1}{2}L_0 = F(t)$

2) $(L_0 x + L_1)\dot{I} - L_0 I - 0 - RI = V(t) \Rightarrow$

$(L_0 x + L_1)\dot{I} - L_0 I - RI = V(t)$

$(L_0 + L_1)\dot{I} - (L_0 + R)I = V(t)$

Based upon this relationship between the energy transferred to the ball and the parameters of stroke length and solenoid inductance, the optimal values based upon any given voltage can be determined. This allows for much more effective construction of the kicking circuit.

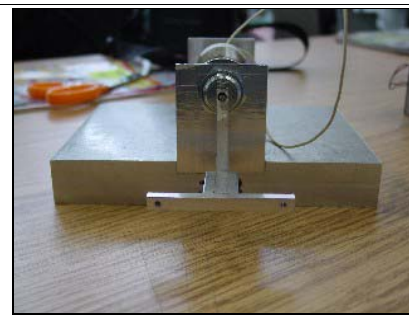


Figure 4-10 Front face of kick stand

Since the stroke length test was done independent and concurrently with the mass and accuracy tests, a separate kick stand was machined for efficiency. This kick stand was machined using a hand mill with an aluminum block. The stand was designed such that it can hold different sizes of solenoid that we acquired previously. These solenoids were also made by Magnetic Sensor Systems and their model number was S-25-125-H and S-22-150-HF. These solenoids were wider in diameter but have a shorter stroke length. The reason why we needed to setup the stand was because these solenoids would not fit under the 2002 solenoid mount due to their increased diameter and also the tread diameter at the front of the solenoid was also larger. Therefore we need to machine a kicker stand such that it meets all the increased-size criteria. The kicker stand's final design was shown below. The solenoid would fit into the hole, with its body hanging, while being only secured by a cap onto the front tread. This will ensure the solenoid to be perfectly parallel to the ground. Also underneath the kick stand would be a plate which the kick stand screwed onto, the added weight to the setup would ensure on that the kick stand would not move.

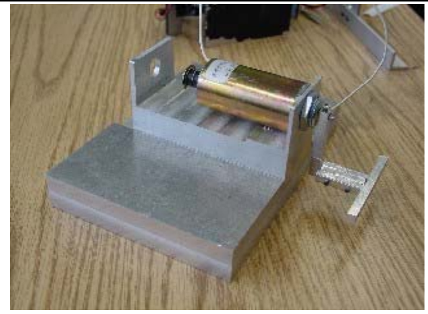


Figure 4-11 Kick stand setup with solenoid and test kicker

For the actual test, we used the kick stand setup as above but only the S-20-100-H solenoid and varied the stroke length of the kicker. The setup of this test is shown below. We modified the stroke length until the maximum stroke length it could allow, which is about 1". Our current kicker is set at 0.5" due to dribbling and drive restriction. Initial thought process indicated we might want to use 0.5" because of, again, dribbling and drive restriction. Testing was performed at 0.3" to the range of 0.9". 54V of batteries were used. Testing results were logged as below.

Table 4-3 Data from stroke length test

0.3"	1.3 seconds
0.4"	1.3 seconds
0.5"	1.2 seconds
0.6"	1.1 seconds
0.7"	1.3 seconds
0.8"	1.3 seconds
0.9"	1.4 seconds

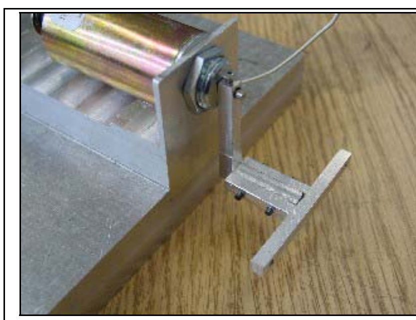


Figure 4-12 Stroke length test setup with kick stand

Due to this result we felt it was not the best way to choose our stroke length based on this test. We believe with the new DC-DC converter kicker, 0.1 seconds or less in performance difference is negligible. Therefore we again decided to use a 0.5" stroke length in order to limit extra space usage.

4.2.6.7 Solenoid Size Test

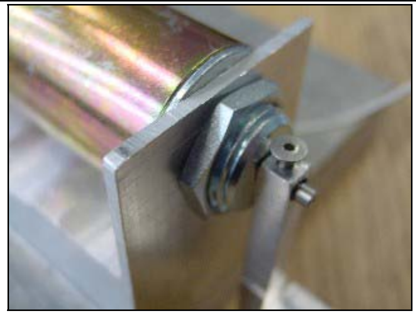


Figure 4-13 Adjustable screw for modifying stroke length

The kicking team has thoroughly searched for different types of solenoids from different manufacturers and found numerous results that may be useful in our applications. We felt that a solenoid is the best actuation that we could use to provide us with both kicking and passing skill. These solenoid findings included a low-profile solenoid, a larger size tubular solenoid and a rotary solenoid. The low-profile solenoid incorporates the same kind of push mechanism as the tubular solenoid; however the solenoid's construction has two major differences as compared to the tubular design. First, it contains more turns of winding. Second, it generally has a shorter stroke length. Low-profile solenoid will provide a greater amount of force at a smaller stroke length. A larger size tubular solenoid is also an option because it generates a greater amount of force at any stroke length if compared to a smaller size tubular solenoid. A rotary solenoid is very much similar to linear solenoid, but it consists of a rotation actuation instead of a linear actuation. Hence the measure of rotary solenoid performance is determined by the torque generated. The kicking team found out from the manufacturer specification that many comparable sizes of rotary solenoids can generate a huge amount of torque, thus we would like to investigate this matter further.

The Solenoid size test was performed using the same kick stand as the stroke length test described above. Different sizes of tubular solenoid were clamped to one end of the kick stand and actuated in order to compare the difference in each solenoid. The kick stand would then be placed at one end of the robotic soccer field and kick the ball towards the other one and timed. The solenoids that we tested were S-25-125-H, S-22-150-HF and S-20-100-H, all with AWG number 23. Testing were done using twice the voltage of our 2002 battery system, which consist of 27V (1 pack of main battery = 12V, and 2 pack of auxiliary battery = 15V), so the overall test system was using 54V. The test performed and log as follows:

Table 4-4 Data from solenoid size test

S-20-100-H	Average 1.3 seconds
S-22-150-HF	Average 1.2 seconds
S-25-125-H	Average 1.4 seconds

We felt that with the additional weight and size these larger size solenoids it will carry, the performance difference has been offset, and therefore we felt it was not justifiable to use these solenoids in our kicker. Also since we knew that we would be using the DC-DC converter that the EE team is supplying us, we felt the performance is already enhanced such that we should not increase the size and weight of the robot.

