Competitive Physics: Teaching Fundamental Principles Through Design

by

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B.S., Mechanical Engineering (2001)

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Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Mechanical Engineering
at the
Massachusetts Institute of Technology

September 2003

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ABSTRACT

A student guide was developed for use in undergraduate design courses. A fully worked example is presented for the students in the form of documentation of the design of a robot from start to finish. The student guide documents the entire design process beginning with overall strategy development to solve a general problem right down to the detailed design and modeling of mechanisms for individual modules.

Throughout the guide the practice of deterministic design is emphasized. Students are taught the importance of basing design decisions on appropriate analysis and to recognize when analysis should be replaced by experimentation. Emphasis is also placed on the application of fundamental principles to design such as reciprocity, Occam's razor, and St. Venant's principle. Finally, students are taught the importance of risk assessment to the design process, as well as the importance of contingency plans and countermeasures to combat identified risks.

Thesis Supervisor: Alexander H. Slocum
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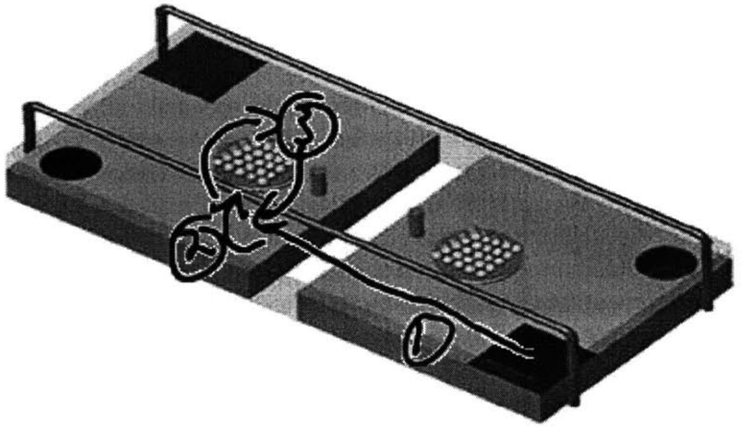
Contents

Chapter 1:
Strategies



Strategy One
Spin Only

1) **Cross Gap**
2) **Move to Disc and Engage**
3) **Spin Disc**

Overall Goal (Functional Requirement):

Design and manufacture a demonstration robot for 2.007 course capable of competing and scoring on the 2003 table. Should demonstrate proper use of fundamental design principles and design practice, proper manufacturing practices, and be re-usable in future years as an example.

Strategy (Design Parameter):

Cross the gap and score by rotating the disc.

Analysis:

Dominant Physics and Variables:

1. Crossing the Gap

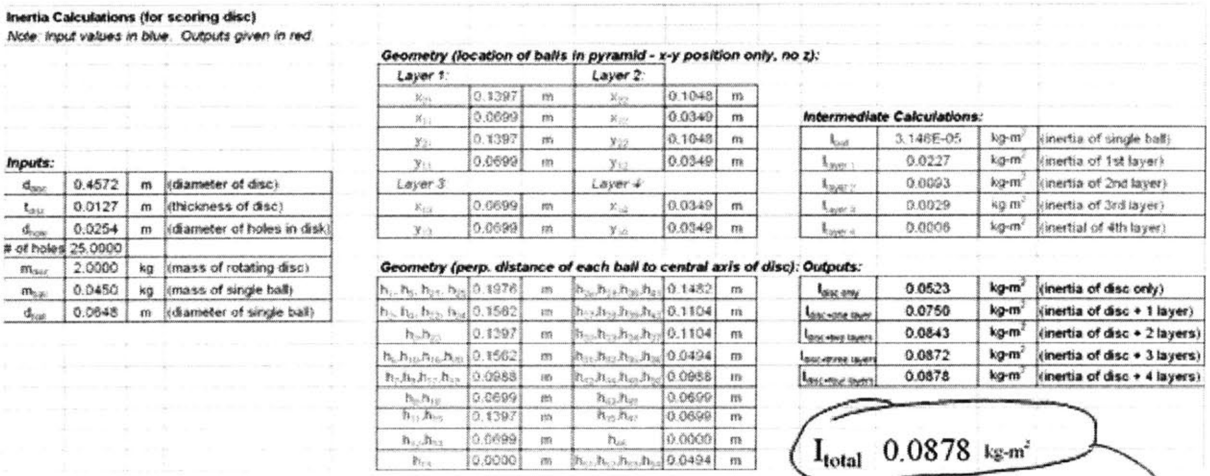
- **Friction** – ($F_f = \mu N$) Important for traction in driving. Must be high enough between wheels and surface (pipe, wall, or carpet) to prevent slip and spinning of drive wheels. At same time, want to minimize friction of spinning shafts, free spinning wheels, and other moving parts within machine to minimize power lost from motors. Affected by varying materials or normal force at interfaces.

- **Motor Power, Torque, and Speed** – All are interrelated. Motors must be able to provide adequate force to move the robot. This will depend on weight of machine, accelerations required, weight of any objects that need to be lifted or carried, etc. Torque can be varied through the use of transmission elements, designed to ensure that the needs of the application are met. Closely related to this is the speed of operation. Varying the torque output of the motors also varies the speed of the motor. However, since at best motor power is conserved (more often it is lost through friction) the motor speed varies inversely with the torque. This interplay between speed and torque must be kept in mind to ensure that the eventual design is able to meet and optimize the requirements for both.

- **Gravity and Center of Mass** – Must provide a force to oppose the force of gravity. While on the table the reaction force from the table takes care of this. Over the gap, though, it must be provided by another means. Either from some sort of bridge spanning the gap, or something attached to the overhead pipe or wall. Additionally, must balance any moments resulting from gravity. Force of gravity acting through center of mass will induce a moment about any axes of rotation (for example: attachments to wall or pipe) that must be countered.

2. Spinning the Platter

- **Inertia and Angular Momentum** – The disc and ball pyramid have an associated inertia. This is equivalent to the mass in a non-rotating system. It directly affects the angular speeds the disc can be rotated at and how quickly the disc can be accelerated to a certain speed. The balls add to the overall inertia of the disc. By removing the balls from the platter, the inertia drops and it requires less torque to achieve a desired acceleration, or stated another way: a given torque will lead to higher angular velocity for a given amount of elapsed time. Angular momentum must be conserved at all times. The angular momentum given to the disc must come from somewhere. In this case the motors.



Inertia Calculations (for scoring disc)

Note: Input values in blue. Outputs given in red.

Inputs:

d_{disc}	0.4572	m	(diameter of disc)
t_{disc}	0.0127	m	(thickness of disc)
d_{hole}	0.0254	m	(diameter of holes in disk)
# of holes	25.0000		
m_{disc}	2.0000	kg	(mass of rotating disc)
m_{ball}	0.0450	kg	(mass of single ball)
d_{ball}	0.0648	m	(diameter of single ball)

Geometry (location of balls in pyramid - x-y position only, no z):

Layer 1:			*Layer 2:*		
x_{21}	0.1397	m	x_{22}	0.1048	m
x_{11}	0.0699	m	x_{12}	0.0349	m
y_{21}	0.1397	m	y_{22}	0.1048	m
y_{11}	0.0699	m	y_{12}	0.0349	m
Layer 3:			*Layer 4:*		
x_{13}	0.0699	m	x_{14}	0.0349	m
y_{13}	0.0699	m	y_{14}	0.0349	m

Geometry (perp. distance of each ball to central axis of disc):

h_1, h_5, h_{21}, h_{25}	0.1976	m	[illegible]	0.1482	m
h_2, h_4, h_{22}, h_{24}	0.1582	m	[illegible]	0.1104	m
h_3, h_{23}	0.1397	m	[illegible]	0.1104	m
$h_6, h_{10}, h_{16}, h_{20}$	0.1562	m	[illegible]	0.0494	m
h_7, h_9, h_{17}, h_{19}	0.0988	m	[illegible]	0.0988	m
h_8, h_{18}	0.0699	m	[illegible]	0.0699	m
h_{11}, h_{15}	0.1397	m	[illegible]	0.0699	m
h_{12}, h_{14}	0.0699	m	[illegible]	0.0000	m
h_{13}	0.0000	m	[illegible]	0.0494	m

Intermediate Calculations:

I_{ball}	3.146E-05	kg-m^2	(inertia of single ball)
$I_{layer\ 1}$	0.0227	kg-m^2	(inertia of 1st layer)
$I_{layer\ 2}$	0.0093	kg-m^2	(inertia of 2nd layer)
$I_{layer\ 3}$	0.0029	kg m^2	(inertia of 3rd layer)
$I_{layer\ 4}$	0.0006	kg-m^2	(inertial of 4th layer)

Outputs:

$I_{disc\ only}$	0.0523	kg-m^2	(inertia of disc only)
$I_{disc+one\ layer}$	0.0750	kg-m^2	(inertia of disc + 1 layer)
$I_{disc+two\ layers}$	0.0843	kg-m^2	(inertia of disc + 2 layers)
$I_{disc+three\ layers}$	0.0872	kg-m^2	(inertia of disc + 3 layers)
$I_{disc+four\ layers}$	0.0878	kg-m^2	(inertia of disc + 4 layers)

I_{total} 0.0878 kg-m^2

Table 1.1: Calculation of the mass moment of inertia of the scoring disc of the 2.007 table. Inertia calculated for disc alone as well as for disc and each layer of the ball pyramid.

Governing Eqs.

- Inertia of Single Ball

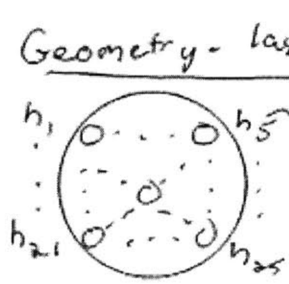
$I_{ball} = \frac{2}{3}mR^2 \leftarrow$ thin-walled hollow sphere

- Inertia of Ball Pyramid

$I_{layer} = (I_{ball}+mh_1^2)+(I_{ball}+mh_2^2)+\ldots$

$I_{total} = I_{layer,1}+I_{layer,2}+\ldots$

Geometry - layer 1



⟶ and so on for other layers

↳ "h" values given in chart above

Compare to value obtained from SolidWorks

Solidworks value = 0.0891 kgm^2

↳ very good match - also not too big should be easy accelerate!!!

- **Friction** – Just as before, only this time between the spinning disc of the table and the spinning wheel of the robot. Important point is that a higher friction force between the robot and table will enable higher accelerations of the disc without slip between the two wheels. This in turn will enable higher maximum rotational speeds to be achieved, or at lest allow the max. speed to be reached quicker and maintained for longer, thus maximizing scoring. Friction can be increased between wheels by changing materials in contact, increasing normal force at interface, or both. Is it more beneficial to engage wheel from top (and use gravity as normal force) or from side and use motors to provide normal force.

- **The Pyramid of Balls** – The balls themselves will greatly affect any attempts to score by spinning. The pyramid increases the inertia of the disc as a whole; more torque is required to accelerate at a given rate. To remove the balls requires dealing with the weight of the balls and the friction holding the pyramid together. Additionally, the balls create an obstacle that can jam a spinner, jam underneath and lift up a vehicle, and just be a general annoyance.

Strategy Scoring Analysis and Timeline (estimates):

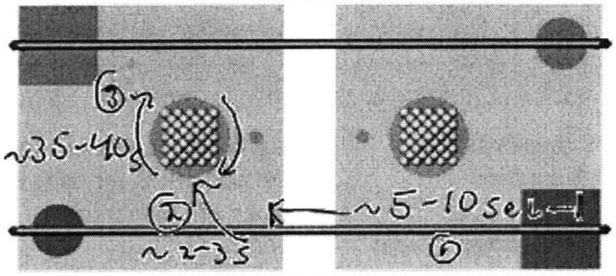
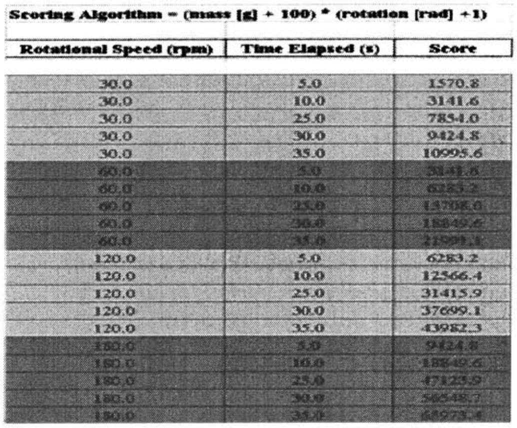


Figure 1.1: Estimated timeline for Strategy 1.



Scoring Algorithm = (mass [g] + 100) * (rotation [rad] +1)

Rotational Speed (rpm)	Time Elapsed (s)	Score
30.0	5.0	1570.8
30.0	10.0	3141.6
30.0	25.0	7854.0
30.0	30.0	9424.8
30.0	35.0	10995.6
60.0	5.0	3141.6
60.0	10.0	6283.2
60.0	25.0	15708.0
60.0	30.0	18849.6
60.0	35.0	21991.1
120.0	5.0	6283.2
120.0	10.0	12566.4
120.0	25.0	31415.9
120.0	30.0	37699.1
120.0	35.0	43982.3
180.0	5.0	9424.8
180.0	10.0	18849.6
180.0	25.0	47123.9
180.0	30.0	56548.7
180.0	35.0	65973.4

Table 1.2: Scoring analysis for Strategy 1. Potential scores for varying rotational speeds and times spent rotating.

- The times chosen for completing each segment of the strategy are conservative estimates. Estimates were based on knowledge gained by watching video of past contests and from experimenting with sample robots available in lab. The range is left broad with the expectation that it will be narrowed as more information becomes available, more design decisions are made, and a clearer picture of the final design to be pursued has developed.

- Table 1.2 to the right provides possible final scores for a spin-only strategy. The analysis presented assumes that no mass is scored at all. As expected, the best way to increase one's score is to spin faster or longer.

Relevant Bench Level Experiments:

1) Ease of Spinning

Setup

- a simple spinner was constructed from a motor and a foam core wheel.
- spinner was connected to a power supply and held by hand against the scoring disc

Results

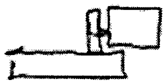
- disc was very easy to spin
- disc accelerates very quickly, but requiring the application of very little force/torque
- disc easily reached ~180 RPM. It was not possible for the disc to reach a higher speed because the foam core wheel kept coming untapped from the motor. The motor itself, though, should be capable of reaching a higher speed.

2) Where to Engage the Disc? Top vs. Side

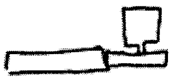
Setup

- The same crude spinner from BLE #1 was used
- Two configurations were tested

i) Top



ii) Spin



Results

- disc spins equally fast in either configuration
- without balls, spinning from top is easier. it is easier to keep normal force exerted on the disc because in this config. gravity is helping.
- filling the disc with balls makes it more difficult to spin from the top. It is necessary to clear away the balls or else they jam or knock away the spinner.

3) Mass Scored by Spinning

Setup

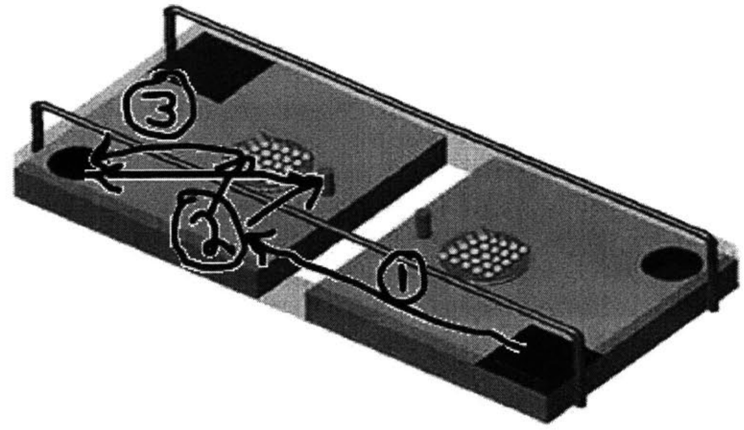
- scoring disc loaded with entire pyramid of balls
- disc spun at varying speeds and accelerations
- number of balls scored as a result of spinning observed

Results

- the faster the disc is spun, the easier it is for balls to come off, also more come off.
- larger accelerations = easier to scatter balls and more balls scatter
- disc is much easier to spin w/out ball on it. any strategy focusing on spinning should therefore attempt to clear off the balls first
- spinning is not a reliable way to score balls. at most, only a handful (~ 4-5) balls score as a result of pure spinning and this scoring is unpredictable. often far fewer will, or none at all, will score.

Risks and Countermeasures:

Risks	Countermeasures
1) scoring disc is wedged/blocked – unable to score points by spinning	1) a. give robot ability to score mass also b. high torque on spinner wheel capable of overpowering blocking opponent c. detachable spinner – remainder of robot free to deal with opponent
2) unable to score enough points through spinning alone	2) give robot ability to score mass as well
3) problems engaging disc	3)
a. height of disc off tabletop varies from table to table	a. i. make robot spinner height easily adjustable ii. make design immune to height difference (i.e. make the engagement wheel extra thick)
b. ball jams between machine and scoring disc	b. i. spin on top of disc – balls on ground are no longer a problem (must be careful now of the balls still on top of the disc, though) ii. include a plow on the machine to guide the balls out of way
c. not enough friction between spinner and scoring disc. spinner slips.	c. i. use drive wheels to provide normal greater normal force ii. spin on top of the disc – gravity now helps you – self-help principle
d. if spinning from the top of disc – balls jam spinner and lift it off the disc. make spinning impossible	d. plow balls off of disc first



Strategy Two
Mass Only

1) **Cross Gap**
2) **Move to Mass (balls or pucks)**
3) **Move Mass to Scoring Bin**

Overall Goal (Functional Requirement):

Design and manufacture a demonstration robot for 2.007 course capable of competing and scoring on the 2003 table. Should demonstrate proper use of fundamental design principles and design practice, proper manufacturing practices, and be re-usable in future years as an example.

Strategy (Design Parameter):

Cross the gap. Score by collecting mass (*Note:* focuses on scoring mass in the generic sense – whether to focus on pucks, balls or both is a concept and will be discussed in the next chapter).

Analysis:

Dominant Physics and Variables:

1. **Crossing the Gap** - Same as for Strategy One. Please refer to that strategy for descriptions.

2. **Collecting Mass**

   - **Gravity/Weight** – Obvious. Gravity helps keep the balls in the pyramid. To score using mass you have to be able to move the objects from one place to another by carrying, pushing, throwing, etc. Can try to move them by converting potential energy stored in objects to kinetic, or alternatively by using the motors to supply the needed energy. In that case usual motor torque/speed concerns apply. Can try to move all the weight at once or bit by bit. Whatever the chosen method the total mass present is fixed and cannot be altered.

   - **Friction –** Of primary importance with pucks. If pushing pucks along carpet must provide enough force to overcome retarding friction force. If clamping and lifting pucks must provide enough clamping force to make friction force between pucks and clamps large enough to counteract gravitational force.

   - **Rotating Disc** – Important if scoring with balls. Rotating disc is a potential hindrance to the gathering of balls; however, it also has the potential of being used as an aid in moving the balls. The possibility exists of using the principle of conservation of angular momentum to convert rotary motion of disc into motion of balls towards scoring buckets.

