Team 9 BattleBot

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CONTENTS

Paragraph Title Page

1.0 SCOPE 5

2.0 ACKNOWLEGMENTS 5

3.0 APPLICABLE DOCUMENTS 5
3.1 BattleBot Rules 5
3.2 Event Procedures 5
3.3 Judging Rules 5
3.4 BattleBot Operations Manual 6
3.5 ANSI Standards 6

4.0 SCHEDULE 6

5.0 BACKGROUND 6

6.0 SPECIFICATIONS 6
6.1 Target Specifications 6
6.2 Final Specifications 7

7.0 DRIVE TRAIN 8
7.1 Theory 8
7.2 Design Calculations 9
7.3 Sprocket Size Calculations 10
7.4 Shaft Fabrication 11
7.5 Sprocket Fabrication 12
7.6 Bearing Block Fabrication 12
7.7 Assembly 12
7.8 Testing 13

8.0 PRIMARY WEAPON/SELF RIGHTING MECHANISM 13
8.1 Capabilities 13
8.2 System Design 14
8.3 Flipping Mechanism Components 16
8.4 Fabrication 19
8.5 Assembly/Testing 19

9.0 PNEUMATICS SYSTEM 20
9.1 Concept Design 20
9.2 Preliminary Design 20
9.3 Revised Design 21
9.4 Testing 22
9.5 Final Design 23

10.0 SECONDARY WEAPON 24

11.0 STRUCTURAL ANALYSIS 24

11.1 Drum Bearing Bracket 24
11.2 Bulkhead 25
11.3 Body 26

12.0 3-D DESIGN AND DRAFTING 26
12.1 Drive Train Design 27
12.2 Shaft Design 31
12.3 Bulkhead and Body Design 33
12.4 Rotating Drum Design 34
12.5 Internal Components 36

13.0 ELECTRICAL SYSTEM 44
13.1 Main Power Schematic 44
13.2 Power Calculations 45
13.3 Remote Control 46
13.4 Speed Controller 47
13.5 Servo Motor Modifications 50

14.0 FABRICATION OF BODY PARTS AND MOUNTS 53
14.1 Bulkheads 53
14.2 Body 54
14.3 Front Motor Mounts 54

15.0 ASSEMBLY 55

16.0 TESTING 57

17.0 BILL OF MATERIALS 58

18.0 CONCLUSIONS 58

APPENDIX A – SCHEDULE 59

APPENDIX B – NEEDS/SPECS/CONCEPTS 62

1.0 NEEDS ASSESMENT 62

2.0 SPECIFICATIONS 63
2.1 Target Specifications 63

3.0 CONCEPT GENERATION AND SELECTION 64
3.1 Concept Generation 64
3.2 Concept Selection 66

APPENDIX C – DRIVE TRAIN CALCULATIONS 73

APPENDIX D – PRIMARY WEAPON SYSTEM CALCULATIONS 88

APPENDIX E – STRUCTURAL ANALYSIS 111

APPENDIX F – MANUFACTURERS PARTS SPECS 119

APPENDIX G – POWER CALCULATIONS 136

APPENDIX H – FUTABA REMOTE CONTROL INSTRUCTIONS 139

APPENDIX I – BILL OF MATERIALS 143

APPENDIX J – DRAWING PACKAGE 145

1.0 SCOPE

The scope of the BattleBot Senior Design project was designed around the failures of the previous Bot in competition. One problem that will be addressed is the ability of the Bot to self-right, or flip back over if inverted. The existing drive train will also be redesigned for greater durability and higher performance. In addition, the effectiveness of the primary and secondary weapon systems will be increased where necessary. Finally, the weight of the Bot will be minimized such that it will be under the maximum weight with all components installed.

2.0 ACKNOWLEGMENTS

The 2002-2003 BattleBot Senior Design Team would like to thank the following sponsors:

1. Capital Rubber and Industrial Supply for donation of pneumatic system hoses and fittings
   Dan and Brian
   (850) 575-1811

2. Dolphin Art for painting of armor
   Terry Freund
   (727) 525-6056

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   Bill Keller and Larry Smith
   (850) 484-0662

6. Systems Specialist Inc. for large donation of pneumatic parts
   Jim Wells and Bill Wade
   (800) 894-2768

3.0 APPLICABLE DOCUMENTS

The documents listed in paragraphs 3.1 to 3.4 are any documents that pertain to the design, construction or operation of the BattleBot.

3.1 BattleBot Rules

BattleBot_Tech_Regs_v2.2
http://www.battlebots.com/download/BattleBots_Tech_Regs_v2.2.pdf

3.2 Event Procedures

BattleBots Tournament Rules and Procedures
http://www.battlebots.com/download/BattleBots_TR&P_v2.1.pdf

3.3 Judging Rules

BattleBots Judges' Guide

http://www.battlebots.com/download/Judges_Guide_Rev_0.9.pdf

3.4 BattleBot Operations Manual

Operations Manual; BattleBot Senior Design Team; 3/2003

3.5 ANSI Standards

Documents JIS 1801 and JIS 1802

4.0 SCHEDULE

The schedule for the project was created early in the design process and was followed as closely as possible. The complete schedule can be seen in Appendix A. During the first semester, the project was on schedule for almost the entire time. At the beginning of the second semester, the project was ahead of schedule but fell behind due to delays in receiving and selecting parts. The machined parts were finished ahead of schedule but the parts, such as solenoid valves and tanks, were delayed due to longer than expected lead time and funding delays. Much of the assembly and testing occurred in the last few weeks of the project but was completed on time.

5.0 BACKGROUND

The basis for this project was established by the Senior Design Team RAD in the 2001-2002 academic years. This team established the baseline for the current robot design. The final design consisted of a wedge shaped robot with a pneumatic lifting arm on top of the robot, and a spinning drum weapon on the back. The BattleBot designed by Team RAD performed well during testing but failed during the BattleBot competition. The faults consisted of a delicate drive train design and construction and lack of consideration for overall weight. Due to weight problems, the pneumatic lifting arm had to be removed prior to competition rendering it totally useless. This crippled the BattleBot's ability to effectively fight and inflict damage and points on opponents. Also, the poor construction of the drive train caused a drive sprocket to misalign resulting in a broken belt. This immobilized the Bot and resulted in its elimination. The failure analysis of last years design guided the design and construction of this year's Bot and greatly enhanced the reliability and ruggedness of the new design.

6.0 SPECIFICATIONS

6.1 Target Specifications

The needs and demands of the customer were evaluated early in the design process and specifications of the ideal BattleBot were determined. The full needs assessment can be seen in Appendix B. The target specifications express the wishes of the designers for the ideal product. The specifications also, however, have an acceptable tolerance range due to the unpredictable nature of the design and the fact that compromises must be made. The target specifications can be seen in Table 6.1. The specification importance (Imp,) is on a scale of 1 to 5 with 5 being the highest.