4.2.6.8 Magnetic Sensor Systems S-20-100-H AWG 23 Solenoid Test

Given our 2002 robot's solenoid kicker, which was a Magnetic Sensor System's tubular push type solenoid S-20-100-H at AWG 23, when we consulted with the manufacturer about our solenoid, we were told that given 12 volts of power at 10% duty cycle, the AWG 22 solenoid would perform a more powerful kick as compared to our AWG 23 solenoid. Last year, the kicking team performed an optimization problem in which we tested the kicking system with our battery system against 6 different kinds of solenoids. The special characteristic about these solenoids was that even though they have the same size compared to each other, they ranged from AWG 19 to AWG 24. During the experiment, we were able to identify AWG 23 as the most powerful solenoid kicker. However this would contradict from what the manufacturer said about AWG 22 being the most efficient. Thus this contradiction strikes us to further investigate into this matter. Originally from specification, at 10% duty cycle, only 12 volts would be needed. We felt that if only 12 volts is needed, it made perfect sense that we should first try to actuate a kick with only the main battery packs and observe the performance since they have a capacity of 12 volts. However when we performed this test, we were able to see a dip in performance. We believed there were many hidden factors, such as unaccounted internal resistance of the circuitry contributed by the EE boards and connectors, thus limiting the amount of current draw to the solenoid. With this in mind, we performed a series of test in which we would actuate a kick without the aid of the IR sensor, thus by using a basic switch we would be able to kick without the need of factoring other internal resistances from the circuit. The results of these tests were similar as compared to the tests performed by actuating the kick via the IR sensor. Along with the performance drop by removing battery packs, we felt these 2 experiments explained that voltage supplied from the battery is a strong function to the solenoid we used, thus we felt by increasing the voltage supply by the battery, we should expect to see an increase in performance. From last year's optimization result when we increased the voltage of the battery packs from 12 volts to 27 volts, we experienced twice the power output from our solenoid kicker. With this in mind, we performed another experiment in which additional set of battery packs were engaged. Originally, we had approximately 27 volts of battery in our robot configuration, but for our testing purposes, we connected two 27 volts of battery packs in series, thus doubling the battery supply to 54 volts. Once this test has been performed, we were amazed with the result. It was measure that the performance of our kicker were doubled, taking half of the time of the old configuration for the ball to reach a certain amount of distances. When we added another additional 27 volts to the 54 volts of battery packs, we again notice an increase in performance, but only by a slight amount. The results of the above test are summarized below.

Table 4-5 Data from voltage test

Voltage supplied by battery pack, connected in series	Time needed to travel 170in.
12 volts	N/A, does not travel 170in.
27 volts	~ 2.6 seconds
54 volts	~ 1.2 seconds
81 volts	~ 1.0 seconds

Therefore we concluded with these results that we would get satisfactory kicking power by supplying the solenoid with 81 volts of battery, and we could eliminate the need of creating a one time kick mechanism. If we were to insert 3 sets of our current battery configuration into the robot to generate 81 volts, it would not be feasible due to the size, weight and volume constraint; thus presently the kicking team is working closely with the EE group to investigate into the possibility of using an array of capacitors which will help generate 80 plus volts from our original battery cells. These investigations are ongoing and the result of these investigations will be available soon.

4.2.7 Idea Selection for inclusion in the Final Design

Through our extensive evaluation of brainstormed ideas by analyses and testing, we came up with a preliminary design that would be implemented. It would be incorporated with the other subsystems, so modifications due to packaging were expected.

As demonstrated by the accuracy test, the combination aluminum and plastic webbed kicker is a vast improvement over the 2002 kicker. It is stronger than the 2002 kicker, yet lighter than the 2001. With this design, we achieved our highest priority – a much more accurate kick system. Next, to achieve the goal of increased kick speeds, we turned to the electrical aspect of the system. By employing capacitors into the system, we raised the voltage of the circuit from a standard 12V to an enormous 110V. This dramatically boosted our kick speeds from an average of 2.1 m/s to about 4.1 m/s – almost twice as fast!

However, when the drive sub-team finalized their design after deciding on the 4-wheel butterfly geometry, the kicking sub-team had go back and redesign the kicker. This was because now there was enough space to mount the solenoid in line. By bringing down the solenoid in line, we would lower the center of mass of the robot, thereby improving acceleration. Furthermore, we believed that an inline kick system would additionally enhance our accuracy and kick speed.

Because the solenoid was now in line, the vertical kick leg is no longer needed. This eliminated a large chunk of material, and thus, would decrease the mass of the kicker. As a result, we decided to change the horizontal portion of the kicker from abs to aluminum. Our reasoning for this was that aluminum has a stronger strength to mass ratio, and with the kick leg removed, there is enough mass to work with. We still tried to design the kicker to be as light as possible, and yet strong enough to prevent deformation. In the end, an aluminum kicker using a truss system became our final design. It had less mass (~2.2 grams) and less volume than even the 2002 kicker.

Since the solenoid mount is still going to be attached to the top plate of the robot, there was no need for a radical change in the part. Because packaging – keeping all the subsystems from interfering with each other, was a huge issue, the mount was designed to best fit the amount of space provided.

With the vertical kick leg eliminated, there was longer a constraint to keep the kicker from rotating around its axis of movement. To solve this, we created a pair of plastic guide bars that would constrict its rotation. The guide bars are mounted onto the solenoid mount and extend forward under the kicker's path. We decided on using plastic, because aluminum on plastic has a low coefficient of friction and we knew that the kicker would be resting and sliding on it.

4.2.8 The Final Subsystem

The final kicking subsystem consisted of several components. A mount connects the whole kicking module to the robot chassis. The solenoid is constrained within this mount. The kicker is attached to the plunger, which slides within the solenoid. The retracting mechanism consists of a spring (taken from last year's design) and a rubber o-ring. In experimentation, the spring was known to fail (by coiling itself out of the e-clip), causing the e-clip to get bent. The o-ring prevents the spring from getting out of its position, and at the same time provides a small cushion for the e-clip. Finally, the kicker is supported by a pair of guide bars extending from the mount that prevents it from rotating.

4.3 Design Documentation

4.3.1 Subsystem Design motivation and goals

The primary goals for the kicking subsystem were ease of maintenance and the achievement of fast, accurate kicks. Previous years had suffered from kicks that were both slow and inconsistent in direction, making precise use of the kicker a difficult task. Through analysis, it was determined that the use of trusses on the kicker, combined with an inline kick, would increase the kick's speed and greatly improve the accuracy. In addition, when used in conjunction with the DC/DC converter and capacitors (used to provide much higher current to the kicking solenoid), the kick system's speed will be further enhanced (which in turn improves accuracy due to the inertia of the ball). Much of the design process that resulted was centered on the implementation of the truss-based kicker while maintaining simplicity of manufacturing and maintenance. To further aid the continuing maintenance of the robots, it was determined that a kicking assembly that could be removed wholly from the robot without dismantling other subsystems would greatly improve access to the module. Thus, the speed at which problems in kicking could be addressed and corrected would be increased. To this end, the kicking system was designed to be compact and independently modular so as to require as few connections as possible with the remainder of the robot.

4.3.2 Approach to Subsystem Design

To facilitate the aforementioned goals, we attempted to design a kicking assembly that was able to maintain both high accuracy and speed with a minimum of parts and as small a width as was feasible. The demand for high accuracy and speed dominated the design process of the kicker itself with robustness, mass and resistance to deflection the primary concerns, and ease of manufacturing as an important secondary consideration. The remainder of the system was designed to support the kicker and prevent flaws in the support assembly that would detract from the kicker's abilities, while also being removable as a single unit without additional disassembly. To accomplish these goals a number of revisions had to be made, and some plans and designs had to be discarded, but in the end the final system satisfied the original goals well.

4.3.3 Initial Design Problems, Limitations and Changes

4.3.3.1 Kicker Design

One of the first design challenges for kicking was the creation of the kicker itself. With the changes in the drive system that allowed for an inline kick, the kicker itself could be much simplified. The kick leg that had previously been used to position the kicking in the proper plane was eliminated and instead the kicker was attached directly to the plunger. This new kicking style called for a radically new design. Prototyping had determined that an aluminum kicker supported by a truss structure would produce the optimal kicker, allowing for low mass and high accuracy. The original design called for a kicker that was symmetric on both the top and bottom of the kicker. This design was then revised by eliminating the symmetry of the top and bottom to allow for easier machining, producing a kicker that could be produced in two setups, as opposed to three. In this revision one of the mounting supports for the plunger was removed from the kicker and replaced with a contact on the rear of the kicking face, reducing mass and eliminating a nut by using material already present to constrain the kicker in one direction. This made for a simpler and more efficient constraint, but required the addition of a lock washer to prevent the loosening of the would-be unsupported nut.