Strategy Scoring Analysis and Timeline (estimates):

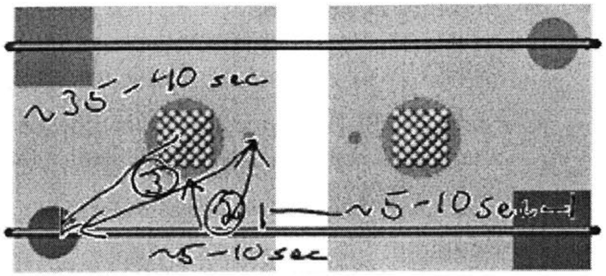
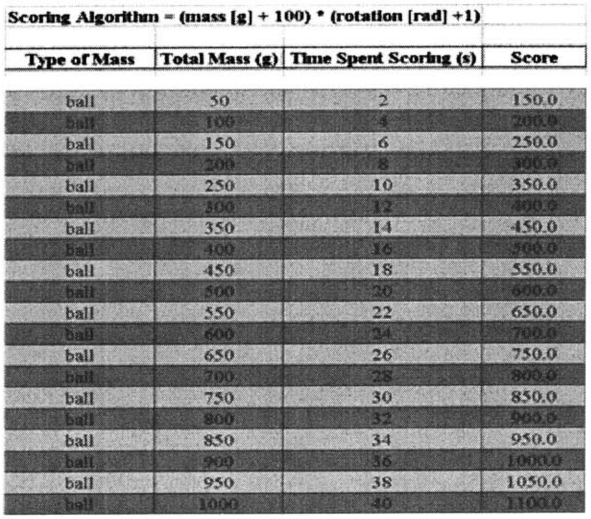


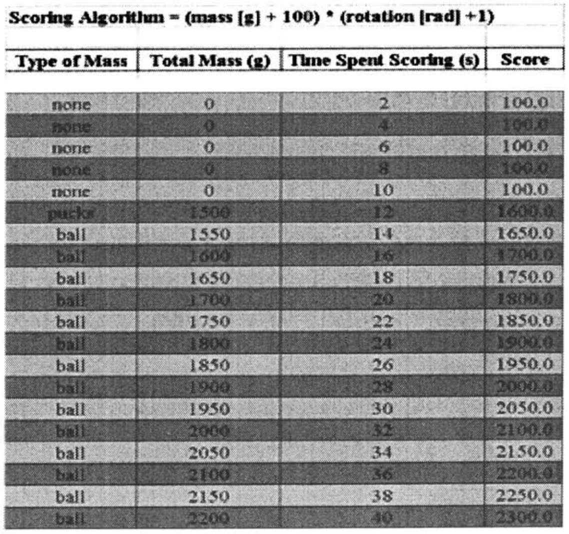
Figure 1.2: Estimated timeline for Strategy 2.



Scoring Algorithm = (mass [g] + 100) * (rotation [rad] +1)

Type of Mass	Total Mass (g)	Time Spent Scoring (s)	Score
ball	50	2	150.0
ball	100	4	200.0
ball	150	6	250.0
ball	200	8	300.0
ball	250	10	350.0
ball	300	12	400.0
ball	350	14	450.0
ball	400	16	500.0
ball	450	18	550.0
ball	500	20	600.0
ball	550	22	650.0
ball	600	24	700.0
ball	650	26	750.0
ball	700	28	800.0
ball	750	30	850.0
ball	800	32	900.0
ball	850	34	950.0
ball	900	36	1000.0
ball	950	38	1050.0
ball	1000	40	1100.0

Table 1.3: Scoring analysis for Strategy 2. Assumes one ball scored every two seconds.



Scoring Algorithm = (mass [g] + 100) * (rotation [rad] +1)

Type of Mass	Total Mass (g)	Time Spent Scoring (s)	Score
none	0	2	100.0
none	0	4	100.0
none	0	6	100.0
none	0	8	100.0
none	0	10	100.0
pucks	1500	12	1600.0
ball	1550	14	1650.0
ball	1600	16	1700.0
ball	1650	18	1750.0
ball	1700	20	1800.0
ball	1750	22	1850.0
ball	1800	24	1900.0
ball	1850	26	1950.0
ball	1900	28	2000.0
ball	1950	30	2050.0
ball	2000	32	2100.0
ball	2050	34	2150.0
ball	2100	36	2200.0
ball	2150	38	2250.0
ball	2200	40	2300.0

Table 1.4: Alternate scoring analysis for Strategy 2. Assumes first ten seconds spent scoring pucks, following which one ball is scored every two seconds.

Timeline

- The act of crossing the gap should prove independent of the act of scoring points. Therefore, the time for segment 2 and 3 should be independent of the particular method chosen for crossing the gap.
- Lacking detailed knowledge of the method to be used to cross the gap a conservative elapsed time of 5-10 sec. is assumed.
- The 5-10 sec. assumed for segment 2 represents all set-up time required to move the machine into position (upon successful crossing of the gap) and engage the mass. This step is allocated more time than in Strategy 1 since engaging the mass would seem to be more involved than simply putting a spinner up against the scoring disc. In particular, any attempt to grab the pucks will require a considerable amount of time for positioning and alignment.

Scoring Comments

Two important points can be gained from the Tables 1.3 and 1.4 to the left:

1) From a pure scoring standpoint, spinning alone far outperforms mass alone. Even at a modest speed of 30 RPM a spin only strategy scores ~ an order of magnitude higher than a mass strategy for a given amount of time spent scoring. Also, the faster you spin the larger the discrepancy. Increasing the rate at which mass is scored will help close the gap, but only marginally. The crucial factor is that a finite amount of mass is present and caps a mass-only score to ~ 4000 points. On the other hand, a spin-only score is theoretically infinite.

2) The puck stack holds tremendous scoring potential. Scoring the pucks alone would give a higher score than 40 sec. of scoring balls at one ball every two seconds. It thus seems wise to try to include the pucks in any scoring strategy that is to involve collecting mass.

Relevant Bench Level Experiments:

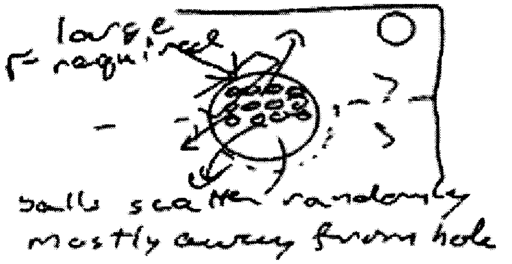
1) Plow Ball Pyramid

Setup

- a broad flat piece of aluminum was used to push against the pyramid like a plow

Results

- a very large force was required to scatter the balls
- scattering was random. very difficult to get balls to scatter towards scoring bin. Table centerline and rule preventing crossing of it prevents ability to push from proper side to optimize scattering of balls



2) Pull Ball Pyramid off

Setup

- Similar to BLE #1 except that this time the aluminum sheet was used to pull against the balls in the pyramid

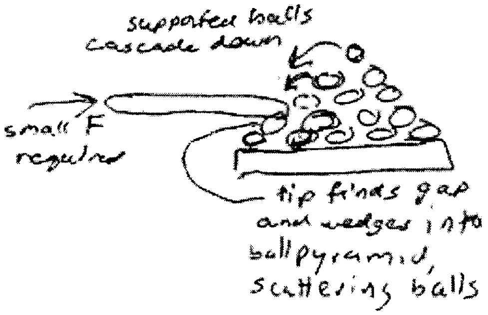
Results

- Extremely high force required
- Geometry makes action difficult and cumbersome
- conclusion – this is not a feasible solution and should be avoided

3) Poke Ball Pyramid

Setup

- a narrow object (¼" steel rod) was used to push against the pyramid.

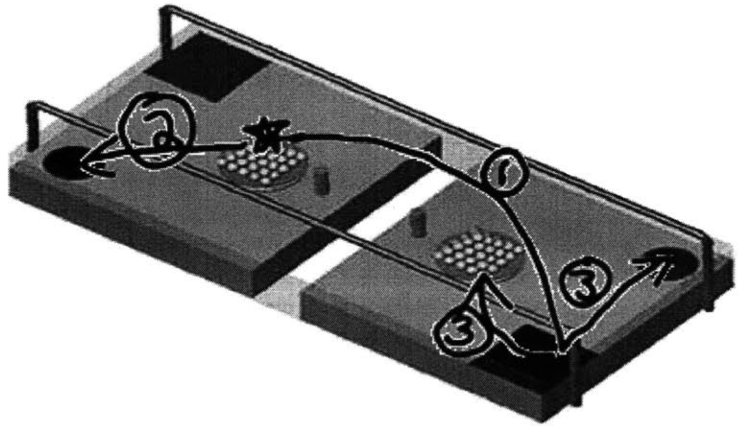


Results

- rod guided itself into gaps between balls and wedged balls apart
- much less force was required than for above
- scattering was more predictable. rod would wedge out a single ball and balls above would fall down into vacated space. This created a cascade effect focused at the point where the rod was inserted with a more easilily predicted motion
- more balls score using this method and so is a better choice

Risks and Countermeasures

Risks	Countermeasures
1) amount of mass on table is finite. mass score is bounded as a result	1) a. give robot ability to score all mass on the table, both the balls and the pucks, to get the maximum mass score possible b. include a spinner on robot to provide ability to score by rotation as well
2) ball pyramid scatters randomly and unpredictably and no balls score	2) include a plow/collector on the front of the robot. Use to "herd" and "guide" balls into scoring bin
3) unreliable ball scoring	3) concentrate on scoring pucks instead
4) opponent blocks scoring bin or gets in the way of robot while trying to transport collected mass to scoring bin	4) a. stack pucks on top of blocker – they will still count towards scoring when blocker removed at the end of the round b. be able to move opponent's blocker – high torque on motors, high friction on wheels or some sort of lifting mechanism to remove blocker c. more powerful robot to move opponent out of way



Strategy Three
Block

1) **Fire "Projectile" at Balls**
2) **Quickly Score Mass**
3) **Block Opponents Disc, Scoring Bin, or Both**

Overall Goal (Functional Requirement):

Design and manufacture a demonstration robot for 2.007 course capable of competing and scoring on the 2003 table. Should demonstrate proper use of fundamental design principles and design practice, proper manufacturing practices, and be re-usable in future years as an example.

Strategy (Design Parameter):

Do not cross gap. Quickly score some form of mass and concentrate on blocking.

Analysis:

Dominant Physics and Variables:

1. **Scoring Mass Quickly**

   - **Projectile Motion/Momentum –** To score mass quickly and thus be able to adopt an effective defense based strategy will almost certainly employ some sort of projectile fired towards the pyramid of balls. Hence all of the projectile motion equations are of utmost importance. They will be used to determine the forces required to cover the distance to the pyramid, the optimal launch angle, etc. Momentum conservation will be used to ensure that enough energy is available to break the pyramid of balls.

   - **Spring Equations –** It is almost a given that the constant force springs will be used to fire any projectiles. A critical calculation, then, will be to ensure that the springs can provide enough momentum to the projectile to carry it across the gap and break up the ball pyramid. It will be necessary to calculate how many springs are needed and how much extension is needed to provide the momentum needed.

2. **Blocking**

   - **Torque and Traction –** The primary factors affecting blocking will be torque and traction. If engaging an opponent's robot directly, you must assure that your robot can produce higher torque than opponent and that you have better traction allowing you to push their robot around rather than vice versa. If attempting to prevent their wheel from spinning, you must be able to counter the torque applied to the wheel by them. Additionally, any mechanism built to resist this spinning must be robust enough to withstand torques applied to it from opponents to spin wheel and also from attempts of opponent to dislodge the blocker. If blocking the bin, blocker must similarly be able to withstand attempts of opponent to dislodge and move blocker.

- **Material Strengths/Joint Strengths/Compliance, etc. –** Any extending mechanisms used to block (particularly if used to prevent wheel from spinning) must be robust. Lengths involved will translate to large moments being applied to blocking mechanism. Materials cannot yield, joints cannot fail, and the mechanism has to be rigid enough to accomplish the task of preventing spinning. Otherwise, this strategy is doomed from the start.

- **Geometry –** Applies primarily to bin blockers. Should be designed with a convex top to prevent mass from being placed on top of it. In this way at the end of a round when the blocker is removed no additional mass will be added to the bin.

Strategy Scoring Analysis:

Not applicable. Strategy relies entirely on preventing opponents from scoring. Scoring will be a minimum with the only emphasis being placed on scoring at least some mass to allow crossing of centerline and blocking without disqualification.

Risks and Countermeasures:

Risks	Countermeasures
1) unable to provide enough force to get projectile over the gap	1) choose a different strategy since this one will not be possible. Cross gap and score conventionally
2) projectile strikes pyramid, but is unable to scatter balls – either not enough momentum transferred or not enough momentum available in the fist place	2) a. aim specifically for the top-most ball. it will be the easiest to knock off b. be able to score another way if something goes wrong. have ability to cross the gap and score or be able to swing an arm across and bat balls toward scoring area
3) projectile misfires – doesn't fire at all or misses target	3) a. choose a different strategy b. have another way to cross gap and score c. make projectile launcher re-loadable d. "two-shot" launcher
4) blockers cross centerline too early leading to disqualification	4) be careful - have partner watching scoring bin to signal you when it is safe to block
5) projectile misses ball pyramid or bounces off pyramid and crosses centerline prior to any mass rolling into scoring bin – result is disqualification	5) tether your projectile

Risks and Countermeasures – Cont'd

Risks Associated with Proposed Countermeasures

1) Countermeasure #2

    a. This will require a very precise mechanism – high precision = large time commitment – there is also no margin for error since missing will certainly lead to disqualification

    b. this solution adds more modules – more modules = more complexity = large time commitment and greater chance for error

    Summary: this is not really a feasible alternative. if this risk proves to be what actually happen then the best course of action would be to abandon this strategy altogether in favor of a more practical one

2) Countermeasure #3

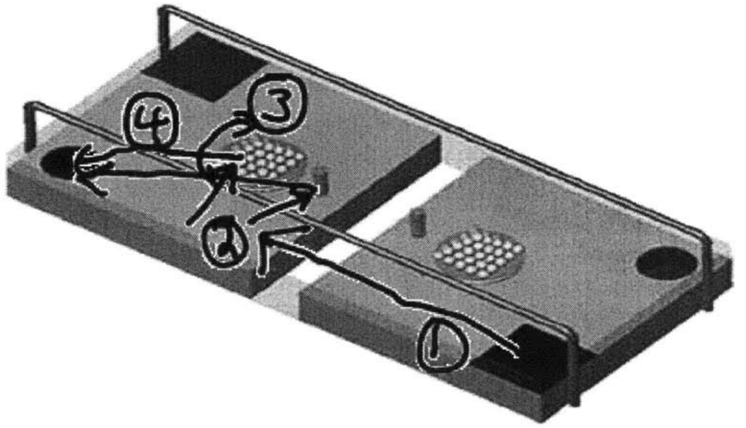
    a. once again this solution adds complexity and all the other disadvantages that come along with it

    b. re-loadable launcher would be very difficult to implement. it would greatly increase complexity and time commitment to the point that the returns would not justify the cost

    c. same argument applies for a "two-shot" launcher returns would not justify the cost. further, the problem could arise that not enough material is available to implement this solution

Implications

The potential benefits of this strategy are far outweighed by its potential. More importantly, the countermeasures are just as risky themselves, if not more so. All of this leads to the conclusion that this strategy should be abandoned in favor of another. The cost in terms of time commitment, potential for failure, frustration, etc. is just too great with respect to the value that can reasonably be expected in return.



Strategy Four
Mass and Spin

1) **Cross Gap**
2) **Move to Mass and Disc**
3) **Spin Disc**
4) **Move Mass to Scoring Bin**

Overall Goal (Functional Requirement):

Design and manufacture a demonstration robot for 2.007 course capable of competing and scoring on the 2003 table. Should demonstrate proper use of fundamental design principles and design practice, proper manufacturing practices, and be re-usable in future years as an example.

Strategy (Design Parameter):

Cross the gap. Score by rotating the disc and collecting mass.

Analysis:

Dominant Physics and Variables:

1. **Crossing the Gap -** Same as for Strategy One. Please refer to that strategy for descriptions.
2. **Spinning the Platter -** Same as for Strategy One. Please refer to that strategy for descriptions.
3. **Collecting Mass -** Same as for Strategy Two. Please refer to that strategy for descriptions.

***Strategy Scoring Analysis* –** Please see separate scoring analysis page.

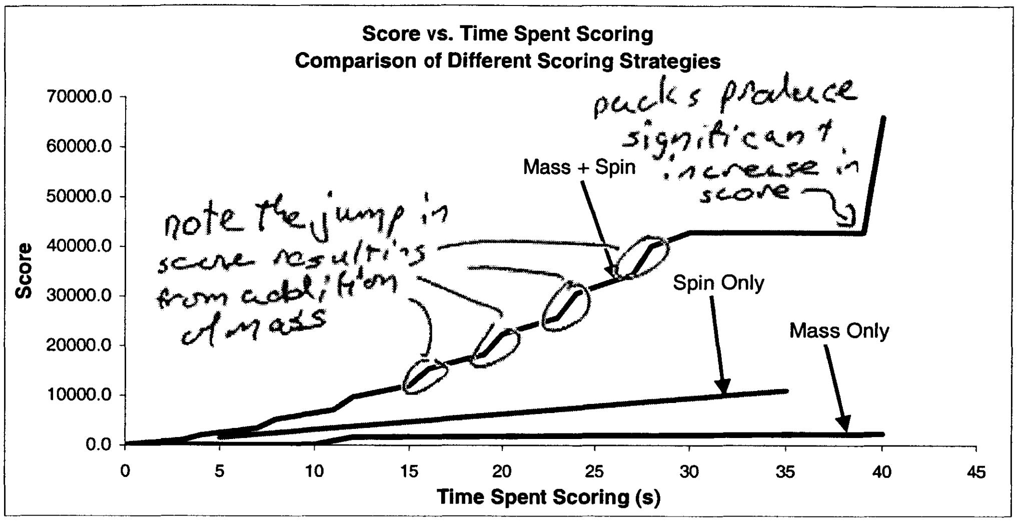
***Relevant BLE's* -** BLE's that applied to previous two strategies apply here as well.

Risks and Countermeasures:

The risks and countermeasures associated with the two unique components of this strategy remain unchanged from those presented above. As such, only risks relevant specifically to this combined strategy are presented here.

Risks	Countermeasures
1) not enough time to complete both modules	1) concentrate on one module at a time – have it completely working before moving on
2) not enough material to complete both modules	2) only make one – the most important. Complete solid model before building
3) not enough time during contest to effectively score with both scoring methods	3) decouple. Be able to do each independent of the other – detachable spinner, etc.

Overall Analysis of Various Scoring Strategies



pucks produce significant increase in score

note the jump in score resulting from addition of mass

Figure 1.3: Plots of score vs. time spent scoring for the three primary scoring strategies.

Figure 1.3 above demonstrates that a combination of spinning and mass is best if scoring is the primary objective. Particularly noteworthy are the significant jumps in total score resulting from mass being scored. Mass has the effect of shifting the entire spin-only curve upwards, allowing it to reach higher scores quicker than its slope alone would allow.

Given the choice of either spinning or collecting mass, a spin-only strategy is clearly preferable. The score will accumulate at a greater rate and there is no upper bound to the score.