Table 6.1 – Target Specifications

	Metric	Imp.	Ideal Value	Acceptable Values	
				+	-
1	High top speed	4	10 mph	3	3
2	Powerful drive train	5	10 hp	2	4
3	Drive system must withstand constant direction and acceleration changes	5	100 cycles	40	20
4	Bearings must last through entire competition without needing replacement	3	10 matches	2	1
5	Must be highly maneuverable	5	turn within 1 length	0	0.5
6	Drive train must function under the weight of another Bot	3	300lbs	10	80
7	Must operate at full power for entire match	5	5 mins	0	2
8	Tires must resist punctures and cuts	4	75% functional at end of match	25	10
9	Tires must have high traction	4	full power from drivetrain w/o slip	0	10%
10	All repairs must be able to be made between matches	4	20 mins	0	5
11	Power systems must be ready for each match	4	20 mins	0	5
12	Entire bot must make weight with all components installed	5	220 lbs	0	10
13	Self righting quickly	3	7 secs	3	2
14	Primary weapon must be able to function under weight of another Bot	4	300lbs	50	80
15	Impact solid immoveable wall repeatedly at full speed and be fully functional	5	15 times	5	2
16	Must survive being tossed through the air	4	3 ft high drop	2	0
17	Armor must resist puncture from repeated blows by sharp object	4	20 times	10	2
18	Armor must protect entire robot	4	6 sides	0	1
19	Armor must resist temporary encounters with saws	3	3 secs, 4 times	2, 5	0

6.2 Final Specifications

The final specifications reflect the actual performance of the design. Wherever possible, the performance was determined by direct measurement on the BattleBot and will be explained in detail in proceeding sections. The final specifications can be seen in Figure 6.2.

Table 6.2 – Final Specifications

	Metric	**Actual Value**
1	High top speed	8 mph
2	Powerful drive train	Two 1 hp
3	Drive system must withstand constant direction and acceleration changes	>100 cycles
4	Bearings must last through entire competition without needing replacement	>10 matches
5	Must be highly maneuverable	turn within own length
6	Drive train must function under the weight of another Bot	Moved with over 220 lbs
7	Must operate at full power for entire match	5 mins
8	Tires must resist punctures and cuts	Tires were observed to have ideal characteristics
9	Tires must have high traction	Drive train did not slip
10	All repairs must be able to be made between matches	Repairs can be effected in 20 mins
11	Power systems must be ready for each match	Multiple sets of batteries enable continuous power for each match
12	Entire bot must make weight with all components installed	205 lbs +/- 5 lbs
13	Self righting quickly	4 secs
14	Primary weapon must be able to function under weight of another Bot	Observed to lift over 220 lbs
15	Impact solid immoveable wall repeatedly at full speed and be fully functional	Passed tests
16	Must survive being tossed through the air	Passed test
17	Armor must resist puncture from repeated blows by sharp object	Armor resisted punctures but had to be replaced after a long time
18	Armor must protect entire robot	Full protection
19	Armor must resist temporary encounters with saws	Could not test easily

7.0 DRIVE TRAIN

7.1 Theory

Chain drives transmit power from one shaft to another through a chain made of links, connected by rollers which are in mesh with teeth on sprockets attached to each shaft. Chain size is denoted by the chain pitch, or the distance between each link as seen in Figure 7.1.

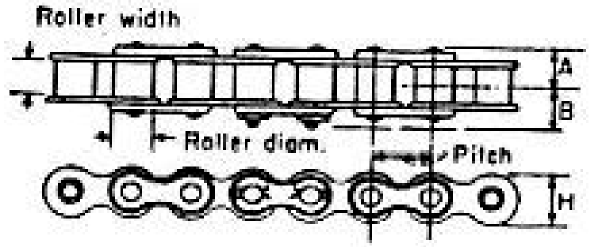


Figure 7.1 – Chain Pitch

The limiting factor on the design of the chain drives is the number of teeth on the small sprocket. This is based on the horsepower being transmitted and the RPM of the small sprocket. The more teeth there are on the small sprocket, the higher the power that can be transmitted. Manufactures of chain drive components have tabulated this data as seen in Table 7.1.

Table 7.1 – Table for Sprocket Sizing Based on Horsepower and RPM

ANSI Pitch No.	**No. Teeth on Small Sprocket**	**Small Sprocket RPM**									
		50	**500**	**1200**	**1800**	**2500**	**3000**	**4000**	**5000**	**6000**	**8000**
25	11	0.03	0.23	0.50	0.73	0.98	1.15	1.38	0.99	0.75	0.49
	15	0.04	0.32	0.70	1.01	1.36	1.61	2.08	1.57	1.20	0.78
	20	0.06	0.44	0.96	1.38	1.86	2.19	2.84	2.42	1.84	1.20
	25	0.07	0.56	1.22	1.76	2.37	2.79	3.61	3.38	2.57	1.67
	30	0.08	0.68	1.49	2.15	2.88	3.40	4.40	4.45	3.38	2.20
	40	0.12	0.92	2.03	2.93	3.93	4.64	6.00	6.85	5.21	3.38
35	11	0.10	0.77	1.70	2.45	3.30	2.94	1.91	1.37	1.04	0.67
	15	0.14	1.08	2.38	3.43	4.61	4.68	3.04	2.17	1.65	1.07
	20	0.19	1.48	3.25	4.68	6.29	7.20	4.68	3.35	2.55	1.65
	25	0.24	1.88	4.13	5.95	8.00	9.43	6.54	4.68	3.56	2.31
	30	0.29	2.29	5.03	7.25	9.74	11.50	8.59	6.15	4.68	3.04
	40	0.39	3.12	6.87	9.89	13.30	15.70	13.20	9.47	7.20	4.68
		Type I		Type II					Type III		

The RPM and horsepower are known, thus the number of teeth on the small sprocket can be read directly from the chart. It can be seen that heavier chains can not run at as high RPMs as smaller chains. Also, as the RPM increases, the power transmitted increases as would be expected. However, as the RPM gets higher, there is a point where the rollers impact the sprocket teeth so hard that the bushings are galled, resulting in a dramatic reduction in power transmitted. Thus, operating at the below this maximum power transmission will lead to the most efficient chain drive with the longest life.

The distance between the shafts is also important. As the distance decreases, the wrap of the chain around the larger sprocket increases while the wrap of the smaller sprocket decreases. Since it is better to have more teeth in mesh with the chain at one time, the center distance should be as great as possible. The recommended distance is 30-50 pitches.

7.2 Design Calculations

An overall gear reduction of between 5:1 and 6:1 was used last year and was satisfactory, so the chain drive was designed with this reduction. It quickly became apparent that a compound reduction would be necessary. With a minimum of 10 teeth recommended on the small sprocket, the large sprocket would have to have at least 50 teeth to accomplish the reduction directly. This meant that for #35 ANSI chain, the large sprocket would have to be approximately 7 inches in diameter. Since the wheels are only five inches in diameter, this would mean that the sprocket would stick out of the bottom of the robot and hit the ground. Thus, a compound reduction was necessary to keep the size of the large sprocket on the wheel shaft to a minimum.