4.3.3.2 Return System Design

A second concern was the durability of the return system for the plunger. Tests had shown that the previous return system failed when subjected to repeated kicks using the new voltage. In response, an O-ring was added to the plunger, dampening the impact that was experienced by the 2002 return system and an unclipped spring of higher spring constant replaced the weaker, clipped spring the old return system had used. After additional testing, these changes have been proven to prevent the failure of the spring and the E-clip.

4.3.3.3 Kicker Restraint and Guiding

Another concern for the mechanical system was the ability to restrict the kicker to the proper plane so that the kick would be as consistent and powerful as possible. Originally a set of two metal pins was proposed, however it was determined that the pins would be too susceptible to deflection and damage if they were to be press fit into the solenoid mount and extend to the full stroke length. This problem was ultimately solved by using Delrin bars to guide the kicker and prevent rotation around its axis, as the bars were relatively rigid, light and simple to attach. Due to space constraints the solenoid mount had two channels cut out of it to allow for the mounting of the bars. The channels were originally cut to allow for the bars to fit snugly within them, but for ease of machining they were later extended to the bottom of the solenoid mount, simplifying two setups.

4.3.3.4 Easily Machined Solenoid Mount Design

A later concern was the difficulty of machining the solenoid mount. The original plans called for a mount that would include a large tubular section to allow for the placement of the solenoid, much like the 2002 design. This decision was made to allow for a well-aligned solenoid and a low mass mount. The difficulty in machining this piece, however, caused the part to be redesigned, resulting in the final unrevised solenoid mount. The current mount maintained the same length as the original piece, as well as two circular points of contact for alignment and attempted to minimize mass while still allowing for a piece that would be simple to machine. The new design was more massive than the original, but as it eliminated the curves and rounds of the previous mount, it could be hand machined much more easily, as well as allowing for easier mounting of the guide bars.

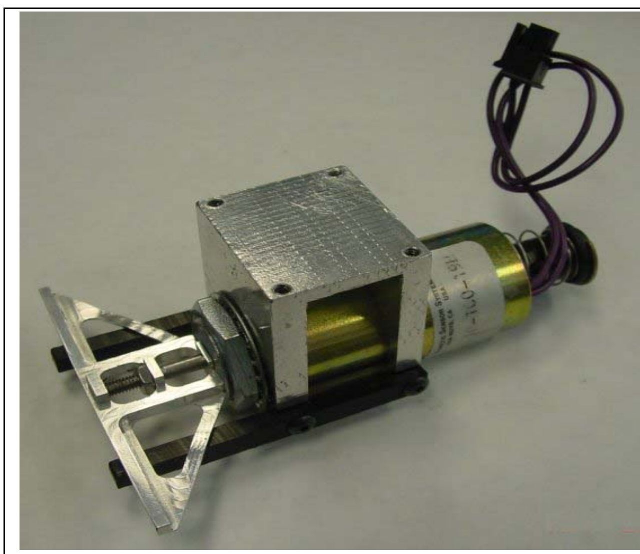


Figure 4-14 Kicking module

4.3.4 Final Design Part Description

4.3.4.1 Solenoid Mount

Figure 4-15 Solenoid Mount

The solenoid mount could be considered the chassis of the kicking subsystem. With the exception of the electrical power connection between the solenoid and the kicking circuit board, the solenoid mount is the only component that comes in contact with a separate system of the robot. The solenoid mount was designed to provide accurate alignment through a two screw, two pin connection to the top chassis plate. In addition, it was designed to provide a large surface of contact with the solenoid to allow for consistent alignment between the solenoid and the solenoid mount, reducing inaccuracy internal to the subsystem. Finally, the solenoid mount was designed to allow for the mounting of the guide bars on either side of the solenoid through the addition of recesses and mounting holes, ultimately allowing for an effective and highly modular assembly.

4.3.4.2 Solenoid

The solenoid itself is a purchased part, with its winding optimized for the new kick voltage. The solenoid's dimensions dictate much of the dimensions of the parts for the remainder of the kicking subsystem, but the solenoid's design itself was fixed.

4.3.4.3 Plunger and Return Assembly

The solenoid plunger is simply an iron plug sized for the solenoid attached to a segment of 1/8" drill rod, the end of which is tapped. This drill rod is sized in length to position of the kick face at the desired distance from the solenoid mount. The drill rod is attached with epoxy to a hole in the iron plug, allowing for a simple yet sturdy fastening. To the rear of the plunger an E-clip is attached onto the existing groove with an O-ring resting against it. The O-ring effectively prevents failure of the spring and E-clip during hard kicking. Between these components and the solenoid mount is a helical spring used for plunger return. A helical spring is used because it allows for maximum compression (the spring can collapse into itself). This prevents damage that would otherwise occur to a non-helical spring. These components together allow for a more robust and efficient return system.

Figure 4-16 Plunger disassembled

Figure 4-17 Plunger assembled

4.3.4.4 Guide Bars

The guide bars are two identical Delrin bars that are mounted to either side of the solenoid mount in an effort to prevent rotation of the kicker around its central axis. The bars are rectangular in cross section, with the lower portion of the forward ends removed to prevent contact with the swing. Two holes are drilled in the bars for fastening to the solenoid mount with screws.

Figure 4-18 Guide bar

4.3.4.5 Kicker


Figure 4-19 2003 kicker

Ultimately, the complete kicking subsystem is designed to support the kicker. The kicker is the only part of the subsystem that comes in contact with the ball, or in fact any surface other than the robot itself. The kicker is made completely of aluminum in an effort to maximize strength while preventing inefficiency due to high mass. Thin T-beam trusses support the kick face at its extremities to prevent deflection at high kick speeds. The kicker is mounted to the drill rod at three points: a thin support at the rear of the kicker, a thick support in the middle against which a nut and lock washer are tightened, and a circular cut out on the kick face itself. This allows for a minimum number of fasteners, providing simplicity, ease of assembly, and decrease in mass, without the sacrifice of a secure connection to the plunger. In addition, the kicker is asymmetric on the top and bottom, allowing for machining in two setups: one for the majority of the cutting and one for the holes through which the drill rod passes.

4.4 Initial Testing and Revision

Through preliminary performance testing it can be said with confidence that all goals for 2003 kicking have been met or exceeded. Accuracy (prior to the failure of the original kicker) was extremely high and kick speed exceeded expectations. In addition, (following minor modifications) the kicking subsystem is easily removable without dismantling the remainder of the robot.

4.4.1 Kick Height Test

The focus of the kick height test was to determine the height at which the greatest peak ball speed could be obtained. The kick height test was performed with the aid of AI and vision to facilitate accurate measures of speed, using a program that calculated speed from the change in position over the course of two subsequent frames (change in position over 1/60 of a second). "The Cheat" (the 2003 prototype robot) was placed first on the field then on progressively thicker metal plates atop the field to raise the kicker to the necessary height during the performance of the test. The height values tested were current height, current height plus .06" and current height plus .185". The tests determined that variation between kicks at any one height was far greater than variance between kicks at different kick heights. However, there seemed to be a subtle trend of higher peak kick speeds at current height plus .06", a height that corresponds almost exactly to the center of mass of the ball. At this height kick speeds at approximately 4m/s were routine with the highest speed greater than 4.8m/s. While a higher kick could theoretically give a higher final speed, our tests gave no substantial indication of this trend (see 70% height analysis above). Furthermore, as the benefits of a higher final speed would likely only be realized on kicks that traveled a significant distance, strategically the majority of kicks are made at a relatively short range and therefore benefit most from a higher peak speed, the height of current height plus .06" was selected for the final height of the kick face. This height increase was facilitated through a slight modification to the solenoid mount, resulting in Revision A.