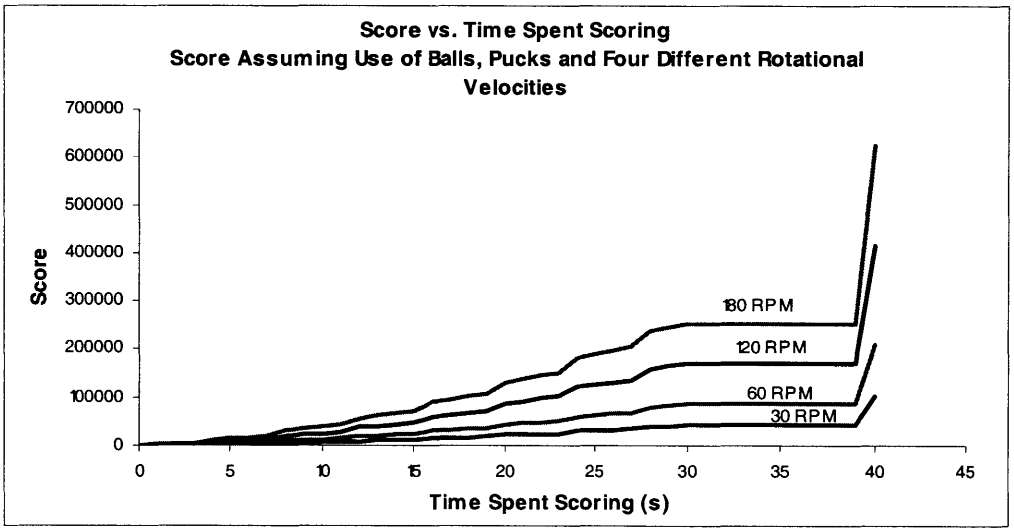


Figure 1.4: Plot showing dependency of spin + mass strategy on rotational velocity achieved.

It is obvious from Figure 1.4 above, and not surprising, that the faster you are able to spin the more points you are able to score for a given period of time. However, it is once again important to note the jumps in score that result from the scoring of mass. In particular, Figure 1.4 shows the huge scoring potential contained within the pucks. Of further significance is the fact that the pucks could realistically be scored at a single time as a single entity. Contrast this to the piecemeal scoring that is inherent in scoring balls.

Binomial Rankings to Determine Relative Importance of Selection Criteria

	scoring potential or potential to stop scoring	simplicity	feasibility	educational value	potential for future applicability	potential for failure/disqual.	sensitivity to opponents actions	time commitment	Total # of 1's in Row
scoring potential or potential to stop scoring	x	—	0	0	0	1	1	0	2
simplicity		x	0	0	0	1	1	0	2
feasibility			x	1	1	1	1	1	5
educational value				x	1	—	1	1	3
potential for future applicability					x	1	1	1	3
potential for failure/ disqualification						x	1	0	1
sensitivity to opponents actions							x	0	0
time commitment								x	

Total # of 0's in Column	0	0	2	2	2	0	0	4
Copy of 1's Totals	2	2	5	3	3	1	0	0
Totals/Rankings	2	2	7	5	5	1	0	4

1. **Feasibility** – Not surprisingly the most important. If strategy fundamentally can't work, then none of the other categories really matter.
2. **Educational Value** – The primary goal of this exercise is to create something that will help future 2.007 classes. The main goal of the design is to provide solutions and guidance to commonly encountered problems in the class.
2. **Future Applicability** – A design with components relevant to future contests and with the potential to "compete" in future contests is more useful than one that only works with a single years contest.
4. **Time Commitment** – Other commitments exist (including teaching commitments). Less time = better and happier. Very important for sophomores who have full course load, and so reflected here.
5. **Scoring Potential** – One goal of the design is of course to score points. Yet, given the motivation for this project, it is not the most important factor as it would be for a sophomore in the class.
5. **Simplicity** – KISS. Simple = Better. It is also important to demonstrate to sophomores the advantages of keeping simplicity in mind during their designs.
7. **Potential for failure/disqual.** – Risk-benefit analysis. In some cases the potential risks of a design may be worth the success that can be achieved. Thus this criteria is of lower importance overall.
8. **Sensitivity to Opponent** – Most opponents will be more worried about their own scoring to concern themselves with the other person on table. Further, this machine will be used primarily as a demo robot and not run against an opponent at all, making this criteria of even less importance.

Strategy Weighted Selection Chart

strategy point scale: 1-10	scoring potential or potential to stop scoring	simplicity	feasibility	educational value	potential for future applicability	potential for failure/ disqualification	sensitivity to opponents actions	time commitment	Totals
Weighting %	10	10	25	15	15	7.5	5	12.5	100%
spin only	5	5	5	5	5	5	5	5	5
mass only	3	5	5	9	10	5	6	5	6.2
block	7	1	5	2	1	1	2	2	2.93
mass + spin	10	2	5	7	7	3	4	2	5.23

Brief Explanation of Rankings:

- **Scoring Potential:** The scoring analyses presented previously clearly demonstrate that a combination of mass and spinning maximizes scoring. Also, I believe that a defensive strategy can be circumvented by good design and so still ranks lower than mass + spinning in this category

- **Simplicity:** If only doing one thing, specific mechanisms can be chosen to keep things simple. Thus just spinning or just collecting mass seems to be equivalent. Adding tasks necessarily makes things more complex. For this reason, block (which will require three distinct tasks) and mass + spin are scored lower. The need to block two scoring avenues and still somehow score mass to keep from being disqualified leads to block having the lowest score.

- **Feasibility:** All seem equally feasible.

- **Educational Value:** Over the years the majority of machines have some form of "car" module. Since block could very well not have a "car" module at all, or a very limited one at least, it scores lower than the other three. Additionally, since pucks and balls have been a part of the contest for years, whereas spinning is relatively new, a robot with modules to manipulate mass is likely to have more educational value than one that only spins the disc.

- **Future Applicability:** Similar argument as above. Mass and mass + spin score highest since balls or pucks are virtually ubiquitous in 2.007 contests, particularly stacks of pucks. Rotary motion is a new innovation, however, and has already taken three different forms.

- **Failure/D.Q:** Block has highest chance of each due to the likelihood of having to fire a projectile at the ball pyramid and also due to the direct confrontation with the opponent that is inevitable. Mass and spin only have about the same probability, mass a little more risky if going for pucks due to proximity to center line of machine. Mass + spin scores lower due to added parts = added complexity = more chance for failure.

- **Sensitivity to Opp.:** Block scores lowest for reason mentioned above. Other strategies ~ equal.

- **Time Commitment:** Block and mass + spin score lowest due to requiring more modules.

Final Strategy Selection - Mass Only

In agreement with the selection chart, it has been decided to pursue the mass only strategy. The decision is based primarily on the desire to pursue a design that will be educational, but more importantly applicable for years to come, thus enabling this document to be most helpful to future students. The changing nature of rotary elements over the past three years and the high probability that future tables will not possess a rotary element similar enough to this years makes solutions involving spinning unattractive. On the other hand, mass based scoring has been a staple of 2.007 for many years and there is no evidence to suggest a change in this approach. A mass only strategy has the greatest potential to lead to a design with mechanisms representative of future student designs and should thus provide the most guidance to future students. Additionally, the simplicity over a strategy attempting to score by both spinning and collecting mass is attractive.

Finally, it should be noted that the elements of the block strategy that are actually meant to block the opponent's disc or scoring bin would work just as well with any of the other strategies presented as with it. They would simply be additional modules added to the modules of the base strategies. These hybrid strategies were not ranked, however, as the only difference would be added complexity and time due to the added modules, and thus they would necessarily score lower than their non-blocking counterparts. Additionally, while a sans blocking strategy was chosen as the primary focus, the idea of blocking the opponent's scoring can be kept in the back of the mind in case extra time exist in the future. Should this situation arise, the idea of blocking mechanisms can be revisited, re-evaluated, and potentially incorporated into the final design.

For a complete and detailed description of this strategy, please see *Strategy 2 – Mass Only* above.

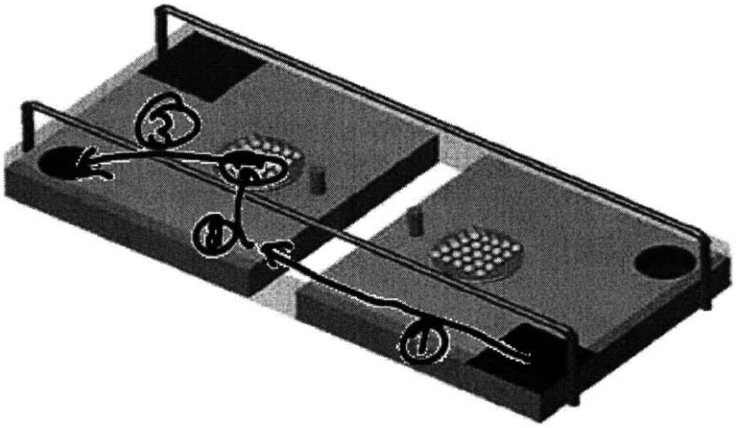
Chapter 2:
Concepts

Scoring Mass:
Concept One – Balls

Strategy (Functional Requirement):
Cross the gap. Score by collecting mass.

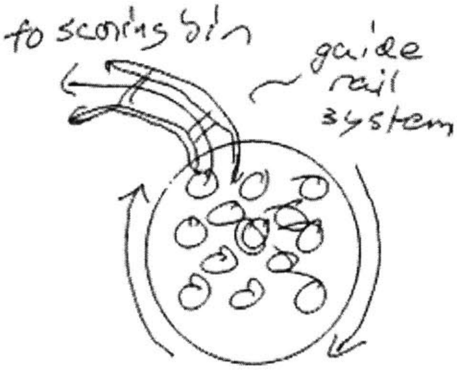
Concept (Design Parameter):
Score by collecting and depositing balls.

Concept Sketches:

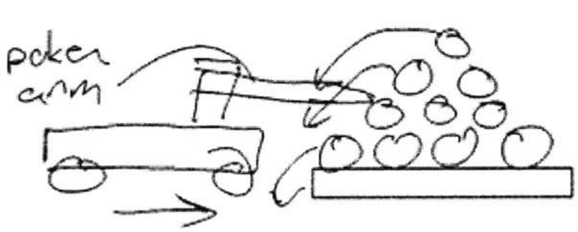


1) **Cross Gap**
2) **Move to Ball Pyramid**
3) **Collect and Score Balls**

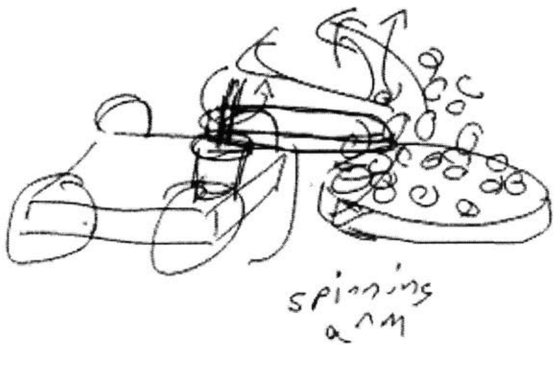
Guide Balls Down Track



Poke Balls



Bat Balls



Analysis:

Dominant Physics and Variables:

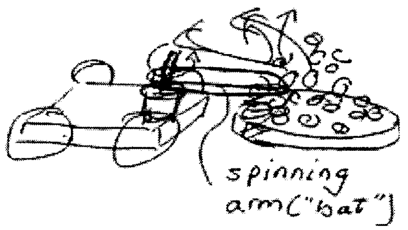
- **Momentum** – Conservation principles will come into effect. Will try to transfer either linear momentum of robot or angular momentum of spinning arm or spinning disc into momentum of balls. To be successful enough momentum must be transferred to break the pyramid and carry the balls to the scoring bin.

- **Power/Torque** – It is necessary to provide enough torque to manipulate the pyramid of balls. It may just be torque at the wheels providing a forward push of sufficient force to knock over the pyramid, or it may be torque on spinning arm providing enough force to break up the pyramid or at least knock balls out of it, or it may be torque to spin the disc and scatter the balls in that way. It may also just be torque to operate a forklift like mechanism to lift a portion of the balls. Whatever the embodiment, though, one must ensure that the motors can provide sufficient torque to accomplish the task. If they cannot on their own an additional transmission will need to be designed. Additionally, one only has a finite amount of power with which to work. The forces required and the velocities at which the forces operate ($P = \Gamma \times \omega$, $P = F \times v$) must be matched to the capabilities of the motor as well as the capacities of the batteries ($P = I \times V$).

Relevant Bench Level Experiments:

- Experiments performed during strategy phase on the ball pyramid are still completely relevant, as are the observation and insights made as a result. Please refer to previous chapter for that work.

- Tested concept of "batting" the balls from the pyramid. Used a robot from the International Design Competition (found in lab) designed to bat the pendulum and turned it loose on the ball pyramid (see illustration below).



  "Batting" concept proved moderately effective. Robot seemed to fairly effectively break up and scatter the pyramid; however, scattering was completely random. There appeared to be no correlation between the number of balls that would score and factors such as the rotational speed of the bat, the vertical location at which the pyramid was hit, or the direction from which the pyramid was hit. This leads to the conclusion that this is not a very reliable method for scoring large number of points. Additionally, these results are somewhat misleading due to the fact that the robot used during the test was outfitted with one of the old Black and Decker motors. These motors provide more torque than the current Tamiya motors and are more robust, requiring less care to be taken to ensure proper support, alignment and loading of the motor shafts. Further tests would need to be done with this years motor to confirm viability of this option.

- Found that if one of the bottom corner balls of the pyramid is removed the balls above it settle nicely into its spot. A hastily constructed welding rod railing system was found to consistently knock out the bottom corner ball of each corner as the disc was spun. The above balls would then fill in its place and in turn be knocked out on the next rotation. Displaced ball also rolled down the rail reliably. If the rail can be correctly shaped and positioned the balls can be made to roll directly into the scoring bins.

Risks and Countermeasures:

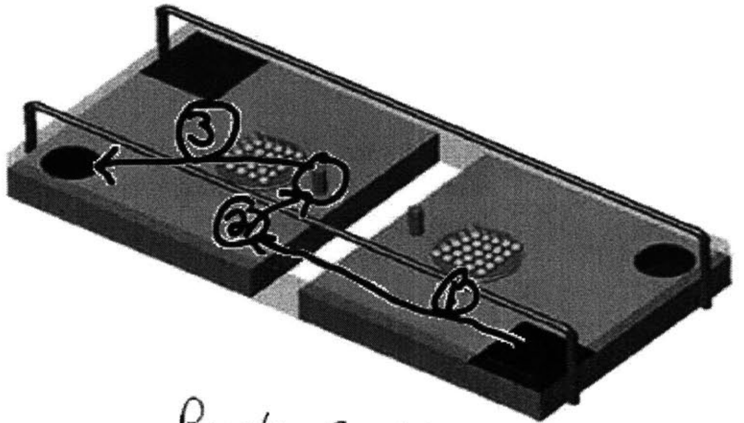
Risks	Countermeasures
1) balls just scatter everywhere and don't actually score	1) use a plow on the front of the robot to herd loose balls to scoring bin
2) balls scatter, fall in gap and become inaccessible	2) engage balls from the direction of the gap in the hope that the balls will scatter away from it
3) unable to generate enough torque to carry balls en masse to scoring bin	3) don't try to carry the balls as a group. scatter the balls instead and herd them towards the scoring bin
4) opponent covers the scoring bin and prevents you from scoring	4) a. stack balls on top of the blocker b. gather the pucks instead which will be easier to stack on top of a blocker c. switch to spin strategy d. make robot strong enough to move blocker

Scoring Mass:
Concept Two – Pucks

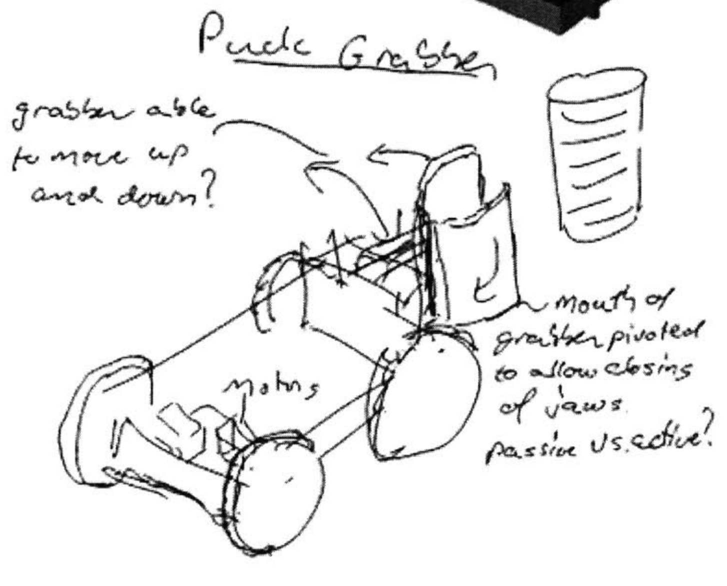
Strategy (Functional Requirement):
Cross the gap. Score by collecting mass.

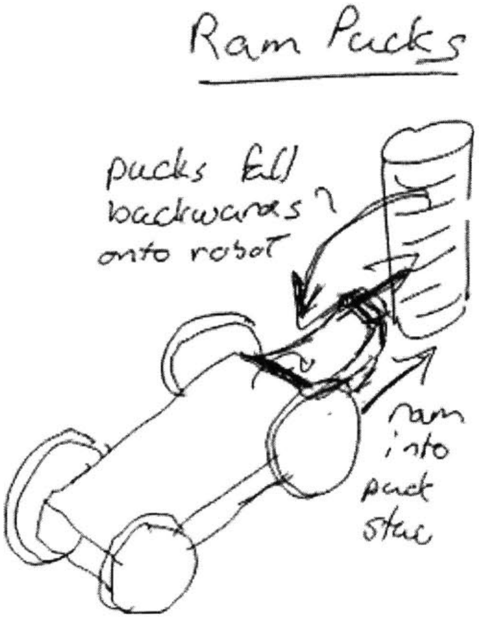
Concept (Design Parameter):
Score by gathering and depositing pucks.

Concept Sketches:



1) **Cross Gap**
2) **Move to Puck Stack**
3) **Collect and Score Pucks**

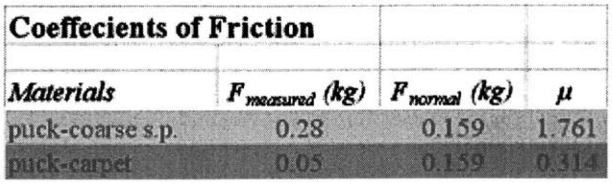




Analysis:

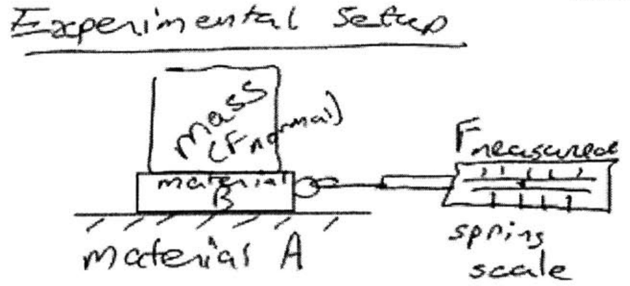
Relevant Bench Level Experiments:

- Measured the coeff. of friction between the pucks and the carpet and the pucks and coarse sand paper. Results are presented to the right in Table 2.1. Experimental setup is illustrated below.