The chain and sprockets for the drive train needed to be as light as possible while retaining high strength. In addition, the space constraints meant that the diameter of the sprockets could not be much larger than 3 inches. The power to be transmitted was approximately 1 horsepower.

7.3 Sprocket Size Calculations

After deciding on steel chain, the size was determined by examining the horsepower capacity as well as the size. As the size of the chain increased, the diameter of the sprockets did also. In addition, as the size increased, the maximum RPM decreased. The sizes near the operating range were #25, #35, and #40 ANSI chain. Using the information seen in Table 7.2, #35 ANSI chain was chosen because it gave plenty of strength, could operate at the high RPM at the motor, but was small enough that the sprockets would fit into the BattleBot.

Table 7.2 – Sprocket Sizing Table with Approximate Operating Ranges of Drive Train Highlighted

ANSI Pitch No.	**No. Teeth on Small Sprocket**	**Small Sprocket RPM**									
		50	**500**	**1200**	**1800**	**2500**	**3000**	**4000**	**5000**	**6000**	**8000**
25	11	0.03	0.23	0.50	0.73	0.98	1.15	1.38	0.99	0.75	0.49
	15	0.04	0.32	0.70	1.01	1.36	1.61	2.08	1.57	1.20	0.78
	20	0.06	0.44	0.96	1.38	1.86	2.19	2.84	2.42	1.84	1.20
	25	0.07	0.56	1.22	1.76	2.37	2.79	3.61	3.38	2.57	1.67
	30	0.08	0.68	1.49	2.15	2.88	3.40	4.40	4.45	3.38	2.20
	40	0.12	0.92	2.03	2.93	3.93	4.64	6.00	6.85	5.21	3.38
35	11	0.10	0.77	1.70	2.45	3.30	2.94	1.91	1.37	1.04	0.67
	15	0.14	1.08	2.38	3.43	4.61	4.68	3.04	2.17	1.65	1.07
	20	0.19	1.48	3.25	4.68	6.29	7.20	4.68	3.35	2.55	1.65
	25	0.24	1.88	4.13	5.95	8.00	9.43	6.54	4.68	3.56	2.31
	30	0.29	2.29	5.03	7.25	9.74	11.50	8.59	6.15	4.68	3.04
	40	0.39	3.12	6.87	9.89	13.30	15.70	13.20	9.47	7.20	4.68
		Type I		Type II					Type III		

Once the #35 chain was chosen, the next step was to size the sprockets. Since a compound train was to be used, the size of the sprockets, as well as the individual reductions of each train could be manipulated. The overall reduction was calculated using Equation 8.1 where $N_1 - N_4$ are the number of teeth on each sprocket and M_1 and M_2 are the reduction ratios.

$$M_{total} = (M_1)(M_2) = \frac{N_2}{N_1}\frac{N_4}{N_3} \tag{8.1}$$

The gear locations are shown in Figure 7.2.

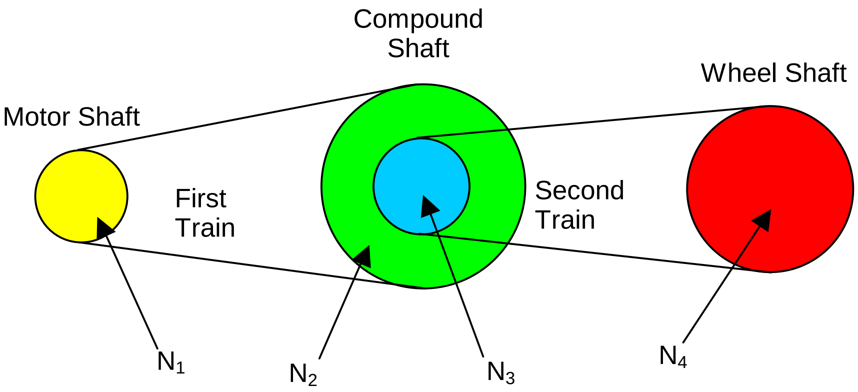


Figure 7.2 – Compound Gear Train

Using MathCad, many combinations of gear ratios and numbers of teeth were explored. From the geometry of the BattleBot, it was determined that the wheel sprocket could not be larger than 21 teeth. If it was any larger, it would hit the bottom of the body. This helped to reduce the number of variables in the problem. After many iterations, it was determined that the more even the reduction ratios were between the two trains, the better the overall design. This was due to the fact that as the first ratio was increased, the RPM of the second train's small sprocket was reduced, resulting in less power capacity as seen in Table 7.2. These calculations can be found in Appendix C.

After many iterations, the sprockets were finally sized and it was determined that they would fit into the BattleBot. The sizes are shown in Table 7.3.

Table 7.3 – Sprocket Sizes

Sprocket Number	Number of Teeth	OD (in)
1	10	1.38
2	25	3.19
3	10	1.38
4	21	2.71

The factors of safety for each train were also calculated. Since the weakest part of the drive train was the small sprocket, the factor of safety of each train was based on that part. Using Table 7.2, the factor of safety was calculated using Equation 7.2 where n was the factor of safety.

$$n = \frac{load_{capacity}}{load_{applied}} \qquad (7.2)$$

The load capacity was obtained from Table 7.2 and the load applied was equal to the horsepower of the motor, or 1 hp. The factor of safety for Train 1 was 2.5, and was 1.7 for Train 2. These calculations can be seen in Appendix C.

Sprockets 1 and 3 were made the same size to reduce the number of different parts required. The overall ratio, calculated using Equation 7.1, was found to be 5.25:1 which was within the tolerance.

Next, the length of chain needed to be calculated. This was done using Equation 7.3 where L is the length of chain in pitches, C is the center distance in pitches, N_1 is the number of teeth on the small sprocket, and N_2 is the number of teeth on the large sprocket.

$$L = 2C + \frac{N_2 + N_1}{2} + \frac{(N_2 - N_1)^2}{4\pi^2 C} \qquad (7.3)$$

The length of chain between the motor and compound shafts was found to be 23.25 inches, between the compound and front wheel shafts was 16.5 inches and between the front and rear wheel shafts was 27.375 inches. These detailed calculations can be found in Appendix C.

7.4 Shaft Fabrication

Each was cut to approximate size from one long piece of stock on a band saw. Then on a lathe they were machined to the right length and the slots for the retainer clips were cut out. The accuracy in the distance between the slots was monitored with a digital readout. The stock that was given was stainless steel that was not grounded and polished, so it was not perfectly round. This meant that each shaft had to be turned down and polished so that the sprockets and bearing would fit correctly. These shafts also included keyways to ensure that slippage of the sprockets would be avoided. The keyways were machined on a mill. The keys were trimmed down to size with a die grinder.

7.5 Sprocket Fabrication

Most of the sprockets were ready to install right from the box. There were a couple of them that needed some work. The two small ones that fit directly on the motor had to be bored out to 12 mm so it could fit on the motor shaft. These also needed to be drilled and tapped for the placement of set screws. This was done on a conventional mill. Finally, a reamer was passed through each sprocket to ensure the preciseness of their holes.