4.4.2 Post-Prototype Accuracy Test

This accuracy test was conducted in an effort to obtain more quantitative data to substantiate earlier results suggesting a high degree of accuracy, perhaps even a θ of less than 2°[1] (θ is defined as the maximum angle from the line perpendicular to the kick face to the line traveled by the ball when kicked as shown in Appendix). A test was designed in which The Cheat was placed on the field 80" from a plastic box to which a piece of paper was attached. The Cheat was then to kick ten times each from the extreme left, extreme right and center of its kick face while the impact positions were recorded. The distance between the leftmost and rightmost impacts would be divided by two and used to calculate θ[2]. The first set of tests conducted to substantiate this claim, however, showed an extremely poor accuracy. While the accuracy was so poor an exact θ was not obtained, it could be estimated as approximately 15°. Upon inspection of the kicking subsystem, it was determined that the

[1] This claim of less than two degrees for θ arises from the statement that variation in position orthogonal to the balls kick direction was less than the diameter of the ball.

[2] i.e. $\theta = \tan^{-1}(\,(\text{distance between marks} / 2\,) / 80)$

inaccuracies were not the result of implicit kicker inconsistencies (i.e. variance in kick angle due to normal elastic deformation in the kicker or deflection of the plunger within the solenoid) but rather due to critical failure of the kicker itself. The truss structure that supported the kicking face had failed by buckling, resulting not only in a lack of support for the kick face, but also in the kick face's permanent plastic deformation. It is believed that this buckling failure was due to the combination of heavy axial stresses as well as significant load concentrations from the guide bars during the kick (see diagram below for explanation of how guide bars contributed to failure). The kicker's trusses were redesigned as outlined above to solve this problem, producing Revision A – reinforcing the truss with a vertical rib along the center.

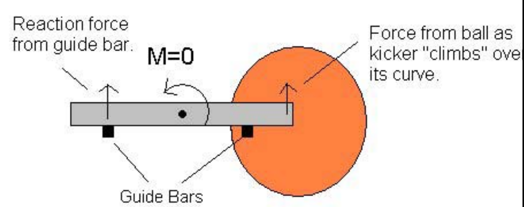


Figure 4-20 Force diagram of kicker as viewed from the back

Figure 4-21 Failed 2003 kicker

Below is the analysis to the increased strength that will be provided by the addition of a rib along the center of the truss.

4.4.2.1 Analysis of Buckling in Truss Beams

Minimum Force for Buckling in a Beam:

$$F_{criticalBuckling} = \frac{EI\pi^2}{L^2}$$

Ratio of Critical Buckling Forces for Two Beams of the Same Material:

$$\frac{\frac{EI_{one}\pi^2}{L^2}}{\frac{EI_{two}\pi^2}{L^2}} = \frac{I_{one}}{I_{two}}$$

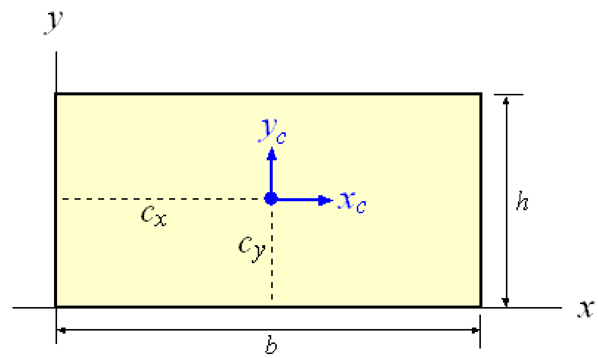


Figure 4-22 Diagram for a rectangular beam

Area Moment of Inertia for Beams:*

Rectangular Beam:

$$I_{one} = \frac{1}{12}bh^3$$

T-Beam:

$$I_{two} = \frac{1}{3}\left(ty^3 + b(d-y)^3 - (b-t)(d-y-s)^3\right)$$

4.4.2.2 Numerical Analysis:

Rectangular:

h= .026"

b= .1"

T-Beam:

b= .1"

s= .026"

d= .052"

t= .05"

h= .026"

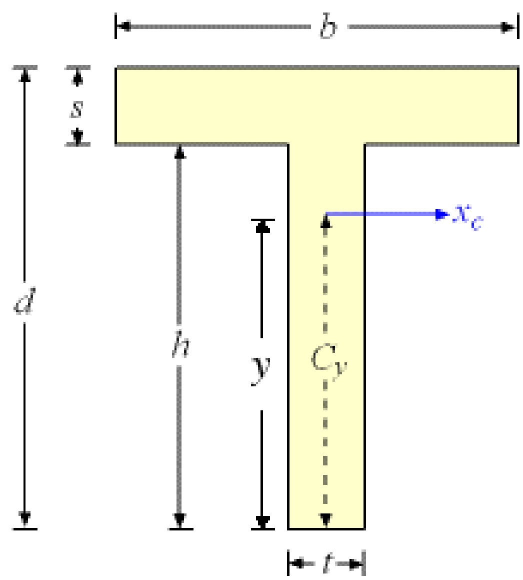


Figure 4-23 Diagram for a T-beam

Ratio of Buckling Strengths: 5.5 : 1

Based upon this increase in buckling strength, it is believed that the kicker will be sufficiently resistant to failure to satisfy all demands for robustness. While the buckling load on the kicker was not calculated, the number of kicks that were required to induce buckling suggested that the kicker was only slightly too weak to resist failure. With such a large increase in buckling, it was determined that, baring a

* Diagrams from Efunda.com

subsequent failure, the introduction of the T-beam geometry was sufficient to correct the problem.

4.4.3 Solenoid Winding Tests – Speed and Reliability

A test has been designed but has yet to be completed in which the solenoid winding will be optimized for the new kicking voltage (≈110V). Solenoids consisting of windings ranging from AWG 19 to AWG 24 will be mounted on The Cheat and used to kick fifteen times for each winding while AI and vision obtain speed information. The winding that produces the highest average kick speeds will then be chosen as the final solenoid winding, so long as robustness is not compromised through failure of the wires when full voltage is applied.

In addition to the above, a scheduled test for reliability was designed in which The Cheat would "machine-gun kick" (kick repeatedly at very short intervals using IR) for a minute, after which the status of the solenoid would be evaluated. This is to verify that the solenoid is not overheating.

The purpose of these two tests is to optimize the solenoid winding for our given system. A thinner gauge has more winding, which results in a stronger magnetic field being generated. However, it is also in greater of melting under the high current. A thicker gauge would have the opposite effects.

4.4.4 Kick System Robustness Test

This is similar to the solenoid winding reliability test, except the entire system – solenoid, kicker, fastener, return system and kicking circuit – would be evaluated. Due to the failure in the accuracy test, however, such a test was both impossible and unnecessary for the kicker in its current form. Quite clearly the kicker fails far too easily and quickly, and therefore must be redesigned as was outlined above in the report regarding the accuracy test.