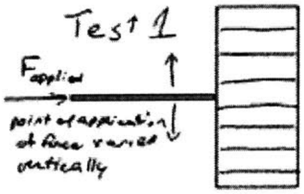
Coeffecients of Friction			
Materials	$F_{measured}$ **(kg)**	F_{normal} **(kg)**	μ
puck-coarse s.p.	0.28	0.159	1.761
puck-carpet	0.05	0.159	0.314

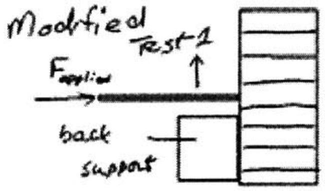
Table 2.1: Coeff. of friction of various materials relevant to Concept 2.

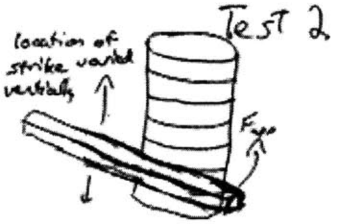


$$\mu_{A-B} = \frac{F_{measured}}{F_{normal}}$$

- Two experiments were performed to test the stability of the puck stack. First, a piece of welding rod was used to push against the puck stack at varying heights in an attempt to qualitatively determine how much force the stack could withstand prior to falling over. Second, a piece of the 1" box extrusion was used to give an impact to the stack at varying heights. Both tests are illustrated below.







The results of these tests proved interesting and the results are given below. Puck 1 refers to the bottom puck in the stack and puck 10 the top one.

Welding Rod Test

Location of Applied Force	Result
Puck 10	only top puck pushed off – moderate force req'd
Puck 9 – Puck 3	entire stack pushed over - moderate force req'd
Puck 1 & Puck 2	entire stack slides along carpet - VERY high force req'd to force pucks to topple

Table 2.2: Results of welding rod test stability of puck stack.

A further test was performed where back support was given to successively higher pucks. In each case, the stack began sliding when force was applied to the puck two places above the uppermost puck to be supported. For example, if support was provided up to puck 5, sliding would begin when a force was exerted on puck 7. These results could prove particularly useful to designs for triggers on puck grabbers. It shows that it is possible to use non-hair push triggers since a considerable force can be before toppling occurs.

The box extrusion test showed that when the puck stack was struck at a single location by an object carrying some momentum, the pucks above the place of impact tended to fall backwards rather than forwards. Additionally, the speed and force required is not terribly large. This is useful since it allows for concepts in which a machine drives into the puck stack (striking it near the bottom) in order to topple the pucks backwards into the machine. The pucks could then be transported to and deposited in the scoring bin.

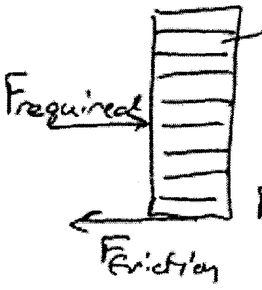
Puck Calculations:

If the desire is to get all of the pucks, there are really only two main approaches that can be taken:

1) Grabbing the pucks and dragging them along the carpet to the scoring bin
2) Grabbing, lifting and carrying the pucks to the scoring bin

Therefore, to choose a concept that focuses on the pucks, one should first be certain that one or both of these methods is actually feasible. The calculations presented below attempt to answer that question.

1) Dragging/Pushing the Pucks



$$M_{stack} = 10 \cdot M_{puck}$$

$$F_{normal} \sim F_{gravity} = M_{stack} \cdot g$$

$$F_{friction} = \mu F_{normal}$$

$$= \mu M_{stack} g$$

To move @ constant velocity $F_{req} = F_{friction}$

$$\hookrightarrow F_{req} = \mu M_{stack}$$

Force Required to Push Pucks		
materials	puck-carpet	
m_{puck}	0.1590	kg
μ	0.3145	
m_{stack}	1.5900	kg
$F_{gravity}$	15.5820	N
$F_{friction}$	4.9000	N

Table 2.3: Calculation of force required to push/drag pucks along the carpet.

Assuming a two-wheel drive vehicle each wheel must provide,

$$F_{wheel} = \frac{4.9N}{2} = 2.45N$$

Using the two most commonly used 2.007 wheel diameters of 0.0914 m and 0.1397 m, the torque on each wheel will be,

$$T = rF = (0.0457)(2.45) = \boxed{0.11\ N\text{-}m}$$

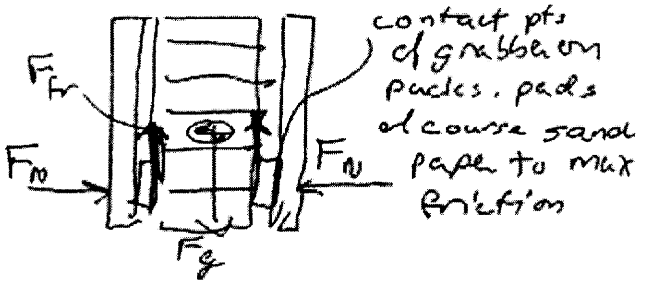
$$= (0.06985)(2.45) = \boxed{0.17\ N\text{-}m}$$

The Tamiya motors with the 100:1 gearbox in place do not fail until ~ 0.25 N-m. This means that the idea of dragging/pushing the pucks is indeed feasible. In practice, however, external gearing should also be added to allow for inconsistencies in the actual friction force felt and to allow the robot to accelerate while pushing the pucks.

Puck Calculations – Cont'd:

2) Lifting the Pucks

First, we will assume that we lift the pucks by squeezing them from two sides. So there will be two contact points with the pucks.



Force Required to Lift Pucks		
materials	puck-carpet	
m_{puck}	0.1590	kg
μ	0.3145	
m_{stack}	1.5900	kg
$F_{gravity}$	15.5820	N
$F_{friction}$	7.7910	N
$F_{normal,\ req'd}$	24.7754	N

Table 2.3: Calculation of force required to lift the pucks.

A frictional force, F_{fr}, will exist at both points of contact and will be proportional to the normal force, F_n, applied.

$$F_{fr} = \mu F_n$$

In order to lift the pucks, the sum of this frictional force must be greater or equal to the gravitational force attempting to pull the pucks downwards.

$$2F_{fr} \geq F_g = m_{stack} g$$

Substituting, it is now possible to find the minimum normal force that must be applied

$$2\mu F_n \geq m_{stack} g$$

$$\boxed{F_n \geq \frac{m_{stack} g}{2\mu}}$$

Clearly this is not an insignificant amount of force that must be applied. Some form of transmission (perhaps a lead screw) will need to be used. Additionally, to apply the forces in the appropriate location it is very likely that some sort of linkage system or similarly complicated mechanism will need to be employed.

Risks and Countermeasures:

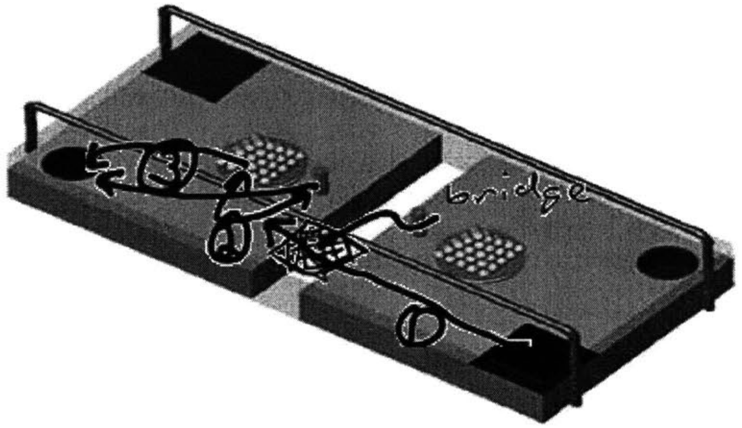
Risks	Countermeasures
1) pucks fall across the centerline when you try to grab the leading to disqualification	1) a. go push a ball in and then come back for the pucks b. grab pucks all the way around so that the front of the grabber prevents the pucks from falling over c. support the pucks from the back. the pucks should slide rather than topple
2) friction force is inconsistent. it may turn out to be larger then calculated	2) design the external gear train with a safety factor of at least two
3) puck grabber does not close properly around pucks. it does not grab the pucks	3) you can still push the pucks around and the puck grabber can be used to herd balls toward the scoring bin
4) opponent knocks over the puck stack before you can grab them	4) again, just try to push the pucks around and herd balls instead. however, this risk seems unlikely since to knock over your puck stack the opponent would have to cross the centerline leading to disqualification. also, the opponent will more likely be to focused on their own scoring to worry about your puck stack

Crossing the Gap:
Concept Three – Bridge

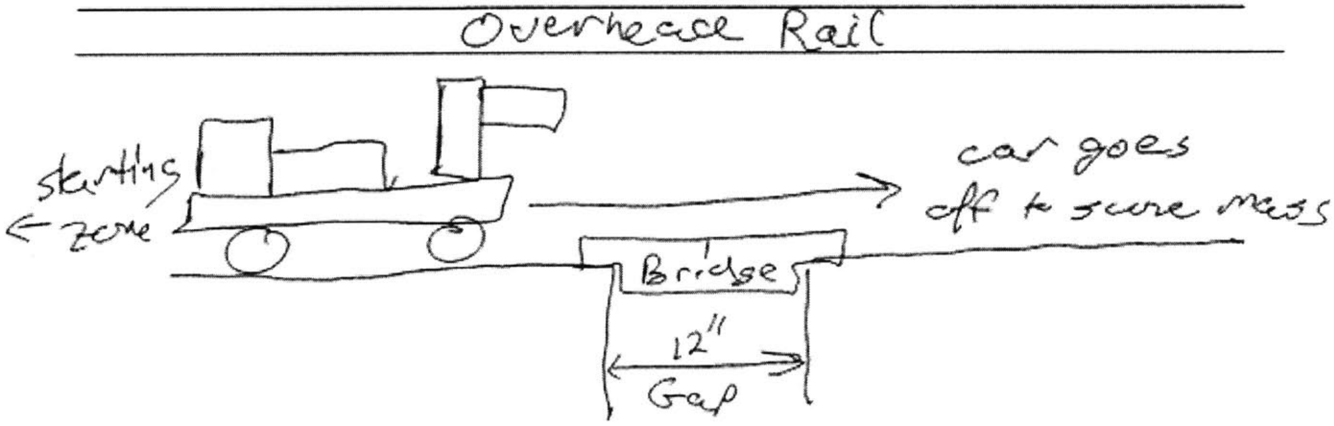
Strategy (Functional Requirement):
Cross the gap. Score by collecting mass.

Concept (Design Parameter):
Use a bridge to cross the gap.

Concept Sketches:



1) **Move Bridge to Gap**
2) **Deploy and Cross Bridge**
3) **Move to and Score Mass**



Analysis:

Dominant Physics and Variables:

- **Friction** –Possible options for deploying the bridge include pushing/rolling the bridge along the carpet to the gap, carrying the bridge to the gap and deploying, "shooting" the bridge into the gap, or powering the bridge itself and driving it to the gap. If pushing, rolling, or shooting the bridge to the gap you want to minimize the friction between the carpet and bridge. Low friction sliding contact, wheels, ball bearings on the wheels, etc. If carrying or driving the bridge you have to be sure there is enough friction between the carpet and drive wheels to prevent slip.

- **Power/Torque** – Power available to move bridge to gap has a finite value. If carrying, pushing, or driving the bridge itself you are limited to the power available from your motors ($P = \Gamma \times \omega$, $P = F \times v$) and from your batteries ($P = I \times V$). You must also ensure that your motors can provide enough torque to move the robot and bridge (depends on masses and accelerations as well as friction forces that must be overcome). If they cannot a transmission of some sort will be needed.

- **Momentum** - If "shooting" the bridge you must provide enough momentum to the bridge to ensure that it can reach the gap. You will need to provide an initial force to accelerate it up to speed. You must be sure that the force is large enough and over long enough duration so that the momentum imparted is large enough to reach the gap before a retarding friction force is able to bring the vehicle to a stop.

- **Beam Bending and Material Strength** – The bridge must be strong enough to support your robot as it drives over. The bridge can be modeled as a beam in bending and the bending stresses and deflections calculated. The design (material, cross-section, dimensions) can then be chosen to ensure that the deflection is minimal and that the bridge does not yield and fail.

Concept Timeline and Scoring Analysis:

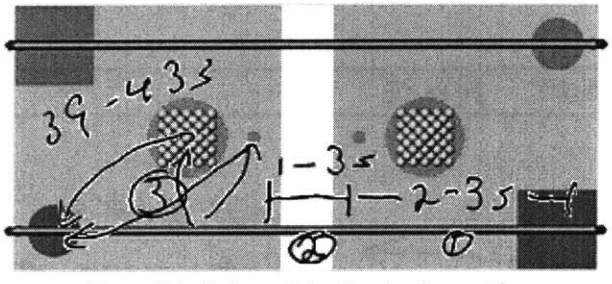


Figure 2.1: Estimated timeline for Concept 3.

Without knowing exactly how and what kind of mass will be scored it is tough to predict an exact score. However, as an estimate the scoring analysis from the Strategy chapter can be used.

Estimated time spent scoring: 39-43 secs

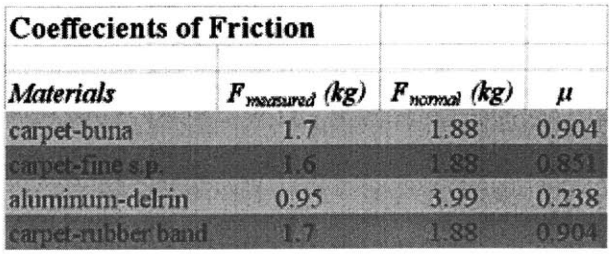
Balls only: ~1150 pts
Pucks alone: 1600 pts
Balls and pucks: ~ 2350 pts

1) **Move bridge to gap (2-3 sec)** – All methods should take about the same amount of time.

2) **Deploy and cross bridge (1-3 sec)** – Carrying a bridge also requires moving the bridge from the machine to the gap and so has the longest deployment time. Pushing has a relatively short deployment time since ideally you can push the bridge into the gap and drive over it without having to slow down. "Shooting" or a powered bridge takes the least amount of time due to the ability to have the rest of the robot riding on top of the bridge as it is deployed. As soon as the bridge falls in the gap you can drive the rest of the robot off and move on to collecting mass.

Relevant Bench Level Experiments:

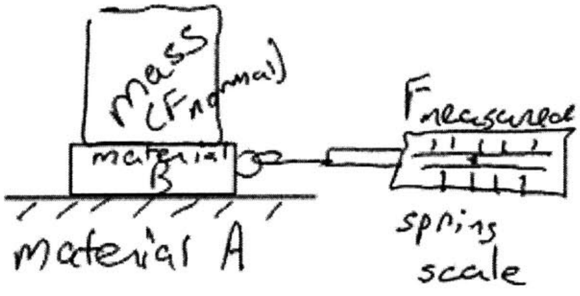
- Measured the coeff. of friction for several material combinations with potential relevance to a design utilizing a bridge to cross the gap. Results are presented to the right in Figure 2.2. Experimental setup is illustrated below.



Coeffecients of Friction			
Materials	$F_{measured}$ ***(kg)***	F_{normal} ***(kg)***	μ
carpet-buna	1.7	1.88	0.904
carpet-fine s.p.	1.6	1.88	0.851
aluminum-delrin	0.95	3.99	0.238
carpet-rubber band	1.7	1.88	0.904

Table 2.4: Coeff. of friction of various materials relevant to Concept 3.

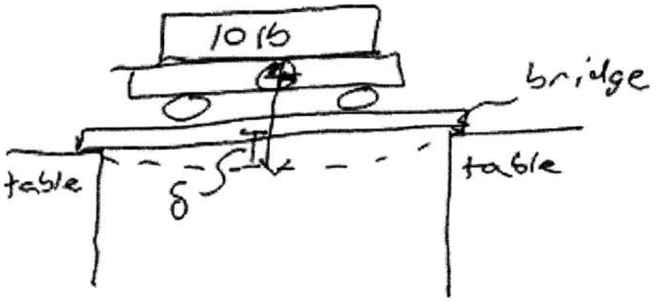
Experimental Setup



$$\mu_{A-B} = \frac{F_{measured}}{F_{normal}}$$

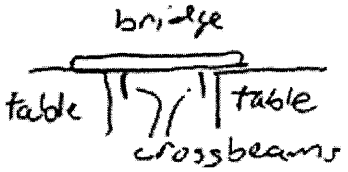
- Tested feasibility of using kit material as a bridge to span the gap. Performed test on aluminum sheet, ABS plastic sheet,¼ " aluminum rod, and ¼ " steel rod. Material was suspended over gap (supported by table on either side) and one of the sample robots from previous years that are available in lab was placed on top. Test machine weighed ~10 lb. Visually observed deflection (if any) of material serving as "bridge". Setup illustrated below.

Results:
- alum. sheet – noticeable but negligible deflection < 5mm
- ABS sheet – noticeable but negligible deflection <10mm, but > alum. sheet
- ¼" alum. Rod - noticeable but negligible deflection < 5mm, but also < alum. sheet
- ¼" steel rod – no noticeable deflection



Based on these results, any of these materials would be a suitable choice from a materials property standpoint. However, the ABS plastic is only 12" long and so barely covers the gap, leaving little margin for error. Also, it is likely more useful in other parts of the machine (such as the chassis), and so would be a poor choice for a bridge material. Similarly, the steel rods are likely more useful in other parts of the machine where high strength may be required. As such, the best choice for bridge material would likely be the aluminum sheet or aluminum rod. The final choice would naturally depend on the nature of the bridge design.

Risks and Countermeasures:

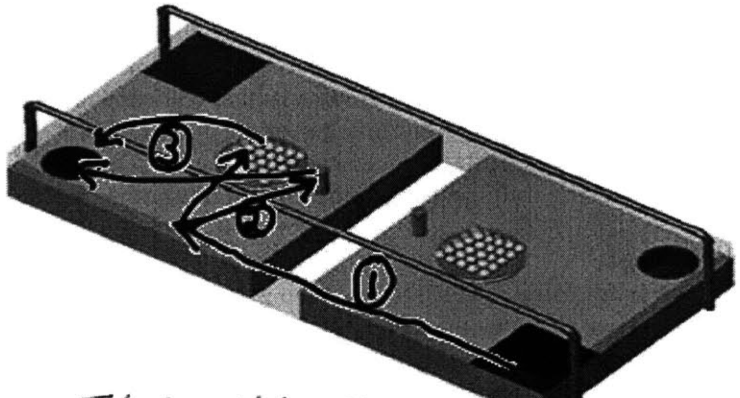
Risks	Countermeasures
1) bridge does not deploy correctly. unable to move it off of robot and into gap	1) push bridge along ground. no reason to have it lifted off of the ground at all
2) bridge does not deploy correctly and falls into gap	2) a. make the bridge very long so that it is not possible for it to fall into the gap b. attach the bridge to the sidewall or overhead rail. this should prevent it from falling in the gap c. give the bridge legs that drop down to touch the floor to support it and hold it up
3) bridge moves while you are driving across it and falls into the gap along with your robot	3) add crossbeams to the bottom of the bridge near the edges of the gap. they will prevent lateral movement of the bridge 
4) opponent knocks bridge into the gap	4) anchor the bridge to the wall so that the opponent can't knock the bridge into the gap
5) opponent tries to use your bridge for his own benefit	5) make it so that only a robot possessing some sort of unique feature will be able to use the bridge
6) robot drives off of bridge and into gap while trying to cross it	6) add guide rails or some other geometry that will constrain the motion of the robot to one dimension and not allow the it to drive off the side of the bridge

Crossing the Gap:
Concept Four - Wall

Strategy (Functional Requirement):
Cross the gap. Score by collecting mass.