7.6 Bearing Block Fabrication

Bearing blocks for the ends of the shafts were all cut out of flat 1/2 inch stock. Each block was precisely machined on a conventional mill. To get a good press fit for the bearings the accuracy of the hole was very important. Too small of a hole then the fit would be too tight and the bearing would not last. Too big and it would fall right out. The ideal size of the hole for a press fit is about 1/2 a thousands smaller then the outer diameter of the bearing. To get close to this a CNC (Computer Numeric Controlled) mill was used as seen in Figure 7.3. With the aid of a computer program, the bearing block was drawn and the path of the end mill was created. With the use of the CNC, the hole came out to just right for a good press fit of the bearings.

Figure 7.3 – CNC Mill

7.7 Assembly

The assembly of the drive train proceeded as expected as expected with no unforeseen problems. Great time and care was taken to ensure that the shafts fit perfectly and easily into the bearings and sprockets. The shafts were polished on the lathe until the sprockets and shafts could be easily assembled by hand. The details of assembly can be seen in the Operations Manual for the BattleBot. The assembled drive train can be seen in Figure 7.4.

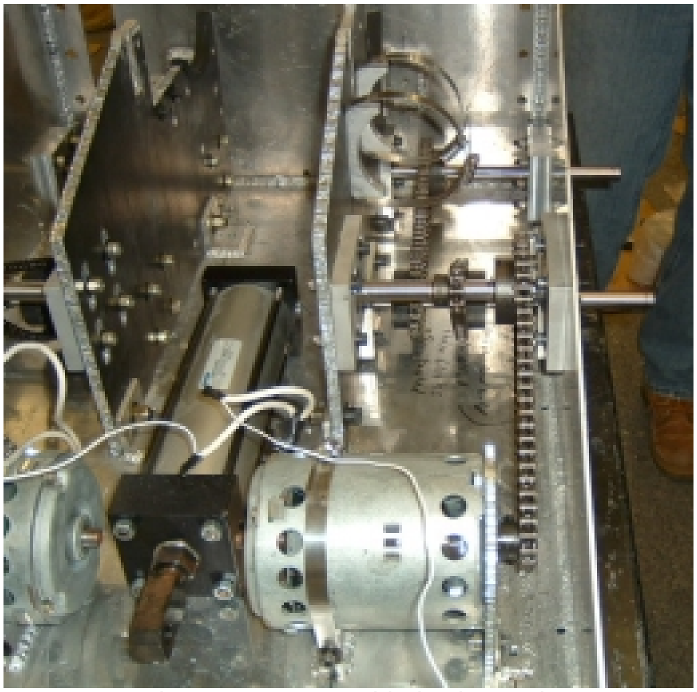


Figure 7.4 – Assembled Drive Train

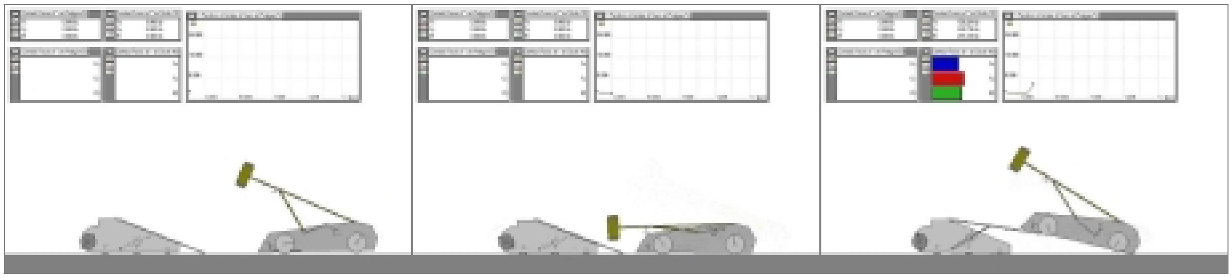
7.8 Testing

The drive train, as seen in Figure was tested by running the BattleBot around the parking lot. After fixing some electrical problems, the drive train performed exactly as designed with no unexpected problems. The drive train proved to be extremely durable and resilient and could not be damaged or broken even under extreme wear.

8.0 PRIMARY WEAPON/SELF RIGHTING MECHANISM

8.1 Capabilities

The BattleBot is equipped with a dual purpose flipping mechanism. Along with being the primary weapon system, the flipping mechanism is capable of setting the BattleBot right side up should it be overturned. When the BattleBot is positioned properly, the device will be activated manually to flip over the competitor. This flipping action is intended to inflict damage on the opponent during the flipping motion and when the opponent hits the arena floor. This will exert strong jerk forces on the opponent that are expected to break internal and external components. Figure 8.1 shows the proposed primary weapon flipping maneuver.



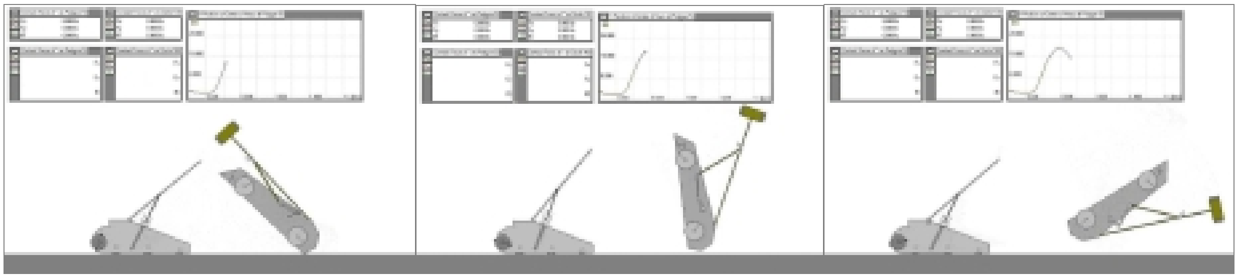


Figure 8.1 – Primary Weapon Flipping Maneuver

The lifting arm part of the flipping mechanism rotates through a range of 71 degrees and exerts a maximum normal static force of 323 lbf at initial rotation. At the end of the extension, the perpendicular force is 147 lbf. In the heavyweight division, the maximum weight of a BattleBot is 220 lb. According to Newton's second law of motion, the lifting arm is capable of accelerating a 220 lb object greater than 14 ft/s^2. Material selection analysis has ensured that the steel c-channel arm will not fail under full load. The details of these calculations and material selection process can be seen in Appendix D.

8.2 System Design

Concept generation and selection set the basic design plan for the flipping mechanism. Based on the selection criteria the flipping mechanism arrangement was chosen for its simplicity, dual functionality and effectiveness. It consists of a long beam-arm, a pneumatic actuator, pin joints and brackets. One end of the beam-arm is attached to the top-front of the BattleBot and rotates about the attachment. The pneumatic actuator connected to the beam-arm forms a four-bar linkage in the form of an inverted slider crank.