4.4.4.1 Solenoid Mount Redesign for Alignment

To maintain the accuracy of kicker, consistent alignment of the solenoid mount is required. To accomplish this, the fasteners between the solenoid mount and the top plate were changed from the four screws that appeared on The Cheat to two screws and two pins, a change incorporated in Revision A of the solenoid mount. Through the addition of press fit pins the solenoid mount will be aligned with better accuracy to the top plate, and therefore the kick should be consistently in the direction expected (i.e. "straight ahead").

4.4.4.2 Solenoid Mount Redesign for Height

In addition, based upon the kick height test the kick could be slightly superior if placed .06" above its current height. In response the center of the hole for mounting the solenoid was placed .06" above its previous position, altering no other facet of the solenoid mount and producing no difficulties. This change was incorporated into Revision A.

4.4.5 Kicker Redesign for Robustness

Following the accuracy test outlined below, it became clear that the current kicker truss system was not strong enough to support the kicker face during repeated kicks at the new voltage. In response the truss connections of the kicker were redesigned to be T-beams through the addition of a rib down the center of the truss. Through theoretical analysis the new trusses are expected to be 5.5 times as strong in buckling as the previous rectangular beams while the increase in mass is essentially negligible (see post-prototype truss analysis above). This modification to the kicker is still in the process of being machined, and is Revision A of the kicker component.

4.5 Future Consideration and Goal for 2004

The kicking team believes that the goal of every year should consider kicking accuracy, kicking strength, and kicking method to be major design objectives, with things such as curved shot, goalie, and different power alternatives (batteries) as research. Since there are initial proposal of lithium polymer batteries being implemented next year, with this in mind the kicking group could well have more space to work with within the robot. We may suggest a new one time kick mechanism as a research goal for next year.

5 Mechanical Design and Integration

5.1 Design Goals and Motivation

In addition to designing a robot that meets all the design specifications, other considerations must be made during design. The first of these considerations is modularity. In 2002, the team made an extremely modular robot, and the modularity greatly simplified maintenance, assembly, and conceptual structure. Second, simplicity in design is an important consideration. A simple design takes less time to machine and assemble. Third, the number of fasteners should be kept to a minimum. A small number of fasteners greatly reduces maintenance time, and also decreases the risk of a part coming loose during competition. Fourth, the design should be robust. A design is unacceptable if it is fragile or can easily break when mishandled. Finally, the robot should be designed for easy and quick maintenance. These considerations are key to making a robot that will be durable and long-lasting.

5.2 Mechanical Interferences

5.2.1 IR sensor mounts / Dribbling face

Because the IR sensor mounts protrude significantly from the side of the swing, they interfere with the front wheels about .01in. To solve this problem, we reduced the IR sensor mount size, lowered them, and asked the drive team to reposition the wheels. As far as lowering the IR sensor mounts, we noted that they were above the ball's centerline. Placing the IR sensor mounts an equal distance below the ball's centerline as they were above it is equivalent as far as how much of the ball will intercept the IR beam. The wheel diameter is much larger than the ball diameter, so moving the IR sensor mounts from their above-ball position (that happens to be at the wheel centerline, their widest point) to their below-ball position allows them to slide under the wheels as the swing is pushed back. After asking the drive team to reposition the wheels, the front wheels were rotated back about the robot center by 5 degrees such that they were further from the IR sensor mounts.

5.2.2 Spur gear

The spur gear for the horizontal dribbler was interfering with the top plate when it was assembled with the drive system. Since the interference was minimal, we cut out the section of the plate that was interfering with the gear.

5.2.3 Ease of Removal

The primary interfacing goal of the kicking subsystem was to provide ease of removal without severely affecting other subsystems. Space for the kicking assembly had been previously far too limited to allow for a compact kicking system that could be easily removed. Due to a change in wheel design, however, there was much more room for the kicking assembly at the bottom of the robot and therefore the solenoid could be moved inline with the kicker itself, improving both the kick and the simplicity of the system. With the kicking subsystem now much more compact and located at the bottom surface of the robot, this goal could be realized. Through the addition of a large U-shaped cut in the bottom plate the entire kicking assembly can be removed without dismantling any portion of the drive or dribbling subsystem. While the motors of the drive system still enforce a strict limitation on the space of the kicking subsystem, the additional space allowed for the interfacing goals of the kicking team to be realized.

5.2.3.1 Stroke Length Limitation

Although the kicking subsystem was granted much more room this year, many considerations regarding interferences with other subsystems still had to be taken into account. The stroke length was limited by the proximity of the kick circuit to the solenoid itself, thereby capping the possible values for stroke length. This concern, however, was not serious as previous data had shown that increasing stroke length would not provide significant improvement to the kick, and could in fact prove detrimental if the contact between the kicker and the ball became an impact rather than a push, thereby losing energy.

5.2.3.2 Solenoid Width Limitation

In addition, the width of the solenoid mount and guiding bars was limited by the motors on either side of the space allotted to kicking. This concern, coupled with the desire to produce guide bars that would be stable, required making the lower portion of the solenoid mount thinner than was desired. Testing performed on The Cheat, however, showed that this concern was unfounded and that the width of the solenoid mount at the bottom was sufficient to allow secure mounting of the guide bars.

5.2.3.3 Guide Bar Interferences

Furthermore, upon the insertion of the kicking assembly into the ProE design of the complete robot, interference between the guide bars and the swing was noticed. This was corrected through the thinning of the guide bars near the swing, eliminating the interference without any noticeable impact on the stability of the guide bars.

5.2.4 Side Dribblers

Because the side dribblers violated the 20% rule, we repositioned the side dribbler mounts. Moving the side dribbler mounts back into the swing .05in (by having the CNC cut their mounting plane .05in deeper into the swing) places the side dribbler assemblies further back on the ball when the ball is dribbling against the horizontal dribbler. In essence, moving the side dribblers back is like moving the entire swing and especially the horizontal dribbler and ball outward until the dribbling system covers no more than 20% of the ball's footprint while dribbling.

5.3 Electro-Mechanical Interface

5.3.1 Board mounting

The Electrical Engineering team asked us to design an easier way to mount the circuit boards than using many screws and standoffs like previous years. Eliminating most of the screws and standoffs reduces maintenance time, as the boards are quicker to remove. The only way to elevate the circuit boards from the chassis plate using existing parts in the 2003 design is to cut slots in the towers and insert the boards in those slots. The circuit boards interfere with the towers (in fact completely cutting them in half) unless material is added to the back of the towers and the slots are cut part way through this thicker section.

5.3.2 IR wire routing

Since there is only a small space between the IR sensor mounts and the front wheels, the wires from the IR sensors must be carefully routed to the main circuit board such that they do not interference with the wheels. This wire routing is still under development with the prototype, but our ideas include holding the wires against the side of the swing with screw heads, tape, or cable ties.

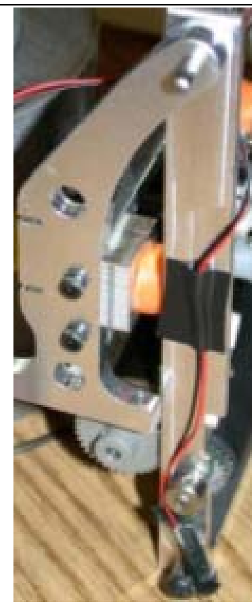


Figure 5-1 IR Wire Routing

5.3.3 Kicker Electro-Mechanical Connection/Interface

In an effort to increase kick speed without losing the benefits of a solenoid driven kick, dual capacitors and a DC/DC converter were used, resulting in an implementation of a separate kicking circuit board. The only electrical connection of the kicking assembly goes directly from the solenoid to this board, which is located directly behind the kicking subsystem. The board contains controllers for the discharging of the capacitors through the solenoid, so no addition control mechanisms are required as part of the assembly, making for a very simple interface with the electrical control system of the robot.