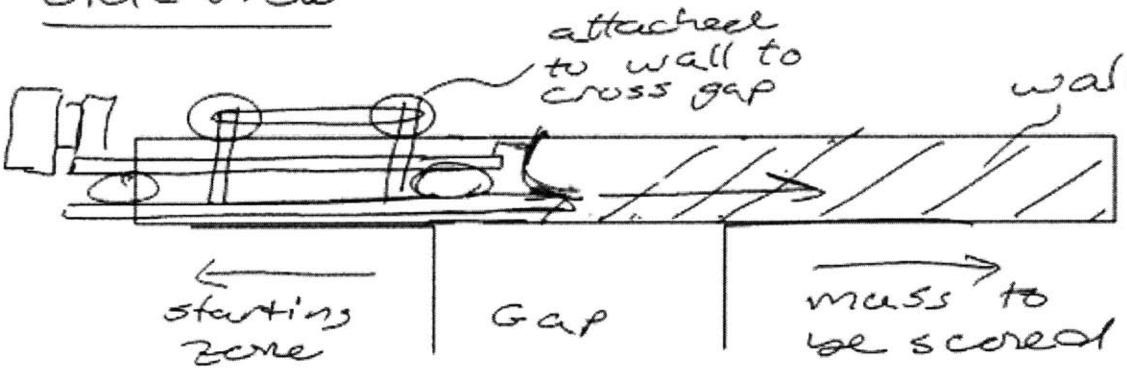
Concept (Design Parameter):
Use a machine attached to the wall to cross the gap.

Concept Sketches:

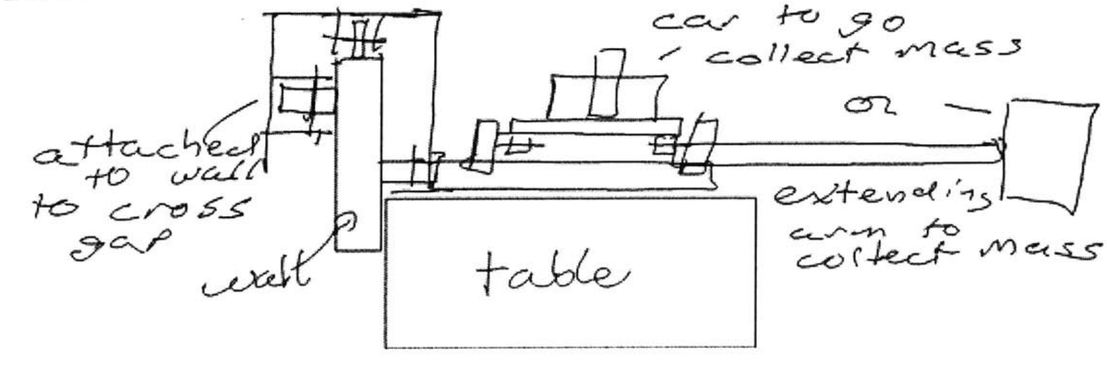


1) **Drive Across Gap Attached to Wall**
2) **Detach From Wall and Move to Mass, or Stay Attached and Reach Out to Mass**
3) **Deposit Mass in Scoring Bin**

Side View



Rear View



Analysis:

Dominant Physics and Variables:

- **Squeezing Force (Normal Force)/Friction** – If using the wall to cross the gap you lose much of the advantage of gravity. Unlike driving on the ground, gravity no longer provides a simple source of normal force helping to ensure that your wheels do not slip. Instead you must now generate a squeezing force to provide the necessary normal force. The force can be provided by springs, motors, or other elements. If designed properly, your robot could also use the moments resulting from gravity influence. Whatever method is chosen you must ensure that the normal force is large enough with the material used on your wheels to prevent slip.

- **Moments –** Crucial to this concept is the fact that you are suspending yourself from the wall. This means that you now have to take into account the moments created by gravity about the point(s) of contact with the wall. Any wheels in contact with the wall or in contact with the ground should be placed such that their reaction forces produce moments that counteract the moment resulting from gravity. This is particularly important when over the gap itself, since in that situation a simple wheel in contact with the table top will clearly not suffice. Failure to accurately account for this moment can lead the wall mechanism to jam, fall off, or the material to deflect unacceptably.

- **Power/Torque** – Same considerations as for using a bridge to cross the gap. Power available to wall crawl across the gap is finite. You have to match the weight of the machine you are trying to accelerate and how quickly you are trying to do so with the capabilities of your motors ($P = \Gamma \times \omega$, $P = F \times v$) and batteries ($P = I \times V$). You must also ensure that your motors can provide enough torque to move your robot as desired (depends on masses and accelerations as well as friction forces that must be overcome). If they cannot a transmission of some sort will be needed.

Concept Timeline and Scoring Analysis:

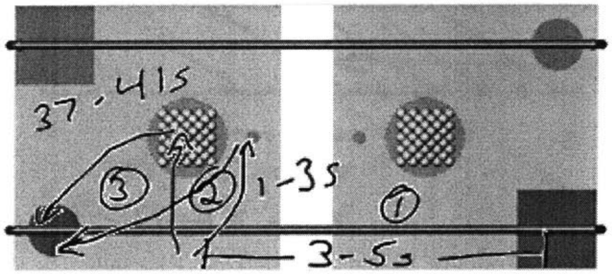


Figure 2.2: Estimated timeline for Concept 4.

Without knowing exactly how and what kind of mass will be scored it is tough to predict an exact score. However, as an estimate the scoring analysis from the Strategy chapter can be used.

Estimated time spent scoring: 37 – 41 secs

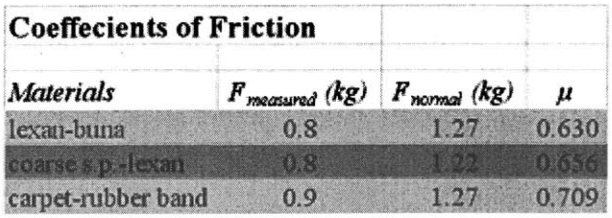
Balls only: 1050 pts
Pucks alone: 1600 pts
Balls and pucks: 2250

1) **Cross gap on wall (3-5 sec)** – All methods should take about the same amount of time to cross gap. The time allotted here merely represents a combination of stages one and two of the previous concept.

2) **Detach from wall and move to mass, or stay attached and reach out to mass (1-3 sec) -** Once across the gap, either a part of the robot must detach and move to the mass, or an arm must be extended to the mass. An arm could conceivably be extended while en route and so adds little time. Detaching another robot, however, would add significant time that was not required of the previous concept. The previous concept also has the advantage that the robot crossing the bridge can position itself more quickly to collect mass since it will already be up to speed.

Relevant Bench Level Experiments:

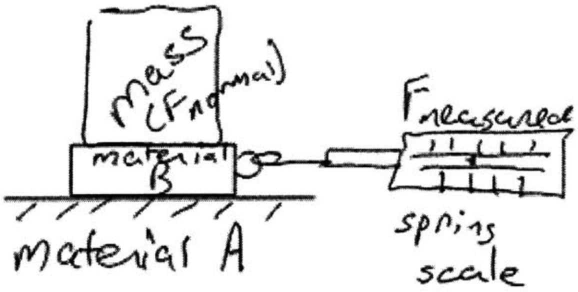
Measured the coeff. of friction for several materials with the lexan wall. This would obviously be important data for any design focusing on using the wall to cross the gap. Results are presented to the right in Figure 2.4. Experimental setup is illustrated below.



Coeffecients of Friction			
Materials	$F_{measured}$ (kg)	F_{normal} (kg)	μ
lexan-buna	0.8	1.27	0.630
coarse s.p.-lexan	0.8	1.22	0.656
carpet-rubber band	0.9	1.27	0.709

Table 2.5: Coeff. of friction of various materials relevant to Concept 4.

Experimental Setup



$$\mu_{A-B} = \frac{F_{measured}}{F_{normal}}$$

Based on these measurements it seems that the large rubber bands provided in the kit are the best choice for increasing traction of any drive wheels in contact with the lexan wall.

Risks and Countermeasures:

Risks	Countermeasures
1) Detachment mechanism fails making it impossible to move from wall to the mass	1) don't detach. use an arm that extends out to the mass
2)	2)
a. the long extending arm is not strong enough at the tip to move the mass	a. don't use an arm. detach from the wall instead
b. long arm is very susceptible to damage by the opponent due to the large moment arm	b. make the arm robust. out of thick, strong materials. or don't use an arm. detach from the wall instead
3) wall clamping mechanism jams while vehicle is over the gap and not being supported by the floor	3) position the wheels in contact with the wall such that the reaction forces balance the moment

Implications

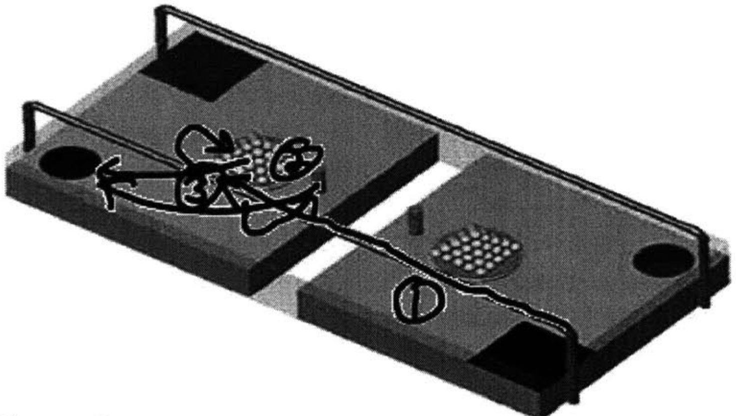
Risks one and two are very cyclic in nature. Each has the other risk as its countermeasure. It becomes particularly problematic since an attempt to go after the pucks is likely precluded if using an extending arm. The moments applied to the arm would just be too great, so an arm is out, but the countermeasure for detachment failure is to use an arm. If anything does go wrong these risks could prove very limiting to this concept.

Crossing the Gap:
Concept Five – Overhead Rail

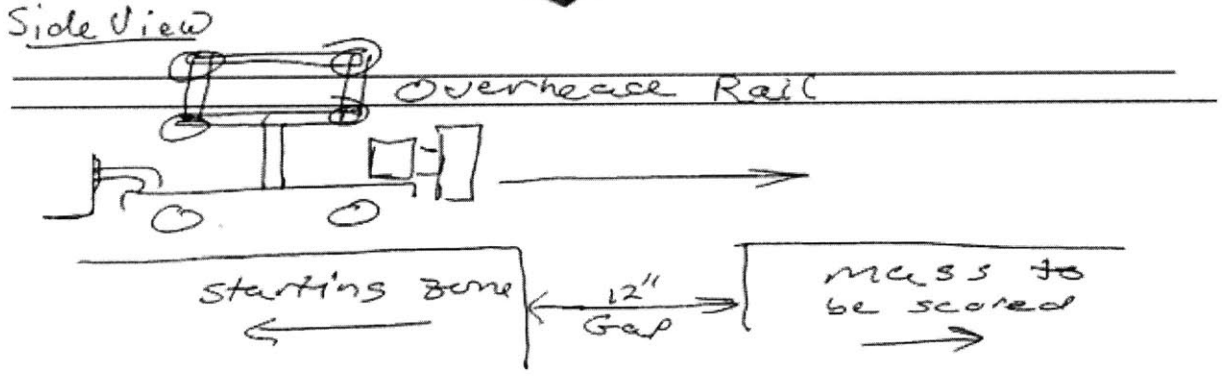
Strategy (Functional Requirement):
Cross the gap. Score by collecting mass.

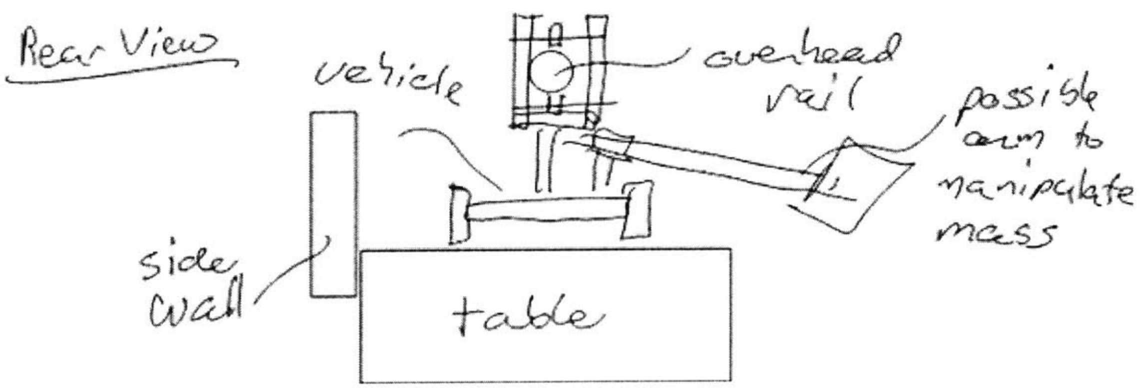
Concept (Design Parameter):
Use a machine attached to the rail to cross the gap.

Concept Sketches:



1) **Drive Across Gap Attached to the Overhead Rail**
2) **Detach From Rail and Move to Mass, or Stay Attached and Reach Out to Mass**
3) **Deposit Mass in Scoring Bin**





Analysis:

Dominant Physics and Variables:

- **Squeezing Force (Normal Force)/Friction** – You must insure that you have enough traction (i.e. your wheels do not slip) for your vehicle to accelerate as desired. However, gravity can once again be a friend and assist in providing normal force. Additional traction can of course be gained through the traditional methods: covering wheels with high friction material or preloading the wheels against the rail with springs to increase the normal force.

- **Moments/Center of Mass –** By suspending yourself from the rail you are asking gravity to try to pull you down, and it will be more than happy to oblige. Gravity will act through the center of mass of your machine (no matter where it may be) and create moments about the contact points on the rail. If your center of mass is not directly beneath the rail then gravity will act to rotate the robot about the rail. Either the robot must be designed with this in mind, or appropriate reaction forces must be designed in (either through contact with the floor or wall) to counter the moment.

- **Power/Torque** – Same considerations as for using a bridge or the wall to cross the gap. Power available to drive on the rail is finite. You have to match the weight of the machine you are trying to accelerate and how quickly you are trying to do so with the capabilities of your motors ($P = \Gamma \times \omega$, $P = F \times v$) and batteries ($P = I \times V$). You must also ensure that your motors can provide enough torque to move your robot as desired (depends on masses and accelerations as well as friction forces that must be overcome). If they cannot a transmission of some sort will be needed.

Concept Timeline and Scoring Analysis:

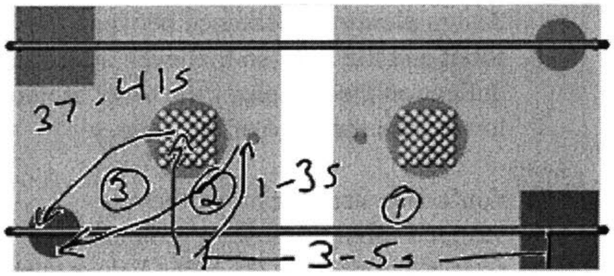


Figure 2.3: Estimated timeline for Concept 5.

Without knowing exactly how and what kind of mass will be scored it is tough to predict an exact score. However, as an estimate the scoring analysis from the Strategy chapter can be used.

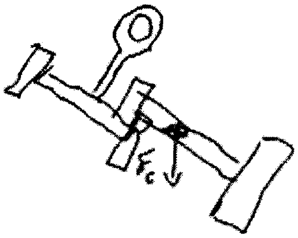
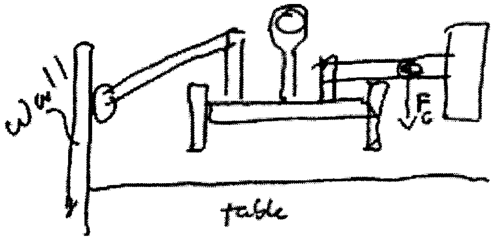
Estimated time spent scoring: 37 – 41 secs

Balls only: 1050 pts
Pucks alone: 1600 pts
Balls and pucks: 2250

1) **Cross gap on wall (3-5 sec)** – There is no fundamental difference from a time point of view between this concept and a wall crawling concept. The same reasons for the time estimate apply as above.

2) **Detach from rail and move to mass, or stay attached and reach out to mass (1-3 sec) –** Again, no fundamental difference exists between this concept and the wall crawling concept. As such, the same reasoning used to arrive at the time estimate for the wall crawling concept applies to this rail riding concept. One difference to note, however, is that detaching from the rail is likely to prove easier than from the wall, from a mechanism point of view, due to the simple fact that in this case you clearly have gravity working to your advantage.

Risks and Countermeasures:

Risks	Countermeasures
1) detachment mechanism fails and vehicle cannot get off of the overhead rail	1) have an arm that extends out to engage the mass so that it is not necessary to leave the rail
2) rail crawling mechanism is too complex	2) a. make the mechanism simple b. choose a different concept with simpler mechanisms
3) unable to keep robot in upright position on rail due to moments, particularly if using an extending arm 	3) brace yourself against the sidewall to counter the moments from gravity 
4) rail deflects too much in the center. robot drops below edge of table and is unable to get out of gap	4) design plenty of clearance between the robot and the floor so that even after rail deflection the wheels of the robot are not lower than the edge of the table
5) robot falls over when detaching from rail	5) don't drop very far off of the rail. suspend robot as close to ground as possible to prevent dropping below edge of table when rail sags over gap.

Concept Weighted Selection Chart - Scoring

Note: Selection criteria and relative weightings are identical to those used to choose a strategy. As such, a discussion of the thought processes taken to arrive at these rankings is foregone and the reader is referred to the preceding chapter. Also, note that while the last concept in the chart was not examined in detail above, it is a logical combination of the other two concepts and so has been included for comparison.

strategy **point scale: 1-10**	**scoring potential**	**simplicity**	**feasibility**	**educational value**	**potential for future applicability**	**potential for failure/ disqualification**	**sensitivity to opponents actions**	**time commitment**	**Totals**
Weighting %	10	10	25	15	15	7.5	5	125	100%
Balls	5	5	5	5	5	5	5	5	5
Pucks	7	7	5	6	7	5	4	5	5.8
Pucks and Balls	8	3	5	7	8	5	6	4	5.8

Brief Explanation of Rankings:

- **Scoring Potential:** Despite the fact that a higher percentage of the overall mass available is represented by the balls, it still receives a lower score than the other options. This is due primarily to the unpredictability and randomness associated with attempts to scatter the ball pyramid. The puck and ball category scores highest for the obvious reason that it includes two scoring methods.

- **Simplicity:** The combined concept scores lowest since it will require more components and thus add complexity. The puck concept scores highest since the pucks are presented in a nice, manageable stack. The unpredictability of the scatter of the ball pyramid leads to that concepts score.

- **Feasibility:** All seem equally feasible.

- **Educational Value:** A concept to score the balls will likely ram the pyramid, scatter the balls and then spend the remaining time driving around attempting to herd balls. The simplistic nature of this design provides little opportunity to demonstrate unique but simple mechanisms to accomplish complex tasks. The pucks stack, on the other hand, offers this opportunity.