Parameters used to develop the system are a minimum lifting force of 300lb, self-righting capability and overall BattleBot dimensions and weight. Determining the forces required to satisfy the design parameters was initially through dynamics general plane motion. Engineering mechanics dynamics principal of work and energy was the proposed method of calculation. This method was found to be more complicated than anticipated. System boundary conditions known to be factual were the BattleBot weight, center of mass, and exterior geometry. Additional boundary conditions were needed in order to use the principal of work and energy. For example, the radius of gyration in conjunction with the coupled forces is needed to determine the rotational kinetic energy. Without the internal configuration of the interior components, the radius of gyration could only be approximated. Another complication is the fact that the force exerted at the edge of the lifting arm is variable throughout the range of motion. It was concluded that additional simplification of the system would yield inaccurate results, thus another method of determining system forces was necessary.

Self-righting capability of the flipping mechanism was analyzed using the Working Model simulation program. Weight, geometry, and approximated forces were included in the program to generate accurate simulations. The body of the BattleBot was created as a polygon object with actual dimensions and approximate weight. Placement of the four-bar linkage lifting arm system was assigned arbitrarily but still following the general guidelines of the proposed design. What ultimately enabled the system to work was found to be a combination of pneumatic actuator force and lifting arm range of motion. After achieving consistent results, with slight parameter modifications due to iteration, it was determined that the pneumatic piston would need to exert about 1300 lbf. A sequence of frames from the simulation is shown in Figure 8.2.

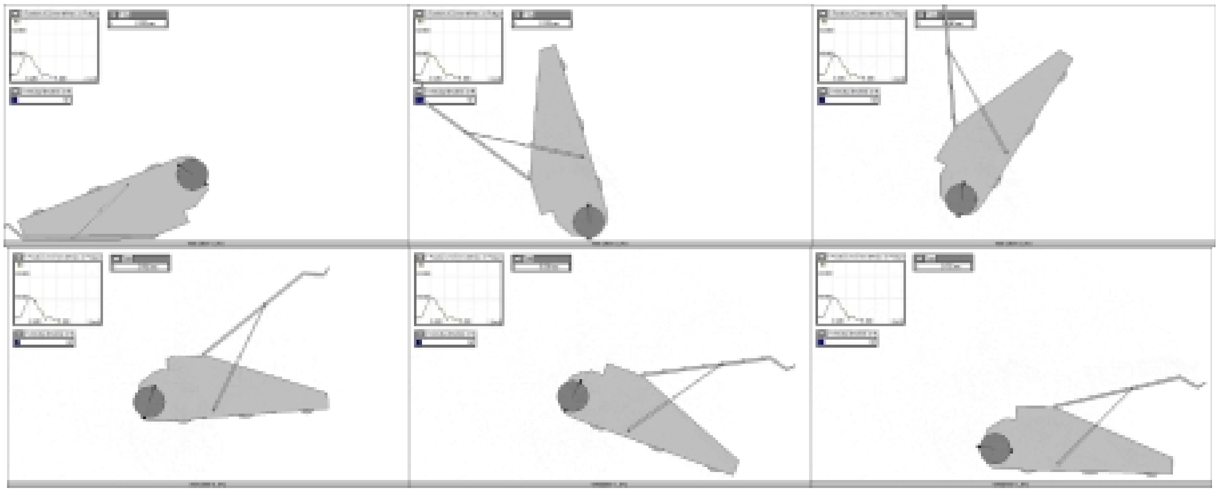


Figure 8.2 – Working Model Simulation, Self-Righting Maneuver

Calculating linkage dimensions, placement, forces and stresses became systematic after the Working Model simulation results were obtained. According to the BattleBots official rules and guidelines, 250 psi is the maximum pneumatic piston operating pressure allowed in competition. A 2-1/2" bore pneumatic piston operating at 250 psi gives 1227 lbf which is about how much force is needed. The pneumatic piston is attached with a pin joint to the lifting arm near its center to reduce bending moment forces on the arm. The dimensions and placement of the linkage components, including the piston stroke length, are mostly constrained by the BattleBot's shell geometry. MathCAD was used to compile a series of mathematical expressions that calculates the linkage range of motion and forces which can be seen in Appendix D. Through iteration, the variables describing piston stroke length and linkage attachment points were determined. After the desired variables were isolated the system became a function of the piston base mount placement. Coincidentally, the best placement of the mount was found to be directly beneath the lifting arm pivot point. The final linkage system design resembles the Working Model simulation combining extended lifting arm range of motion and available forces

Since the lifting arm will be exposed in battle and subject to weapon damage and large forces from the pneumatic piston, detailed material selection was necessary. Along with maximizing strength and durability, minimizing system weight is of major importance. This was done with an objective function, constraint function and material index. Minimizing weight required the use of an objective function describing weight. The constraint function applied is for a lifting arm that does not fail under bending. "A material index is a combination of material properties which characterizes the performance of a material in a given application". A material index is composed of three things that describe the design of a structural element. Functional requirements, geometric parameters and material properties are the three groups that are said to be separable. The material properties function of the material index was isolated and used to find the appropriate materials on a strength-density chart. Properties of several selected materials were used separately in the material index formula. The material with the largest material index number optimizes the strength to weight ratio. Aluminum wrought alloy 6061-T6 produced the largest material index number, however, structural steel A36 was selected despite the fact that it only yielded the second highest index number. The material selection method used does not take into account all design factors and engineering judgment was required. While aluminum has a strength-to-weight ratio advantage, the material is relatively soft and is not suited for opponent contact in battle. Increased weight was compensated for by selecting a c-channel cross sectional shape for the steel lifting arm.

8.3 Flipping Mechanism Components

The flipping mechanism is a steel c-channel beam-arm powered by a pneumatic piston as shown in Figure 8.3.

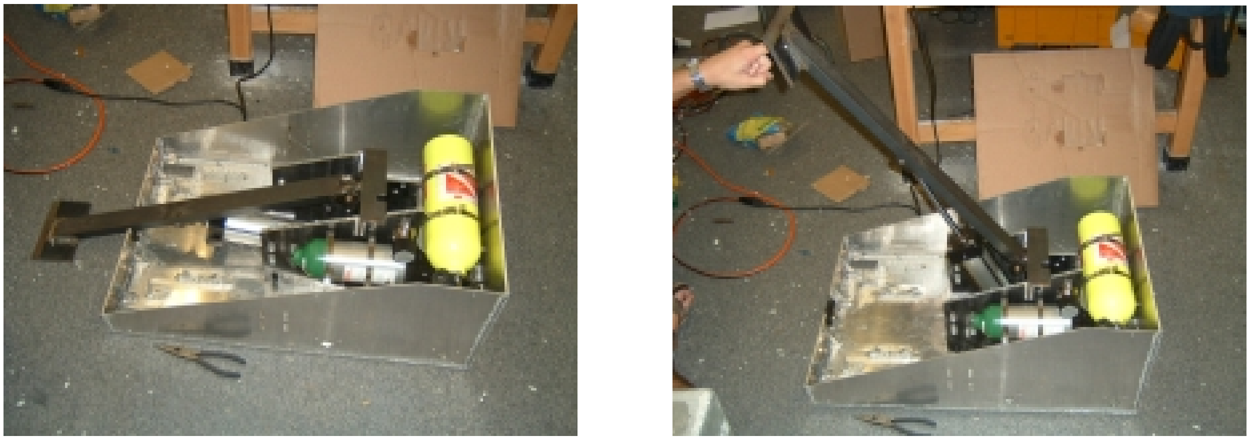


Figure 8.3 – Flipping Mechanism System

A 7-1/2" long steel L-angle saddle rests on aluminum inserts and is fixed to the carbon fiber bulkheads with bolts. The saddle support system is shown in Figure 8.4.