5.4 Ancillary Parts

Due to the location of the kicker in bottom center of the robot and its isolation from ancillary parts there were no real concerns regarding such parts insomuch as they would affect the kicking design. While such parts could influence other subsystems and in turn affect kicking, the kicking subsystem could not be modified until the effects of such changes were made clear on other more proximate systems and therefore ancillary parts played little explicit role in the design decisions of the kicking system.

6 Final Design Illustration

6.1 Supplier Information

Supplier information Company	Website
ADFF	
Campus store	www.store.cornell.edu
Maryland metric	www.marylandmetric.com
Parker steel	www.metricmetal.com
Magnetic sensor	www.solenoidcity.com
Maxon motors	www.maxonmotor.com
MicroMo motors	www.micromo.com
McMaster Carr	www.mcmaster.com
Laird Plastics	www.lairdplastics.com
Small parts Inc	www.smallparts.com
stock drive parts	www.sdp-si.com
bocabearings.com	www.bocabearings.com

6.2 Manufacturing Processes

6.2.1 Kicker

Since we made the kicking accuracy our foremost priority, it not only depends on the material properties such as deflection, but the overall machining precision is also very important. With this in mind, we decided to machine the kicker with the CNC mill instead of doing it by hand. The decision was based on the fact that with the new kicker design was so small and delicate such that only the CNC was the only option to make it. The truss wing on the side has a thickness of 0.025 inch, and also, we want the kick face of the kicker to be perfectly perpendicular to the stroke of the solenoid, only by CNC machining can we do that.

The overall process was simple and swift. Since the design of the kicker should have been drawn up in Pro Engineering at this point, one can simply use that drawing in I-DEAS. In Pro Engineering, open the part file of the kicker, in this case F-03-04-0004.prt, and use the export option under the file command. This would provide you with further options as to which export format to be used. We would choose to use step file as the format, select the location in which the step file would be stored, and export only solid modeling. Then we turn our attention to I-DEAS, open a new model file using a custom name, in this case-kicker, and under the file command we can use the import option. We then select step file as what we are going to import and browse for the file on the network or computer. After the import has been completed, the exact 3D model from Pro Engineering would be imported onto our model file and appeared on the computer screen. Since we do not need to make any modifications to the drawing itself, we can go directly to manufacturing and create a job. With the job created, we can turn to assembly setup and correctly place the kicker on the coordinate same as the one as the CNC machine. We also have to find a way to clamp the kicker onto the machine, since the kicker is small in both size and height, we cannot clamp it alone onto the vise. In order to cut the stock on the CNC machine, we will have to make a machinable fixture to clamp it. We then turn our attention back into design phase of I-DEAS and drew out a fixture as the one below.

Therefore we extract 2 of these when we work on the assembly setup and we would have the machinable fixture as a clamp to the stock. Next we turn our attention back to manufacturing option, and create operations under this setup. We would require a Facemill operation to clean up the top face of the stock, and then we need to use a volume clear operation to cut out the excess materials of the stock in the shape of the kicker. Last operation would require us to do the profile with no tolerance therefore we would have a finish surface. Last but not least, we would need to drill out the plunger hole on the kicker using a normal hand mill. This operation was not performed on the CNC machine because of the complexity of the setup it would require on the machine thus we felt using a hand mill to drill the hole is the optimal way to do it.

CNC model file – kicker.mf1
By importing Part # - F03-4-0004 (Currently we are using F-03-4-0004revA for the modified kicker), we have the kicker in our model file. The tools necessary for our operations are –
0.625" end mill for Face Mill Operation
0.3125" end mill for Volume Clear Operation
1/8" end mill for Volume Clear and Profile Operation
1/16" end mill for Profile Operation

By using the CoroGuide CoroMill Plura program available at the computer inside Emerson machine shop, we can figure out each tool's statistics (such as feed speed, spindle speed and engage speed, etc) by specifying the cutting diameter, tool diameter and cutting depth. A sample printout of tool's statistics is shown below.

Fixture is needed in order to make the kicker. Using a rectangular block of 2"x2"x3", cut a 0.375"x0.25" groove at one corner of the block.

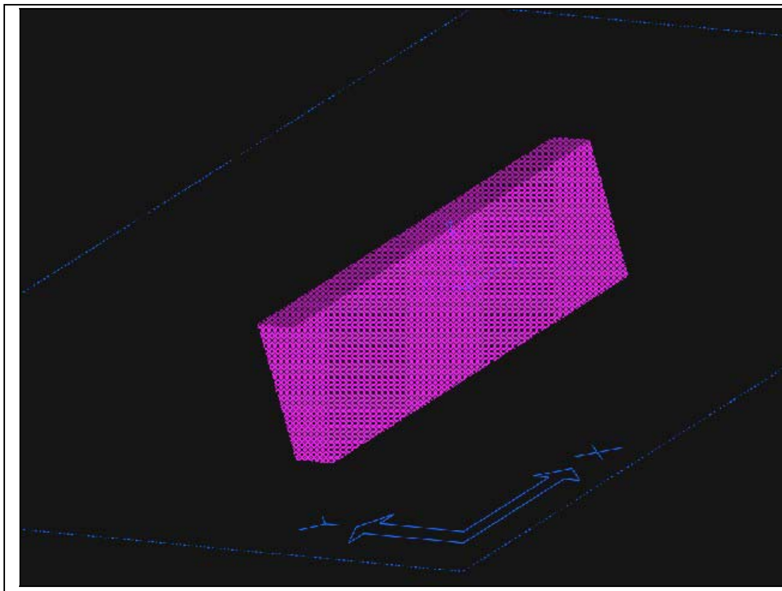


Figure 6-1 Blank screenshot from SDRC I-DEAS

Repeat once to make 2 of these blocks. Restriction on the second block is that it has to be directly opposite to the corner cut on your first block so that it can be used as a clamp. Blanks for kicker are needed as 3"x1"x0.375", and this blank can be placed into the fixture.

Only one setup is needed with the kicker, and the operations are listed as follows:

Face Mill

Volume clear – outer surface

Volume clear – inner surface

Profile – outer surface

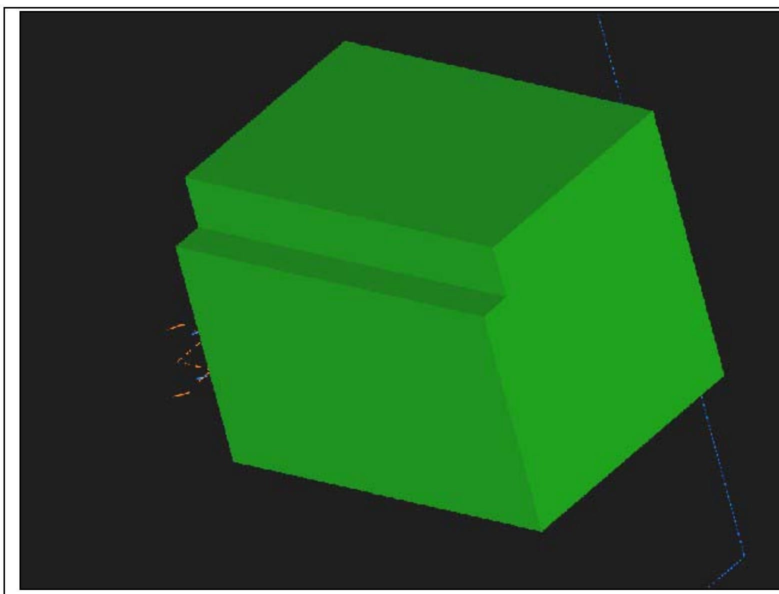


Figure 6-2 Fixture as Seen in SDRC I-DEAS screenshot

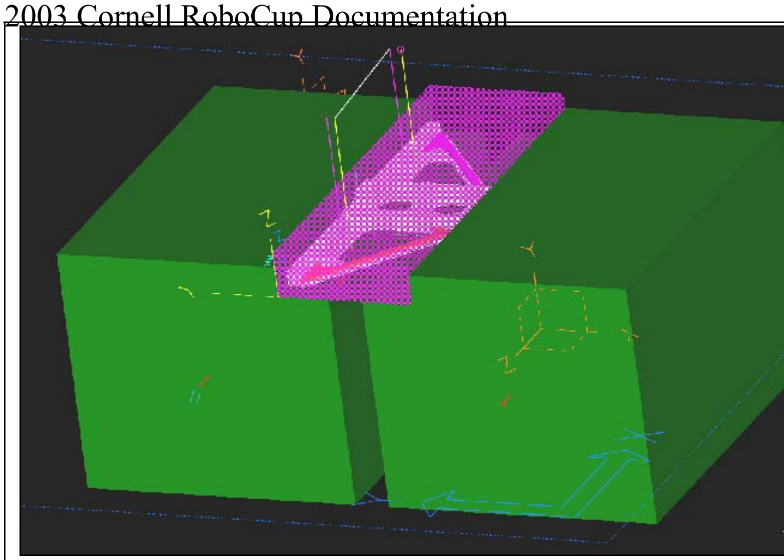


Figure 6-3 Setup of kicker manufacturing. The green block is the fixture, the magenta block is stock, and the pink is the kicker

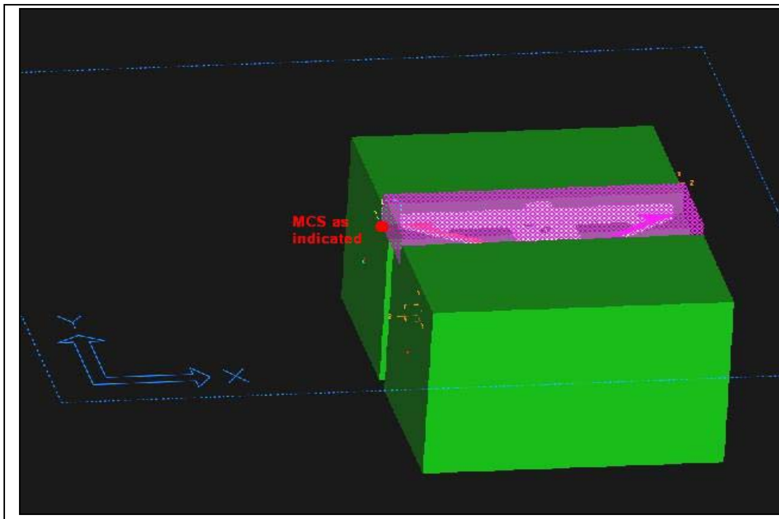


Figure 6-4 MCS for manufacturing of kicker.

Profile – inner surface

The picture below shows the indicated MCS for the CNC machine, and also pictures on how the setup should be. The entire cutting procedure takes approximately 10 minutes, setup time takes 20 minutes, cutting fixture takes 10 minutes, and blank preparation takes 20 minutes.

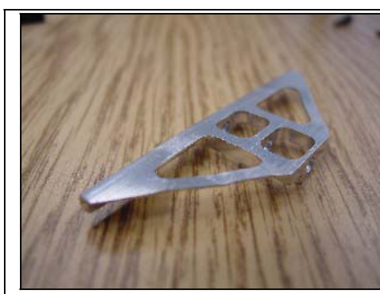


Figure 6-6 Bottom view of finished kicker

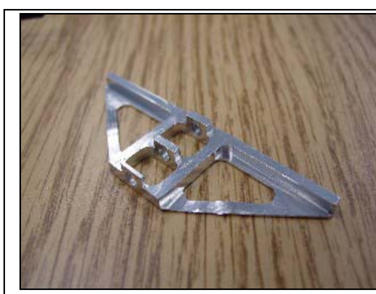


Figure 6-7 Finished kicker

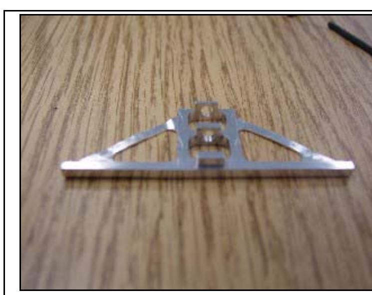


Figure 6-5 Front view of finished kicker

6.2.2 Solenoid Mount

The solenoid mount of 2003 is similar to the solenoid mount of 2002 in which we mounted the solenoid upside down from the top plate. The advantage by mounting the solenoid upside down is we would lower the center of mass of the robot due to the weight of the solenoid being moved down. Another advantage of this design is that drive system setup can now allow the kicking team to convert the solenoid in line with the kicker (what we called in line kicker), thus eliminating the L-shape kicking leg and therefore making our kicker much more accurate. The major difference between the solenoid mount of 2003 to 2002 aside of the fact that we would have an in line kicker, is that we would hang the solenoid using the solenoid mount, with 2 round surface of solenoid diameter aligning the solenoid, and a hole of diameter equal to the thread diameter of the solenoid's front end to secure the solenoid in place. We would also require shaving off the bottom part of the solenoid with 2 reasons, first the ground clearance from our solenoid is limited, and second the weight saving from trimming the solenoid mount can be significant.

Since the solenoid mount was not as complicated and not as delicate as the kicker, we can then use a normal hand mill to machine this part. This way, we are able to optimize the use of machine allocation.

To begin the machining of the solenoid mount, size the block to the specified dimensions, and place the blank into the vice with the top facing up. Drill the specified pin and screw holes and tap the screw holes on the same setup. Keep in mind that there is a .25" depth that will not be tapped (because of the tip of the tap), so drill the hole an extra .25" deep. Turn the block on its side and drill the guide bar mounting holes, being careful to match their position and offset to the holes used for mounting the solenoid mount to the bottom plate, the tap them. Turn the block on the other side and drill the corresponding holes on that side, also tapping them on the same setup. Then setup the block so that the rear of the solenoid mount is facing up. Step drill the center hole to just short of .75" diameter specified in the drawing, then use a .75" end mill to finish the hole. Then use a 1" end mill to create the larger diameter hole to the specified depth. Using a boring bar, increase the diameter of the 1" hole to 1.007" allowing for an easy press fit of the solenoid into the mount. Then place the block in the vice so that the bottom is facing up and the front and back are in contact with the vice. Mill away the two channels for the guide bars, then mill away the center of the block using repeated passes until the top of the mount is the desired thickness. The appearance of the finished solenoid mount is as follows.