- **Future Applicability:** Both balls and pucks have been virtually ubiquitous in 2.007 contests over the past number of years. However, the embodiment of pucks in the contest has almost always been a stack. The balls, on the other hand, have taken a number of different forms over the years. The consistency of the form of the pucks leads to its higher score.

- **Failure/D.Q:** Pucks could be accidentally knocked over or pushed across the center line (leading to D.Q.). Thus the puck concept receives the lowest score. The combined concept receives the highest score since if something goes wrong with one scoring option the other is still available.

- **Sensitivity to Opp.:** Combined concept scores highest since more options are available. Puck concept scores lowest since having the stack knocked over would greatly hinder ability to score.

- **Time Commitment:** Combined concept scores lowest due to requiring more modules.

Concept Weighted Selection Chart – Crossing the Gap

strategy point scale: 1-10	scoring potential	simplicity	feasibility	educational value	potential for future applicability	potential for failure/ disqualification	sensitivity to opponents actions	time commitment	Totals
Weighting %	10	10	25	15	15	7.5	5	12.5	100%
Bridge	5	5	5	5	5	5	5	5	5
Wall	4	3	5	6	7	5	5	3	4.9
Overhead Rail	4	3	5	5	5	5	5	4	4.6

Brief Explanation of Rankings:

- **Scoring Potential:** Scoring derives directly from the scoring analyses presented above. A bridge leaves the most time for scoring and so receives the highest score.

- **Simplicity:** By choosing to focus on the pucks above any concept utilizing the rail or wall will almost definitely require detaching a smaller robot (a long extending arm would not be feasible for dealing with the pucks. This detachment requirement will add complexity and lead to a lower score.

- **Feasibility:** All seem equally feasible.

- **Educational Value:** Wall crawler score marginally better due to higher likelihood of being applicable to future tables. Aside from that consideration, though, all options provide unique opportunities to demonstrate proper design practices and use of fundamental principles.

- **Future Applicability:** 2.007 tables have almost always had walls. This trend is likely to continue and so a wall crawler would be applicable to future contests. This is the first table to feature a gap (making a bridge useful) or an overhead rail and so those concepts score lower.

- **Failure/D.Q:** All have their own unique issues. Bridge could fall in gap. Rail-rider could fall off rail or get stuck in gap if rail sags too much. Wall-crawler could jam on wall or fall off. Equal score for all.

- **Sensitivity to Opp.:** All concepts are susceptible to actions by the opponent. No one seems to have an advantage.

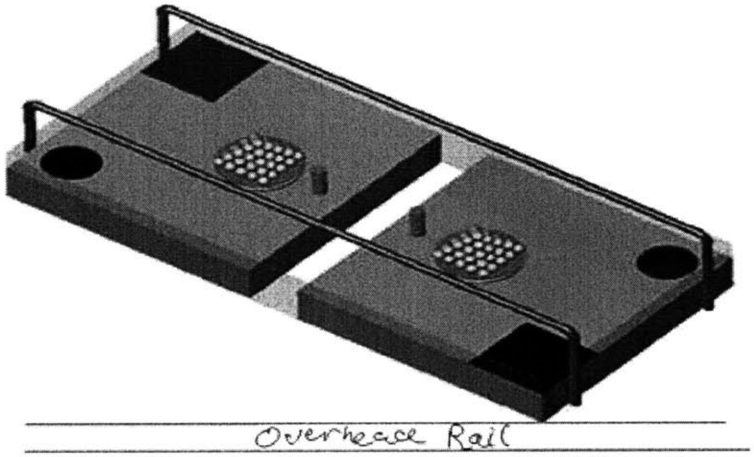
- **Time Commitment:** A wall crawler or rail-rider should require more components and requires more attention to physics. This will add complexity and thus time. Rail-rider scores better since gravity can be used to your advantage.

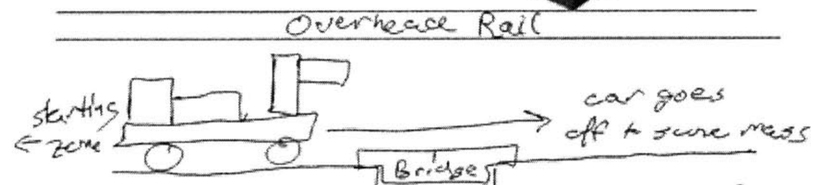
Final Concept

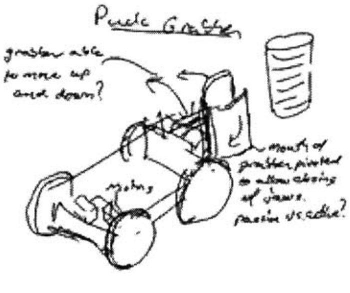
Strategy (Functional Requirement):
Cross the gap. Score by collecting mass.

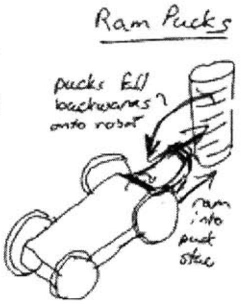
Concept (Design Parameter):

1) Use a bridge to cross the gap
2) Score using pucks.









In agreement with the selection charts presented above, it has been decided to pursue an overall concept that utilizes a bridge to cross the gap and focuses on the puck stack for scoring.

The decision to focus on the pucks only, despite the fact that the combined concept received the same score, results from an overriding desire to keep things as simple as possible. A single scoring approach should minimize components and so meets this requirement. The idea of scoring balls will, however, be kept in mind. Should extra time become available, the possibility of adding a ball scoring component can be explored.

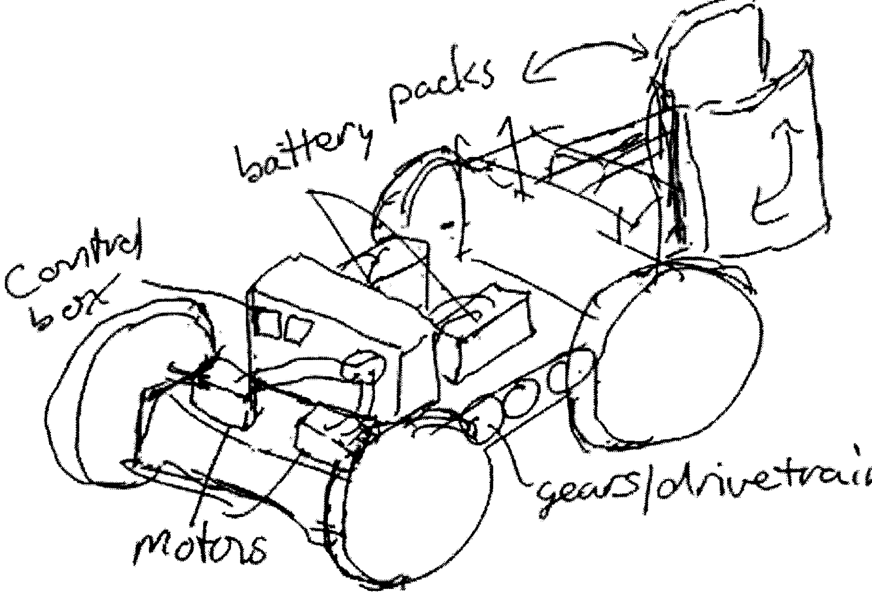
Finally, while there are naturally risks associated with the chosen concepts (as laid out above) it is my opinion that this strategy offers the least amount of risk of any. More importantly, it is my belief that the risks that do exist are the most easily addressed and remedied (with the minimal amount of added time and complexity) of any of the presented concepts.

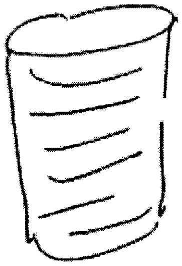
For a complete and detailed description of the individual components of this final concept, please see *Concept 2 – Pucks* and *Concept 3 – Bridge* above.

Chapter 3:
Most Critical Module

Module Identification

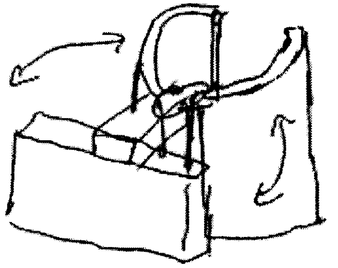
Overall Machine Concept (with individual modules identified):



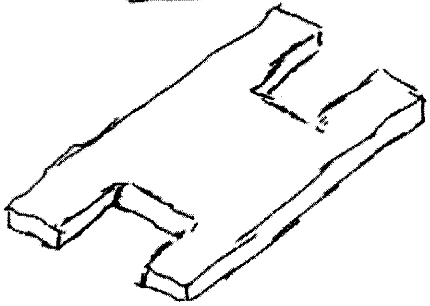


Machine Modules:

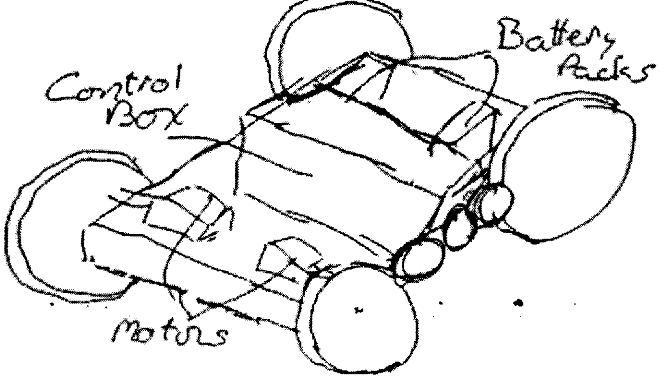
Puck Grabber



Bridge



Chassis & Control System



Most Critical Module (MCM) Selection Chart

	bridge	chassis/drive train	control box/electrical system	puck grabber	Total # of 1's in Row
bridge	x	1	1	1	3
chassis/drive train		x	1	1	2
control box/electrical system			x	0	0
puck grabber				x	

Total # of 0's in Column	0	0	0	1
Copy of 1's Totals	3	2	0	0
Totals/Rankings	③	②	⓪	①

Explanation:

1. **Bridge Module –** This is the Most Critical Module (MCM). If the robot is unable to get across the gap, then none of the other modules will really mean anything. Scoring modules, defensive modules, all become useless if the bridge does not work and is the robot is not able to cross the gap. For this reason, the bridge module is the most important of all modules.

2. **Chassis/Drive Train –** Need to be capable of moving around. Have to be able to drive across the bridge, drive to the pucks, and maneuver the pucks to the scoring bin. It is also important to be sure the drive train can provide sufficient torque to move the pucks. In the end, having a working puck grabber or a completely wired control system is of little use if you do not have a working chassis/drive train.

3. **Puck Grabber –** Scoring is obviously important. Once it is certain that the robot can position itself to score (i.e. the bridge and chassis/drive train modules are known to work), the ability to score becomes most important. In this case, that means a working puck grabber module.

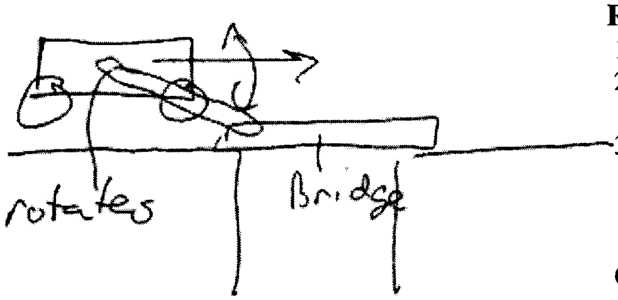
4. **Control Box/Electrical System –** This includes all wiring, control box mounting, battery pack mounting, etc. It needs to be done, but should be straightforward and consume relatively little time. The largest potential problem is running out of room on the chassis for the control box and battery packs. So long as this is kept in mind during the design of the chassis, though, this module should cause few problems.

Most Critical Module
Bridge Module

Functional Requirements:
1. Span the gap
2. Support the robot
3. Deploy quickly
4. Reliable and repeatable

Module Ideas:

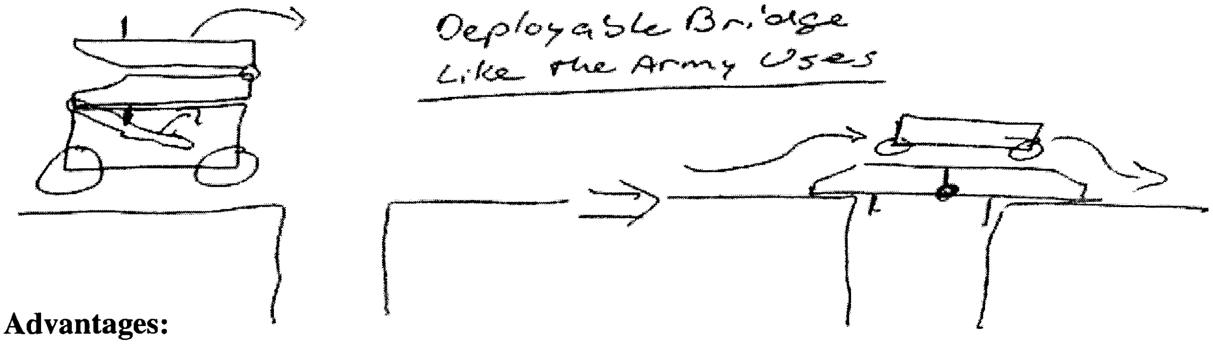
Idea 1: Rigid single piece bridge (eg. made of sheet metal) rotated into place in gap.



Risks/Disadvantages:
1. extra motor needed to deploy
2. complicated mechanism to allow proper motion of bridge
3. bridge always connected to robot, cumbersome and in way, or complicated mechanism needed to detach bridge

Conclusion:
Not an ideal choice for bridge module.

Idea 2: Unfoldable bridge carried on robot, much like the ones used by army to cross waterways.



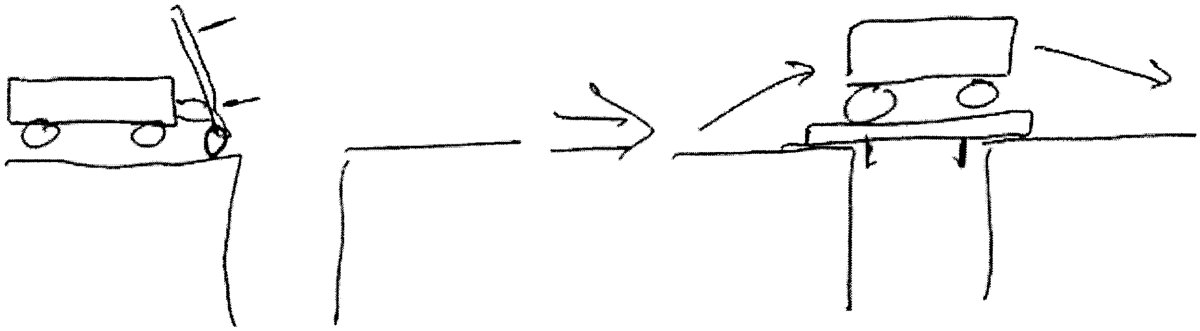
Advantages:
Technology already developed and used by army, so base work has already been completed. No need to design completely from scratch since foundation already exists.

Risks/Disadvantages:
1. complicated mechanism to deploy
2. mechanism required to release bridge
3. motor needed to deploy bridge, or if not a motor than another complicated mechanism

Conclusion:
Not an ideal choice for bridge module.

Module Ideas – Cont'd:

<u>Idea 3</u>: Sheet metal bridge w/wheels. Push bridge in front of robot and into gap.



Advantages:

1. passive deployment mechanism – no extra motors needed beyond motors of drive wheels.
2. simple – just sheet metal and wheels. no complicated mechanisms
3. quick deployment – no need to stop at edge and then initialize deployment. just push bridge to gap, allow it to drop in, and drive across. ideally all one motion.

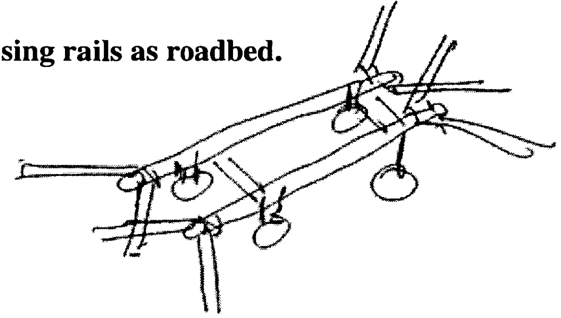
Risks:

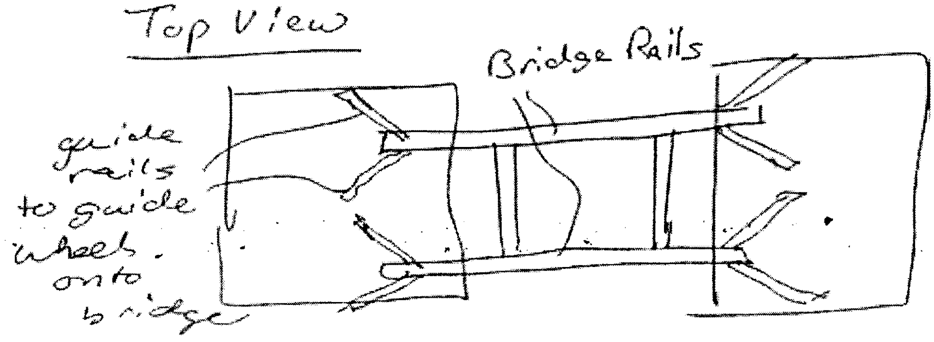
1. not repeatable. bridge may not always deploy, or it may deploy differently each time. at a different angle, a different position relative to wall, etc.
2. bridge may fall into gap if deployed incorrectly
3. potential problems pushing bridge – may jam in carpet. may require huge force to push. could fall prematurely during pushing. may become entangled with the rest of the robot.
4. vehicle may fall off bridge while crossing bridge

Conclusion:

A potentially good choice for the bridge module, though some refinement is still needed.

<u>Idea 4</u>: Bridge on wheel using rails as roadbed.





Advantages:

1. simple, no complex mechanisms to deploy
2. potential for vehicle to ride on top of bridge from the very start. should save time since all robot would need to do is drive off once bridge is deployed in gap
3. grooves would be required in wheels to allow mating with bridge rails, but these same grooves would ensure that robot cannot accidentally fall off bridge while crossing
4. bridge/robot assembly could be "launched" from starting zone. this would make for very rapid deployment.

Risks:

1. not repeatable. bridge may not always deploy, or it may deploy differently each time. at a different angle, a different position relative to wall, etc.
2. bridge may fall into gap if deployed incorrectly
3. potential problems pushing bridge – may jam in carpet. may require huge force to push. could fall prematurely during pushing. may become entangled with the rest of the robot.

Conclusion:

A potentially good choice for the bridge module, though some refinement is still needed.

Overall Assessment:

Ideas 3 and 4 are more practical and more likely to be successful than the other ideas, yet each still has its drawbacks. Foremost among these is the unpredictability of the deployment. In particular, there is nothing to ensure that the bridge will always deploy at the same location on the table, or in the same orientation, or that it will even deploy at all. It could simply fall into the gap.

The simplest way to combat this problem is to add a guide from the side wall. This will serve the dual purpose of ensuring that the bridge always deploys in the same location and orientation, as well as making it impossible for the bridge to fall into the gap without deploying.

Idea 4 has a number of advantages over Idea 3. First, its roadbed requires a unique wheel structure to be used. Not only must the wheels be grooved to accept the rails, but the robot's wheel base must also match that of the bridge. This has the benefit of making it virtually unusable by your opponent in the case that he has lost the use of his own bride, but still desires to re-cross the gap.