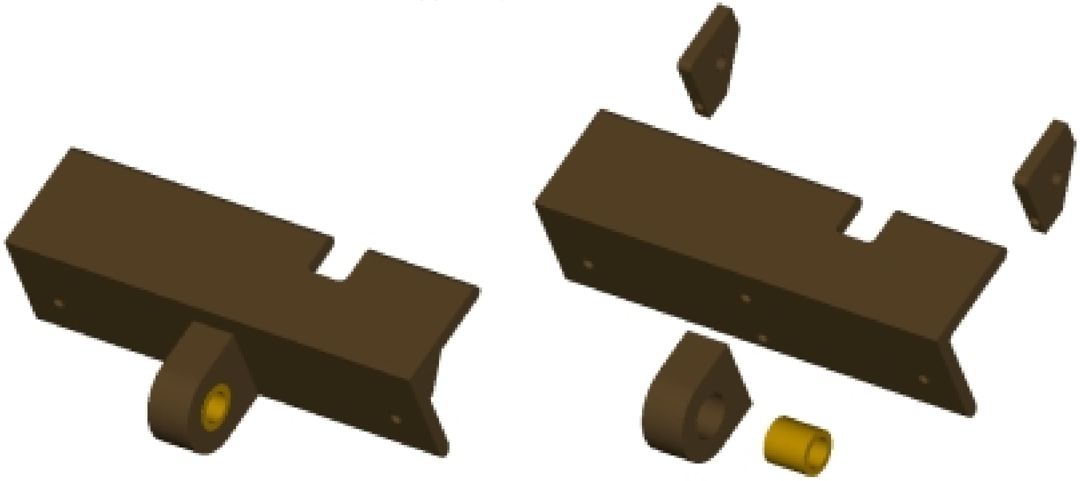


Figure 8.4 – Saddle Support

The end of the lifting arm is clevis mounted to the lifting arm eye bracket, which is welded to the side of the saddle. This joint is what the arm rotates about. Figure 8.5 shows the beam-arm clevis pin joint.

Figure 8.5 – Lifting Arm End Clevis Joint

A 7”x4”x3/8” metal flat flipper plate is welded to the other end of the lifting arm. In competition, the flipper plate extension will enhance the possibility of the primary weapon making contact with the opponent. Figure 8.6 shows the flipper plate connected to the lifting arm.

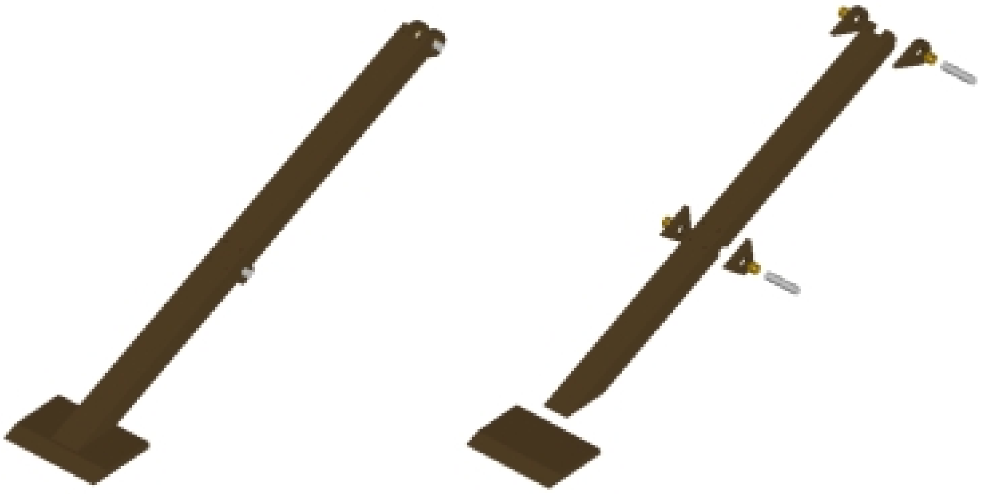


Figure 8.6 – Flipper Plate

An NFPA rod-eye, screwed on the end of the piston shaft, connects to the clevis bracket arrangement on the underside of the lifting arm near its center. A diagram of the rod-eye is shown in Figure 8.7.

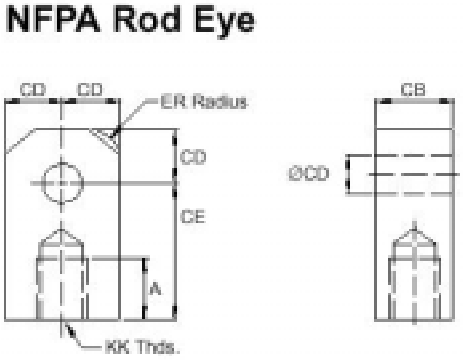


Figure 8.7 – NFPA Rod Eye

Figure 8 shows the middle clevis pin joint with NFPA rod-eye.

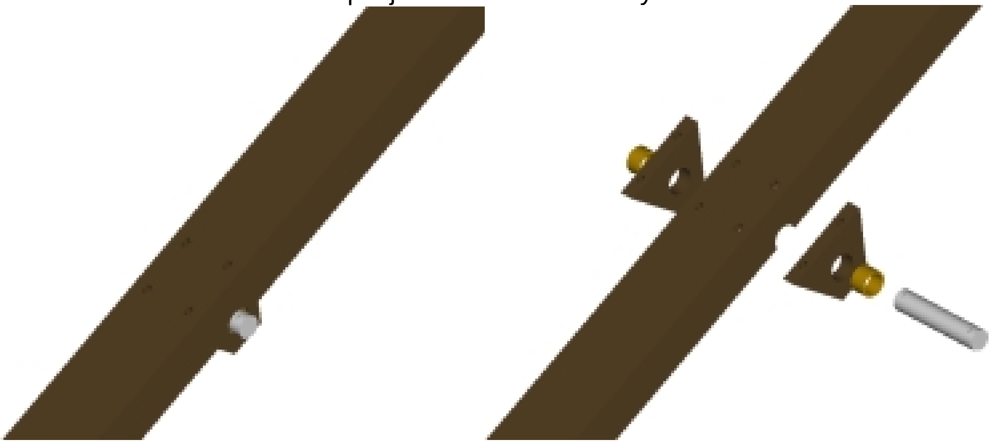


Figure 8.8 – Lifting Arm Middle Cleivs Pin Joint

The pneumatic piston selected to be the lifting arm actuator is a VICKERS Series VP tie-rod cylinder. This type of piston was chosen for two reasons. Tie rod cylinders are structurally stable. This is definitely important in this type of application, where it will be partially exposed in battle. Should the piston shaft require lubrication, the cylinder can easily be dismantled. The only drawback to this type of piston is its added head and cap weight, as opposed to a disposable closed frame piston. The custom made VP10EKCA1AN0800, 2-1/2" bore, 8" stroke, pneumatic piston operates with compressed nitrogen gas. Details of the pneumatic system are covered in the pneumatic system section of this report. Since the piston shaft fully extends during operation, an air cushion system is included as specified in the model code. The air cushion prevents damage to the internal cylinder piston and seal when the shaft extends to full range. The piston is shown diagrammatically below in Figure 8.9.