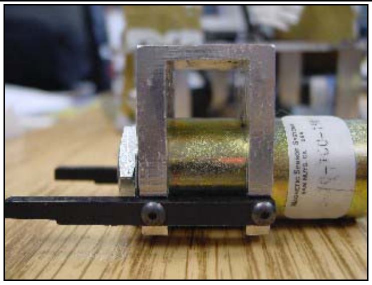


Figure 6-8 Side view of solenoid mount with guide bars attached

Figure 6-9 Top view of solenoid mount, with locking hex nut

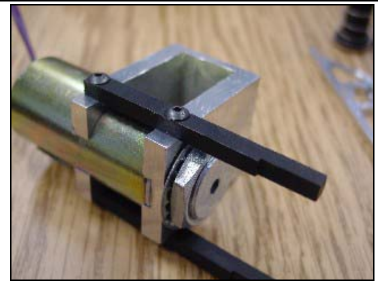


Figure 6-10 Final isometric view of the bottom of solenoid mount

6.2.3 Plastic Kicker Guide

The kicker guide was design in order to restrict the rotation of the kicker. Due to the fact the plunger are free to rotate inside the solenoid, if we did not implement the kicker guide, the kicker would be free to rotate. It would not be secured and the robot would not be able to kick correctly. Previous year's design also had to implement a guide in the form of a channel for the kicking leg, thus limiting the rotation of the kicker. Since this year we would have an in-line kicker with the kicker itself being a trusses, a side wall is not a feasible design. Therefore we came up with the idea of using two guide rails, which one on each side would be screwed onto the solenoid mount, and it would stick out and contact the bottom of the kicker trusses. With one on each side, it would effectively restrict the rotation of the kicker thus allowing the kicker to stay in place.

Figure 6-11 The plastic guide would restrict kicker rotation effectively

Figure 6-12 Plastic guide bars

The kicker guide was made in plastic for the ease of manufacturing and the application requirement in which strong material such as aluminum would not be necessary. Also we felt if the kicker and the guide's surface would be rubbing against each other, plastic on aluminum instead of aluminum on aluminum would be a better choice due to less surface friction. Another reason is plastic would be a weight-saver; therefore we decided on the use of plastic over aluminum. The guide would be a rectangular block, therefore we are only require to size a plastic stock to a certain size on the hand mill, and drill 2 holes on each side for fastening, and the plastic guide would be complete. The finished product is seen to the right.

6.2.4 Hat

CNC model file – hat-fixture.mf1

In order to accurately machine this hat using a flexible material such as Poly-Styrene, we would need a fixture in order to support it inside the CNC machine. Therefore a fixture is made in order to do this function. The fixture was design such that it could hold onto the Poly-Styrene material using 5 holes. We designed the fixture as a 5"x5"x0.375" rectangular plate, with five ½" extrusion aligned in a cross pattern. On each extrusion we would drill a 0.2080" hole and use a ¼"-20 tap to tread the inside of the hole. With this we can use ¼"-2-screws to secure the Poly-Styrene in place. We also drill five ½" hole in a cross pattern onto the Poly-Styrene, and we can place this onto our fixture.

The tools necessary for our operations are –
1/2" end mill for Volume Clear Operation
#2 Center Drill for Center Drilling Operation
0.2080" Drill for Drilling Operation

¼”-20 Tap for Tap Operation

By using the CoroGuide CoroMill Plura program available at the computer inside Emerson machine shop, we can figure out each tool’s statistics (such as feed speed, spindle speed and engage speed, etc) by specifying the cutting diameter, tool diameter and cutting depth.

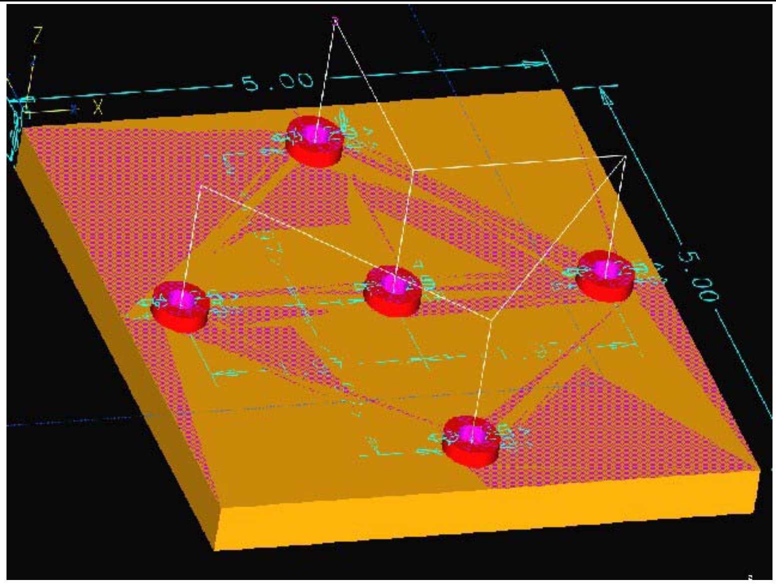


Figure 6-13 Fixture as seen in SDRC I-DEAS screenshot

Blanks for fixture are needed as 5”x5”x1/2”.

Only one setup is needed with the fixture, and the operations are listed as follows:
Volume Clear
Center Drill
Drill
Tap

6.3 Manufacturing Notes

Fixtures were made for the fabrication of many parts. Some parts required machining with multiple setups, but none of the parts required the complexity of setups required for the 2002 robot.

There were some surprises during part fabrication that required changes to manufacturing methods, but not the design itself. The machinability of some polymeric materials proved unpredictable, and some high-speed machining methods showed need for more accurate blank preparation.

The prototype configuration testing chassis was originally machined out of 1/8" Lucite® acrylic sheet, as an experiment to test the use of lighter materials for the robot chassis. Even with ample cooling, the Lucite® would melt and bind onto the cutting tool, making cuts larger than expected. Worse still, When the cut had almost finished, the Lucite® shattered, completely ruining the piece. This problem was remedied when this piece was cut from 6061 T6 aluminum.

The wheel hubs presented a similar but different problem. Although the polycarbonate material didn't melt, it was evident that it did resist being machined. Most internal cut features were .001-.004" undersized, which prevented the wheel hub blanks from fitting on their fixture. Polycarbonate proved more forgiving than the acrylic, but attempting to force the undersized cuts onto fixtures caused stress fractures. As an interesting aside, a machine crash occurred where a tool holder was smashed into a nearly complete wheel hub. Instead of shattering or cracking, the hub deformed to conform to the shape of the impacting tool holder. It was very difficult to fracture this mangled wheel or to remove it from the fixture.
The Delrin® nylon material used for the initial rollers would tend to cut oversize, and the cutoff operation would cause a brittle fracture, which would have to be cleaned-up by hand. Adding the undersized internal cuts on the wheel hubs to the oversized external cuts on the rollers, made a wheel that wouldn't allow all of the rollers to be inserted, let alone allow them to freely rotate. Quite unintentionally, the wheel rollers were oversized by the stretching of the O-rings about their circumference with a 0.531" O.D., instead of 0.500" that the hubs were designed for. This required modifications to the hub, to remove further interference.
To correct this problem, the solid models used for machining (different from the design models) were changed to enlarge internal features, and reduce external features, to accommodate the spring-back of the polycarbonate. Machining order was also adapted to reduce the likelihood of problems. The rollers were later changed to aluminum, which did not have as many machining issues. There was brief consideration of switching the material of the wheel hubs from the polycarbonate to aluminum also, but it was decided that the possibility of having aluminum-aluminum galling would be a certainty, and the idea was rejected.

Aluminum fabrication was not without problems or pitfalls. Some blanks that were produced to make the top and bottom plates had fixturing holes that were too large for the fixture pins that were to fit snugly within. This was the unfortunate result of improper fixturing during the manual blank preparation. Also, the blanks were much larger than the tool paths were designed to cut, which would cause a continuous ring of material to be left after the outline of the part is cut. This caused dangerous conditions, when the rings would rattle around a tool rotating at 8000 rpm.

7 Appendices

System Schedule

Dribbling System

Drive System

2003 Mechanical Drawings