The rails of Idea 4 also help to protect the robot from accidentally driving off of the bridge. Since the bridge rails will be seated in the robot's wheel grooves, sideways motion will not be permitted. In essences, the rails limit the robot to one-dimensional motion and thus take away a potential failure mode.

Finally, the rails allow for the potential of "launching" the robot and bridge simultaneously toward the gap. The robot would sit on top of the bridge and be deployed along with it. The rails would prevent any chance of the robot sliding off of the bridge sideways. All that would be needed is a way to restrain the robot from sliding off of the bridge in the forward or backward direction.

In light of the discussion above a modified Idea 4 will be pursued for the bridge module. The revised functional requirements, design parameters, and sketches are presented below, as well as the detailed design and solid model.

Most Critical Module (Bridge Module)
Design Overview

Functional Requirements:

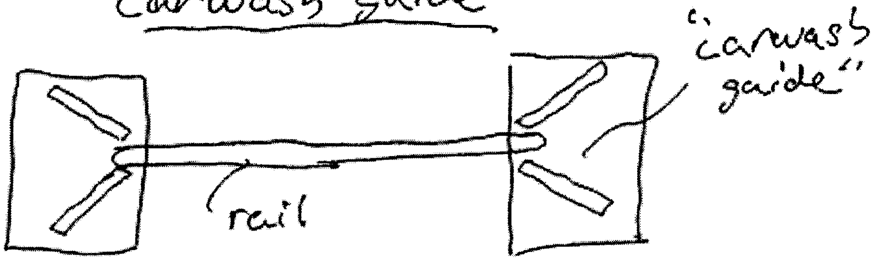
1. Span the gap
2. Support the robot
3. Deploy quickly
4. Reliable and repeatable

Design Parameters:

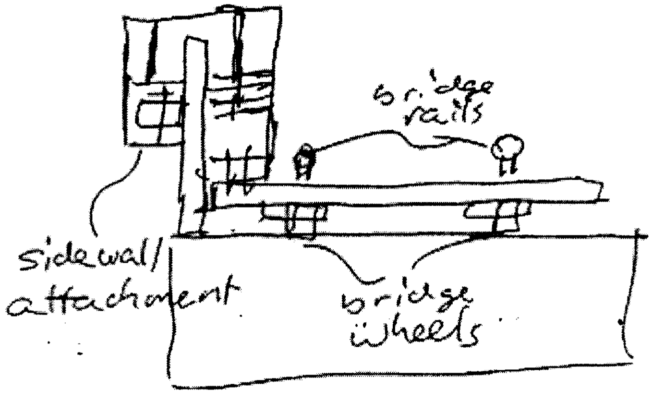
1. use "rails" to provide discreet path across bridge
2. put bridge on wheels
3. "launch" bridge to gap with robot riding on top
4. "car wash guides" to guide robot wheels onto bridge rails
5. sidewall attachment to insure repeatable and consistent deployment of bridge

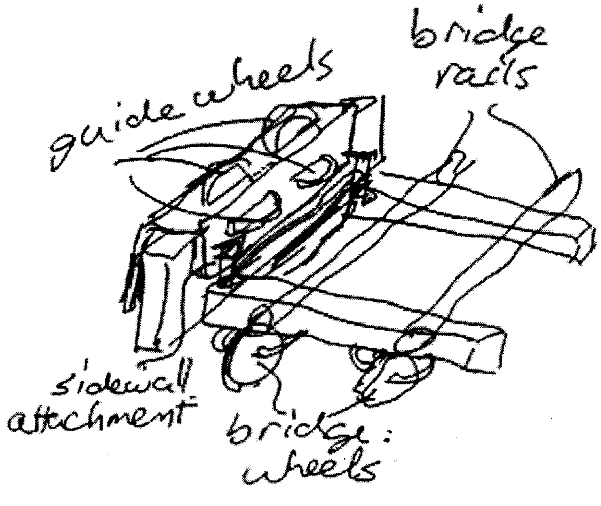
Preliminary Sketches:

Single Rail and "carwash guide"



Bridge w/sidewall





Analysis:

Two critical engineering calculations are required by this design:

1) Beam bending calculations for the bridge rails
2) Bridge deployment calculations for "launching" bridge

1) Beam Bending Analysis

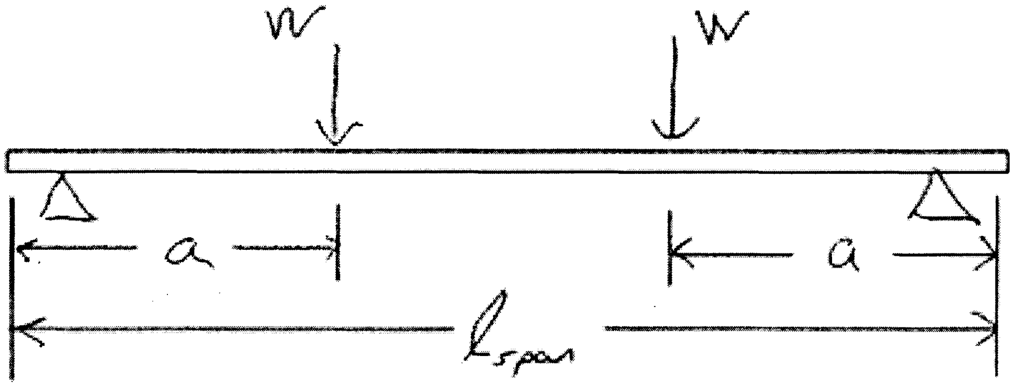
In performing these calculations we are primarily concerned with determining the bending stress, $\sigma_{bending}$, and the maximum deflection, δ_{max}, for the material-geometry combination of interest. The ultimate goal is to choose a geometry that can be easily manufactured from kit materials and a material that will neither yield nor deflect excessively. Additionally, the 10 lb weight limit for the entire robot encourages us to also use as light and as little material as possible.

Given the make-up of the kit materials the best choice of material for the bridge rails is either the ¼" diameter aluminum rod or the ¼" diameter steel rod. Both are provided in sufficient length to span the 12" gap (unlike the larger ⅜" diameter aluminum or ½" diameter steel). If capable of withstanding the loading, the aluminum would be a preferable choice for a number of reasons. First, it is lighter than the steel and so better for the overall weight budget. Of perhaps greater importance, however, is that it would free up the steel for use in applications that demand a high strength material, for example spinning shafts attached to motors and wheels. Deflection in these shafts could result in improper alignment of bearings and lead to motor failure or wheels that simply will not spin. Finally, steel typically makes a better sliding bearing surface than aluminum and so would be the material of choice for the shafts of wheels utilizing only sliding contact.

<u>**Model for Bridge Rails**</u>

Assumptions:

- simply supported
- two unclamped ends
- weight is assumed to be evenly distributed among all four vehicle wheels
- vehicle wheels represented as two symmetrical points loads, *W*, at a distance, *a*, from either support
- in reality, this model applies only for the unique orientation in which the vehicle is exactly halfway across the bridge. however, this situation also represents the orientation of highest stress and largest beam deflection, and so is sufficient by itself.

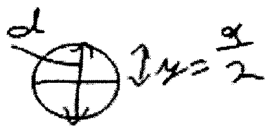


Section Modulus

$$\text{section modulus}(Z) = \frac{\text{moment of inertia}(I)}{\text{dist. from neutral axis's to extreme fiber}\,(y)}$$

$$Z[m^3] = \frac{I[m^4]}{y[m]}$$

for a beam w/a circular cross-section:



$$I = \frac{\pi d^4}{64} = 0.049 d^4$$

$$Z = \frac{\pi d^3}{32} = 0.098 d^3$$

Bending Stress

The maximum bending stress in the rails will occur at the loading points. Due to the symmetry of the loading, the stress at each loading point, and at every point in between, will be equal and given by:

$$\sigma_{bending} = -\frac{Wa}{Z}$$

Assuming that the weight of the vehicle is evenly distributed over all four wheels

$$W = \frac{F_{g,car}}{4} = \frac{m_{car}g}{4}$$

and

the wheelbase of the car

$$a = \frac{l_{span} - l_{wheelbase}}{2}$$

$$\Rightarrow \sigma_{bending} = \frac{m_{car}g(l_{span} - l_{wheelbase})}{0.784\, d^3}$$

Will the ¼" Dia. Steel or Aluminum Rails Yield?

In conducting the failure analysis, conservative values are chosen for all parameters that are at the discretion of the designer. In this way, the stresses given below represent a worst-case scenario. In addition, for added safety and confidence a standard safety factor of two is included.

Parameter Values Utilized for Failure Analysis:

$l_{span} = 18''$ (max. length of rods available in kits)

$l_{wheelbase} = 8''$ (far smaller than actual)

$m_{car} = 10$ lb (weight limit for entire robot. assume entire 10 lbs taken by car. In reality, it will weigh less since some mass will be in bridge itself)

Failure Criterion:

$\sigma_{bending} = 56.25$ MPa (calculated bending stress in bridge rails)

$\sigma_{yield,steel} = 370$ MPa $\quad \sigma_{steel} < \dfrac{\sigma_{yield,steel}}{2 \leftarrow \text{safety factor}}$

$\boxed{\text{No Yield}}$

$\sigma_{yield,alum} = 275$ MPa $\quad \sigma_{alum} < \dfrac{\sigma_{yield,alum}}{2 \leftarrow \text{safety factor}}$

$\boxed{\text{No Yield}}$

Beam Deflection

Given the loading configuration described above, the maximum deflection of the rails will occur at the center point of the rail, half-way between the vehicle wheel load points. Assuming the conservative parameter values specified above the deflection of the steel and aluminum rails is as given below. Again, this represents a worst case scenario, and the actual deflections will be far less.

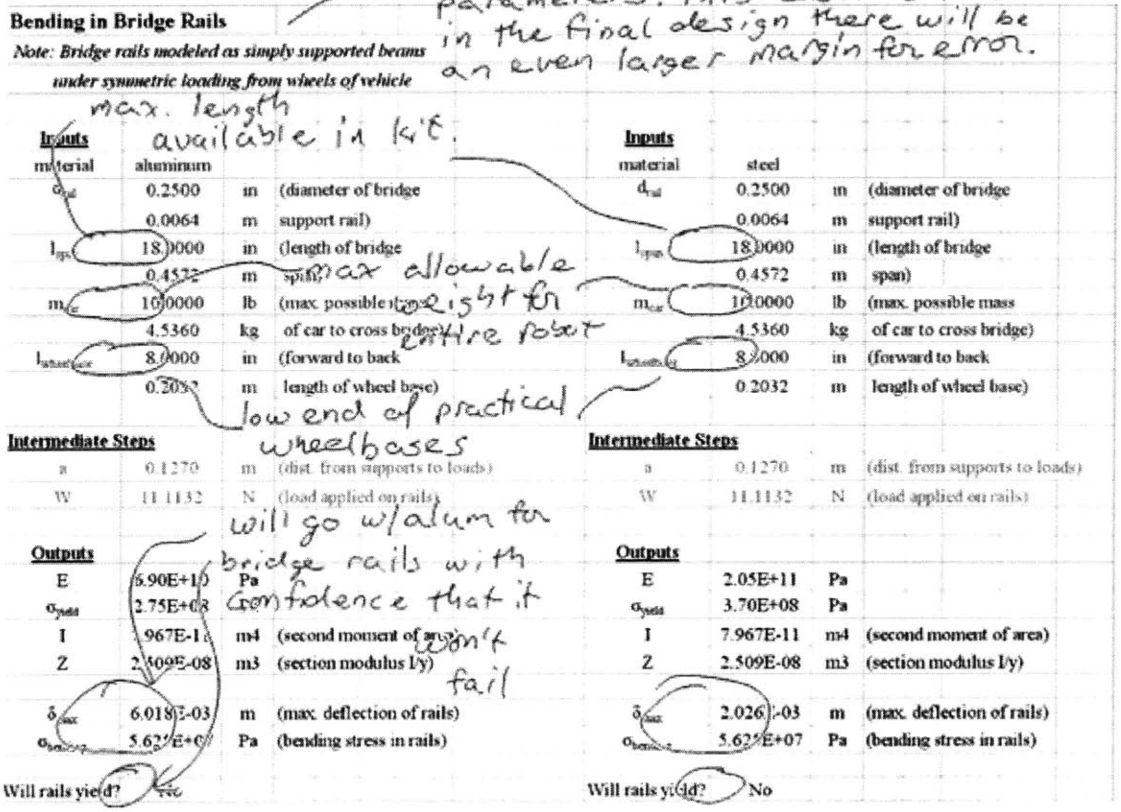
$$\delta_{max} = \frac{Wa}{24EI}(3l_{span} - 4a)$$

$$\delta_{max} = \frac{m_{car}\, g\, a}{96\, EI}(3l_{span} - 4a)$$

$$\boxed{\delta_{max,\,steel} = 0.002\,m \Rightarrow 0.08''}$$

$$\boxed{\delta_{max,\,alum} = 0.006\,m \Rightarrow 0.24''}$$

Note the conservative values chosen for all important design parameters. This ensures that in the final design there will be an even larger margin for error.



Bending in Bridge Rails

Note: Bridge rails modeled as simply supported beams under symmetric loading from wheels of vehicle

max. length available in kit.

max allowable weight for entire robot

low end of practical wheelbases

will go w/ alum for bridge rails with confidence that it won't fail

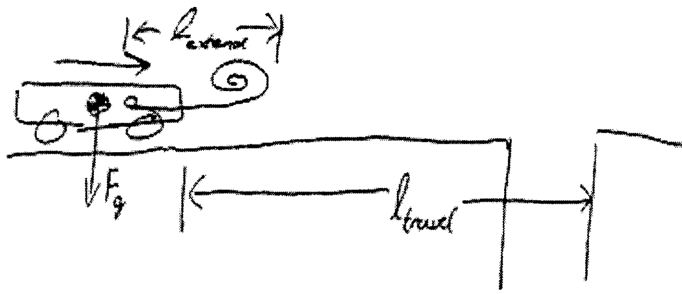
Inputs				**Inputs**			
material	aluminum			material	steel		
d_{rail}	0.2500	in	(diameter of bridge	d_{rail}	0.2500	in	(diameter of bridge
	0.0064	m	support rail)		0.0064	m	support rail)
l_{span}	18.0000	in	(length of bridge	l_{span}	18.0000	in	(length of bridge
	0.4572	m	span)		0.4572	m	span)
m_{car}	10.0000	lb	(max. possible mass	m_{car}	10.0000	lb	(max. possible mass
	4.5360	kg	of car to cross bridge)		4.5360	kg	of car to cross bridge)
$l_{wheelbase}$	8.0000	in	(forward to back	$l_{wheelbase}$	8.0000	in	(forward to back
	0.2032	m	length of wheel base)		0.2032	m	length of wheel base)
Intermediate Steps				**Intermediate Steps**			
a	0.1270	m	(dist. from supports to loads)	a	0.1270	m	(dist. from supports to loads)
W	11.1132	N	(load applied on rails)	W	11.1132	N	(load applied on rails)
Outputs				**Outputs**			
E	6.90E+10	Pa		E	2.05E+11	Pa	
σ_{yield}	2.75E+08	Pa		σ_{yield}	3.70E+08	Pa	
I	7.967E-11	m4	(second moment of area)	I	7.967E-11	m4	(second moment of area)
Z	2.509E-08	m3	(section modulus I/y)	Z	2.509E-08	m3	(section modulus I/y)
δ_{max}	6.018E-03	m	(max. deflection of rails)	δ_{max}	2.026E-03	m	(max. deflection of rails)
$\sigma_{bending}$	5.62[illegible]E+07	Pa	(bending stress in rails)	$\sigma_{bending}$	5.62[illegible]E+07	Pa	(bending stress in rails)
Will rails yield?	No			Will rails yield?	No		

Figure 3.1: Conservative bending analysis of aluminum vs. steel bridge rails.

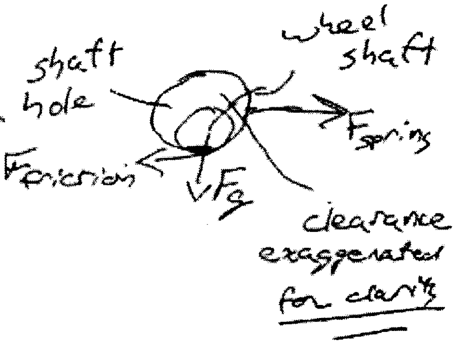
Results/Conclusions

Neither the steel nor the aluminum rod will yield even in the worst case analyzed above. The smaller deflection of the steel is certainly more attractive than the nearly ¼" deflection of the aluminum, but given that this is a worst case estimate, both are acceptable. In light of the results, then, aluminum bridge rails will be pursued in this design. The analysis above has shown that aluminum will more than adequately accomplish the job and it has the additional benefits that have been highlighted at the beginning of this analysis section.