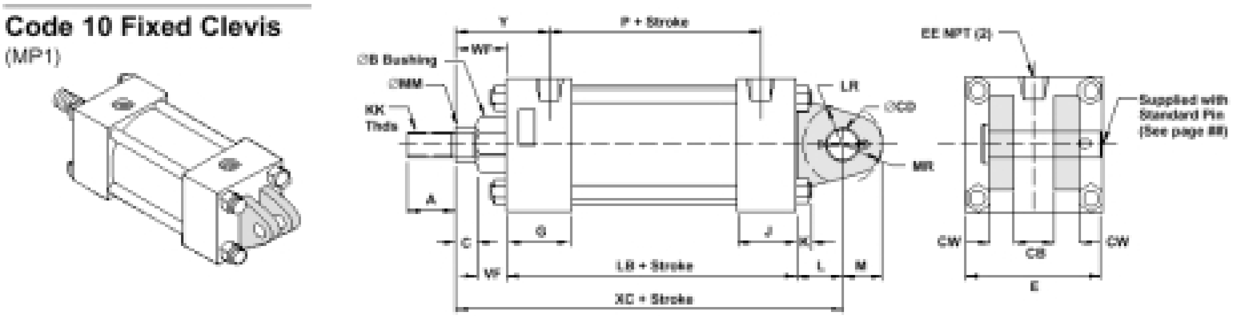


Figure 8.9 – Vickers Tie-Rod Cylinder

The last major component of the flipping mechanism is the cylinder cap bracket. It is a fabricated aluminum part so it could be welded to the aluminum base of the BattleBot's shell. The cap bracket is shown in Figure 8.10.

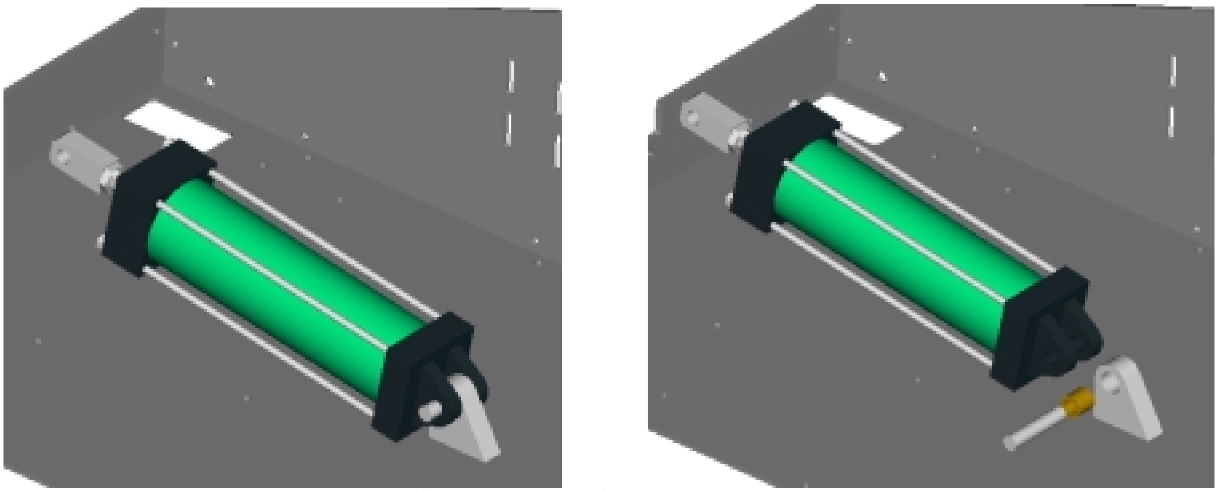


Figure 8.10 – Cylinder Cap Bracket

8.4 Fabrication

To make the saddle a piece of angle iron was used. This is heavier that aluminum but the strength was needed to support the force of the primary weapon. The point where the arm is attached was cut and then grounded to have a nice round edge. The hole was lined with a brass bushing made on the lathe. Then the whole fixture was welded to the angel iron. Small little iron triangles were welded to the inside to the angle. These are the points used to fasten the saddle to the bulk head.

The arm is made out of a long piece of c-channel. The connection points where that arm is attaches to the saddle and the piston were cut and grounded to make them round. Then they were welded on. At the tip of the arm a metal plate with a sharp edge milled out was welded on.

8.5 Assembly/Testing

Assembly of the flipping mechanism was a simple process. A single part-fit-check was conducted without problems. After mounting the saddle and cap bracket, the linkage was put together with steel pins and secured with cotter pins. Clearance between the bottom of the flipper plate and the floor is approximately 1/4”, a result of precise part fabrication. Manually rotating the linkage through its entire range of motion was done easily without binding.

Only a few modifications to the flipping mechanism were made from the initial design. Originally, an NFPA eye bracket was to be used to mount the cap of the cylinder to the base of the BattleBot. Instead of spending thirty-five dollars, a fabricated base mount was made from scrap aluminum. Another modification was the incorporation of brass bushings. These were fabricated and installed in the clevis pin joints for a means of solid lubrication. An important material property of brass is, when polished, it has a low coefficient of friction. Friction in the linkage joints causes the system to operate slower and resists forces that could otherwise be transmitted to the flipper plate. One other adjustment made was the method of attaching the saddle to the bulkheads. Carbon fiber composite bulkheads are lightweight and strong but require inserts that prevent shearing. Aluminum inserts, supporting the saddle and saddle bolts, were fastened to the bulkheads with epoxy finalizing the design of the saddle.

The engineering design team is confident the flipping mechanism will be an effective weapon in combat. The linkage moves smoothly without binding and its clevis pin joints and saddle mounting system make it structurally stable. Since the lifting arm is made from steel A36 it will effectively resist damage from saws and impact weaponry. Offensively, the flipping mechanism will be invaluable. Once the opponent is overturned and possibly damaged from colliding into the arena floor, the secondary weapon system can be used to perpetuate destruction. Should the BattleBot become overturned, unlike some competitors, it has the capability to self-right thanks to the dual purpose flipping mechanism.