2) Bridge Deployment Analysis



Sliding Friction Resulting From Rotation of Wheel Shaft Inside of Hole



Segment I: Acceleration

During this segment two forces are acting on the bridge/car assembly. First, there is the forward force provided by the constant force springs. This will be constant throughout the time that the springs are engaging the vehicle and serves to accelerate the vehicle forward. Opposing this force is a frictional force arising from the friction in the spinning shafts of the wheels. This force will act to decelerate the vehicle at a rate dependent on the coefficient of friction between the shaft and bearing.

pos. accel. positive force

$$a_{springs} = \frac{nF_{springs}}{m_{bridge/vehicle}}$$

neg. accel neg. force

$$a_{friction} = -\frac{F_{friction}}{m_{bridge/vehicle}} = \frac{\mu g m_{bridge/vehicle}}{m_{bridge/vehicle}}$$

$$\hookrightarrow a_{friction} = -\mu g$$

$$\Longrightarrow \underline{a_{net} = a_{springs} + a_{friction}}$$

$$v_{f,segment\,1}^2 = \overset{0}{\cancel{v_o^2}} + 2a_{net}x_{extend}$$

extended length of const force springs

$$v_{f,segment\,1} = \sqrt{2a_{net}x_{extend}}$$

(final velocity achieved accel from springs force)

Segment I: Acceleration – Cont'd

$$x_{extend} - \cancel{x_0}^{0} = \frac{1}{2}(\cancel{v_0}^{0} + v_{f,segment\,1})t_1$$

$$t_1 = \frac{2x_{extend}}{v_{f,segment\,1}}$$

Segment II: Deceleration and Bridge Deployment

During this segment the springs are no longer acting on the vehicle and so there is no force to produce a forward acceleration. The only force now present is friction, acting to decelerate the vehicle.

total distance that must be traveled for bridge to deploy

$$v_{deployment} = \sqrt{v_{f,segment\,1}^2 + 2a_{friction}(x_{travel} - x_{extend}}$$

Velocity of bridge/car at time of deployment

$$t_2 = \frac{2(x_{travel} - x_{extend})}{v_{springs} + v_{deployment}}$$

(time to deploy from end of acceleration)

Overall

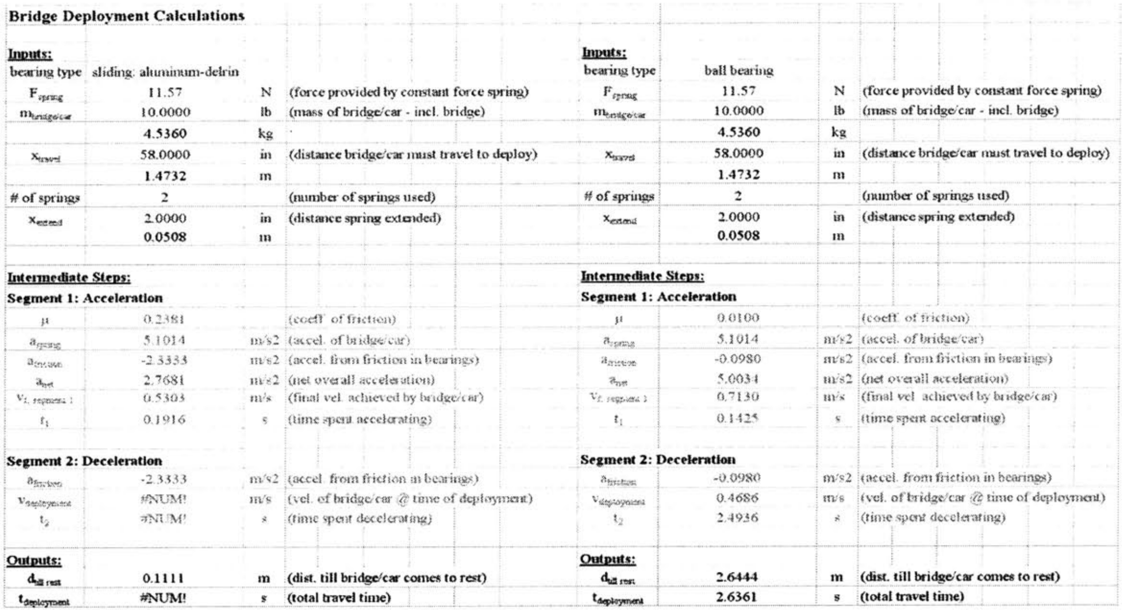
Total Time:

$$\underline{\underline{t_{total} = t_1 + t_2}}$$

Maximum Possible Travel Distance Before Coming to Rest:

$$\cancel{v_f^2}^{0} - v_{f,segment\,1}^2 = 2a_{friction}(d_{till\,rest} - x_{extend})$$

$$\underline{\underline{d_{till\,rest} = -\frac{v_{f,segment\,1}^2}{2a_{friction}} + x_{extend}}}$$



Bridge Deployment Calculations							
Inputs:				**Inputs:**			
bearing type	sliding: aluminum-delrin			bearing type	ball bearing		
F_{spring}	11.57	N	(force provided by constant force spring)	F_{spring}	11.57	N	(force provided by constant force spring)
$m_{bridge/car}$	10.0000	lb	(mass of bridge/car - incl. bridge)	$m_{bridge/car}$	10.0000	lb	(mass of bridge/car - incl. bridge)
	4.5360	kg			4.5360	kg	
x_{travel}	58.0000	in	(distance bridge/car must travel to deploy)	x_{travel}	58.0000	in	(distance bridge/car must travel to deploy)
	1.4732	m			1.4732	m	
# of springs	2		(number of springs used)	# of springs	2		(number of springs used)
x_{extend}	2.0000	in	(distance spring extended)	x_{extend}	2.0000	in	(distance spring extended)
	0.0508	m			0.0508	m	
Intermediate Steps:				**Intermediate Steps:**			
Segment 1: Acceleration				**Segment 1: Acceleration**			
μ	0.2381		(coeff. of friction)	μ	0.0100		(coeff. of friction)
a_{spring}	5.1014	m/s2	(accel. of bridge/car)	a_{spring}	5.1014	m/s2	(accel. of bridge/car)
$a_{friction}$	-2.3333	m/s2	(accel. from friction in bearings)	$a_{friction}$	-0.0980	m/s2	(accel. from friction in bearings)
a_{net}	2.7681	m/s2	(net overall acceleration)	a_{net}	5.0034	m/s2	(net overall acceleration)
$V_{f,\ segment\ 1}$	0.5303	m/s	(final vel. achieved by bridge/car)	$V_{f,\ segment\ 1}$	0.7130	m/s	(final vel. achieved by bridge/car)
t_1	0.1916	s	(time spent accelerating)	t_1	0.1425	s	(time spent accelerating)
Segment 2: Deceleration				**Segment 2: Deceleration**			
$a_{friction}$	-2.3333	m/s2	(accel. from friction in bearings)	$a_{friction}$	-0.0980	m/s2	(accel. from friction in bearings)
$v_{deployment}$	#NUM!	m/s	(vel. of bridge/car @ time of deployment)	$v_{deployment}$	0.4686	m/s	(vel. of bridge/car @ time of deployment)
t_2	#NUM!	s	(time spent decelerating)	t_2	2.4936	s	(time spent decelerating)
Outputs:				**Outputs:**			
$d_{till\ rest}$	0.1111	m	(dist. till bridge/car comes to rest)	$d_{till\ rest}$	2.6444	m	(dist. till bridge/car comes to rest)
$t_{deployment}$	#NUM!	s	(total travel time)	$t_{deployment}$	2.6361	s	(total travel time)

Figure 3.1: Conservative analysis to determine feasibility of deploying bridge by using the constant force springs. Compares feasibility using delrin sliding contact bearings vs. ball bearings.

Results/Conclusions

A conservative feasibility study is presented in Figure 3.1 above. The weight of the bridge/car to be accelerated is assumed to be the maximum allowed by the rule (10 lb), and a modest spring extension of 2" is used. Additionally, it is assumed that only two of the available four constant force springs are used. Two distinct cases are presented. The first examines the use of simple sliding contact between the wheels and the wheel shaft. The wheels are assumed to be made of delrin (the lowest friction material available in the kit) and the shafts made of aluminum. The second case studies the use of ball bearings to eliminate the sliding friction.

Sliding Contact Bearings

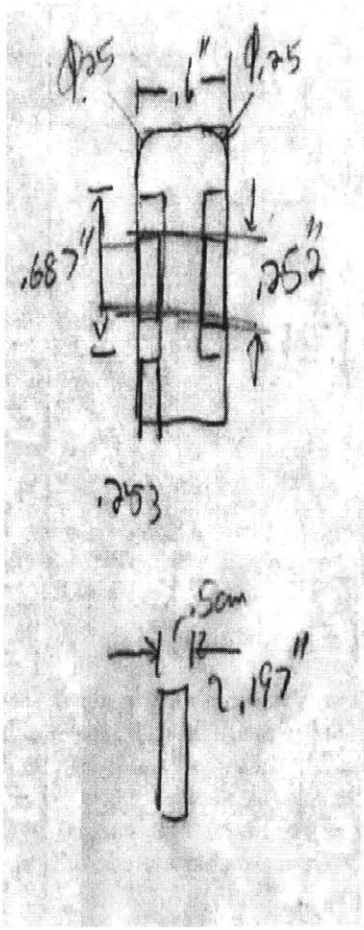
Despite the low friction of the delrin, the analysis clearly shows if using sliding contact bearings an attempt to deploy the bridge using the constant force springs is not feasible. The friction force opposing motion is so high and the velocity imparted by the springs so low, that the bridge/car complex comes to rest before it is able to reach the gap and deploy. In fact, if using only two constant force springs an extension of nearly 28" of extension is required to deploy the bridge. Even if four springs are used an extension of 14" is required. In light of this knowledge, sliding contact bearings cannot be used in any design attempting to utilize springs to deploy the bridge.

Ball Bearings

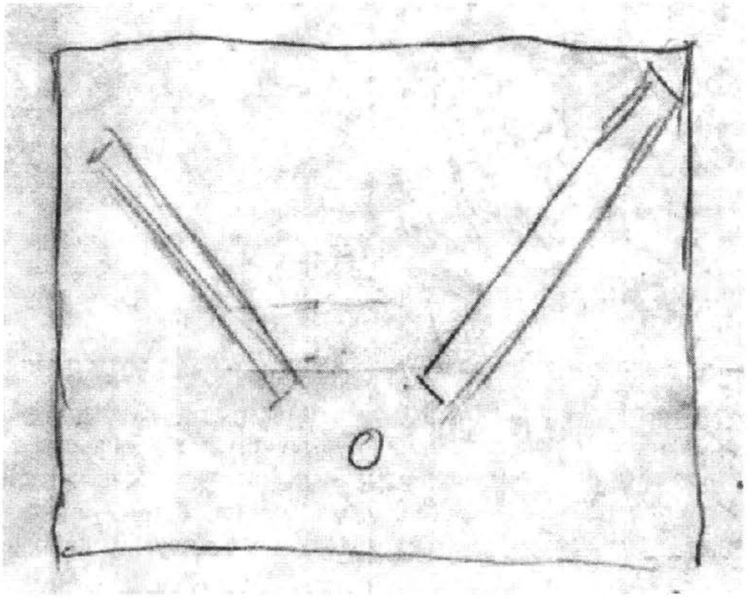
Contrary to the sliding contact bearings, ball bearings should all the springs to deploy the bridge/car complex with relative ease. Even with only two springs being used and a modest extension of 2", a 10 lb robot could be "ejected" approximately 2.6 m. This is far beyond the 1.47 m required to deploy the bridge. Further, the bridge could be deployed in around 2.6 s, and even faster if more springs and a larger extension is used or if the overall weight of the robot is less than 10 lb. This speed of deployment is of course greatly desirable. Therefore, with the feasibility of a spring launched bridge demonstrated the decision is made to pursue said design.

Detailed Design and Manufacture of MCM

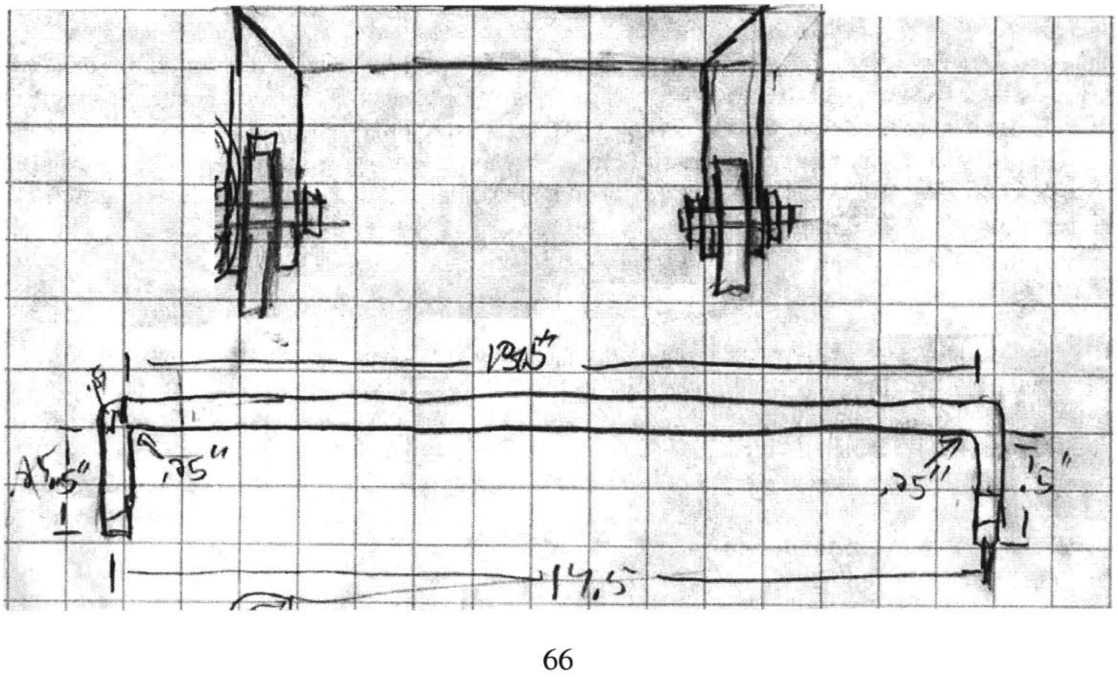
Bridge Wheel w/ Ball Bearings



Carwash Style Guide Plate

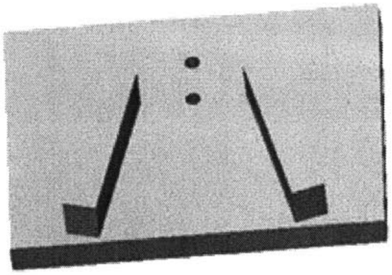


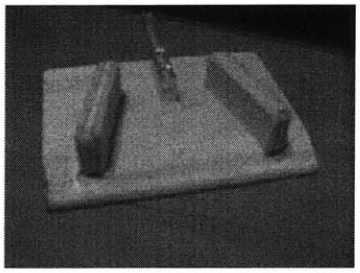
Bridge Crossbeam



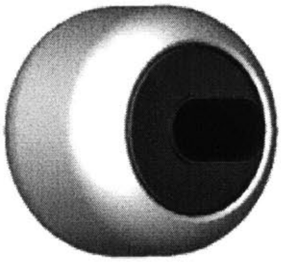
Detailed Design and Manufacture of MCM – Cont'd

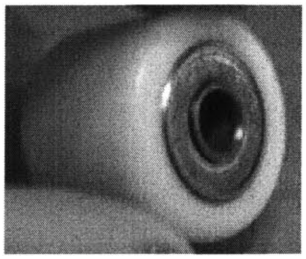
Carwash Style Guide Plate



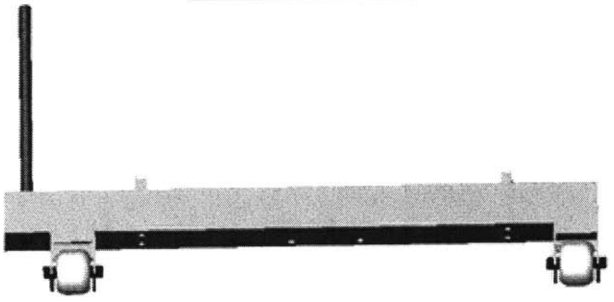


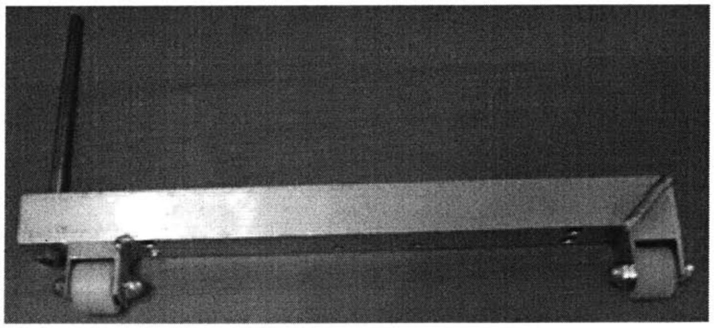
Bridge Wheel w/ Ball Bearings



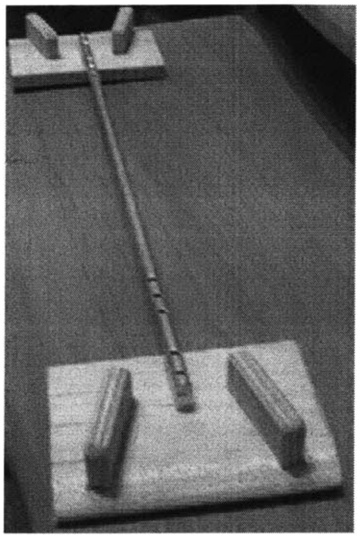


Bridge Crossbeam

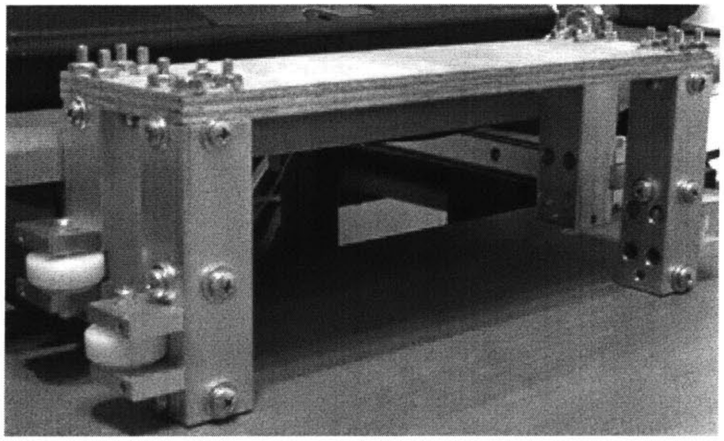




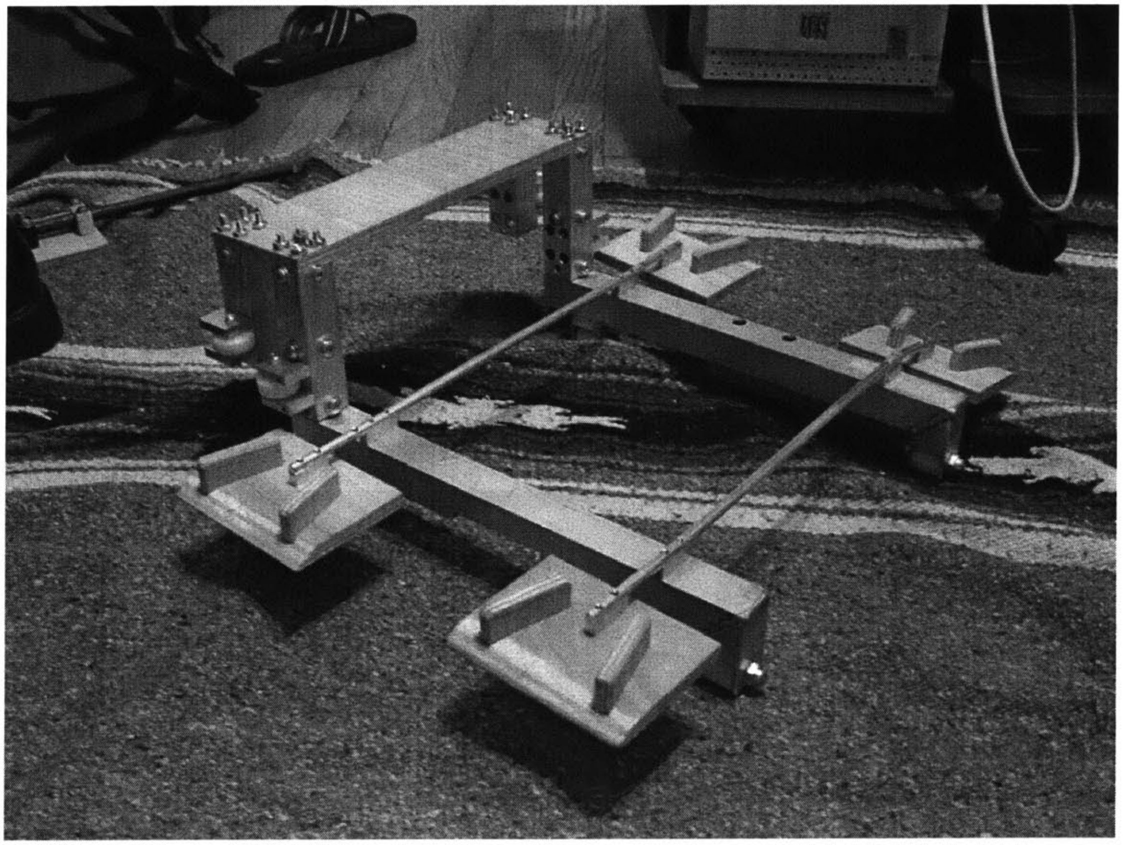
Bridge Rail Assembly



Sidewall Attachment



Full Bridge Assembly



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