9.0 PNEUMATICS SYSTEM

9.1 Concept Design

To power the pneumatic cylinder for the Primary Weapon System, an adequate pneumatics setup must be chosen. To power a pneumatic cylinder on a mobile and ungrounded system, a remote fluid reservoir is required. The fluid reservoir takes its shape as a containment tank connected to the pneumatic cylinder. From the reservoir to the cylinder, the fluid must be conditioned and controlled to provide proper cylinder operation.

BattleBot technical Regulation 8.2.1 restricts the allowable gas types used on a BattleBot to either Nitrogen (N_2), Carbon Dioxide (CO_2), or both. The maximum allowable storage pressures for the gas types are: 2500 psi for nitrogen and 1000 psi for carbon dioxide (Tech. Reg. 8.2.2). Nitrogen was chosen as the working fluid in the pneumatics system. By using nitrogen, some of the 2001-2002 BattleBot Team pneumatics system components could be reused. The working fluid for the previous setup was air, and being that N2 is an inert gas with no corrosive properties, the same reservoir tank could be used. Under the given storage conditions more N_2 can be stored on the BattleBot than CO_2, and with a limitation of 250-psi actuation pressure (BattleBot Technical Regulation 8.2.6) a higher amount of cylinder firings can be made per match.

9.2 Preliminary Design

To maximize the amount of nitrogen storable in a minimal volume, the highest allowable storage pressure of 2500 psi was chosen with use of the existing Luxfer Cylinders reservoir tank. With a reservoir pressure of 2500 psi and a cylinder operating pressure of 250 psi, a regulator must be used to step down the N_2 pressure. Once the operating pressure is established, the flow must be controlled to the double acting pneumatic cylinder. The flow control can be performed by way of a valve.

There are two main types of valves that can be remotely operated to control flow in a pneumatic circuit, solenoid actuated valves and pilot actuated valves. A solenoid-actuated valve was chosen for the pneumatics setup for simplicity. A pilot actuated valve, in our case, would require the use of two extra solenoid valves to control it thereby further complicating the system, adding weight, and requiring further integration. A 4-way 2-position solenoid actuated valve is required to operate the double acting pneumatic cylinder that was chosen to allow exhaust gas to be vented from one end of the cylinder, while the other end is being energized, Figure 9.1.

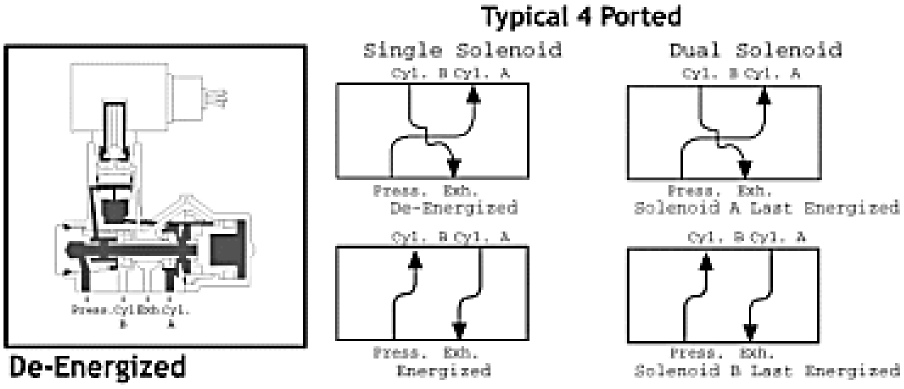


Figure 9.1 - 4 Way Valve Diagram

The 4-way 2-position solenoid actuated valve chosen was ASCO Piston/Poppet Single Solenoid Valve #8344G1. The valve was chosen for its sturdy solid construction and market availability.

A fault of the previous BattleBot design was the slow energizing of the pneumatic cylinder. A lack of pressure in the system and lag time from the regulator was believed to be at fault. To remedy this situation, a buffer tank was introduced into the pneumatic circuit to ensure that the circuit is always pressurized to the operating pressure of 250 psi and an ample volume of N_2 available. A tank, smaller than the reservoir, was placed inline with the reservoir and valve to ensure the 250-psi operating pressure was maintained. The tank chosen, for compatibility with the reservoir tank on hand produced by Luxfer Cylinders, was Luxfer Cylinders M004. A layout diagram of the entire pneumatic circuit can be seen in Figure 9.2.

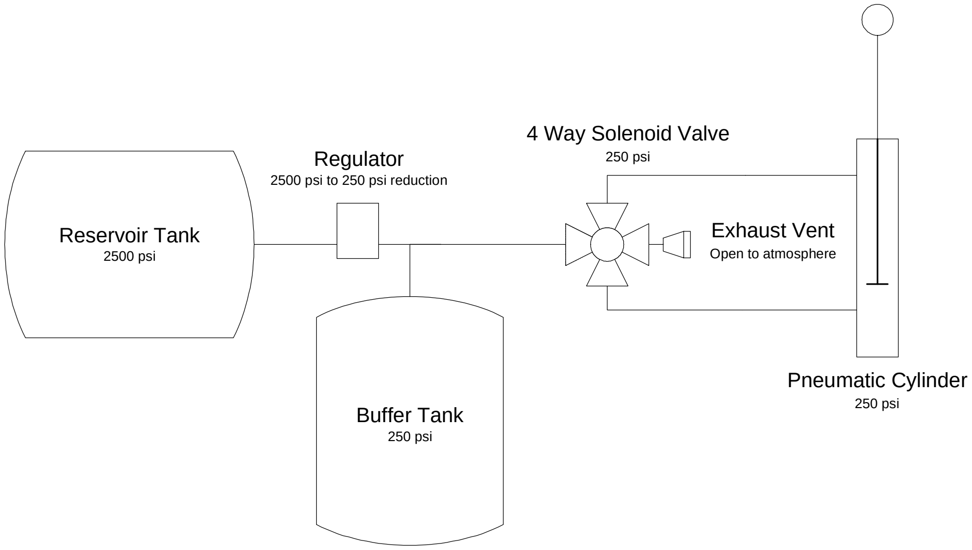


Figure 9.2 – Pneumatics System 4-way Valve Setup

9.3 Revised Design

In working with pneumatics and hydraulic part supply companies, many, in particularly ASCO, reported having the necessary valves available but where unable to supply. Due to the high operating pressure of 250 psi on a pneumatic system, a 4-way valve could not be found off the shelf. Suppliers that were able to "custom make" valves to operate at such a pressure would require a 3-6 month waiting period for production. As a solution, multiple 2-way valves were placed into the pneumatics setup to create the function of a single 4-way valve.

To create the function of a 4-way valve using only 2-way valves, four 2-way valves would be needed. The pneumatic cylinder has two ports, one for actuation in extension and the other for retraction. A 4-way valve would allow for an input from the nitrogen gas supply, an output for each of the two ports of the pneumatic cylinder, and an output for exhausting gas. With these 4 openings, you can achieve the effect of pressurizing one end of the cylinder while exhausting the other. Using only 2-way valves, you need to place 2 valves on each line running to the cylinder ports. The first (inlet) valve of each line would allow air to travel into that branch of the pneumatic setup and the second valve would be in parallel to the cylinder port, allowing for exhaust, as shown in Figure 9.3.

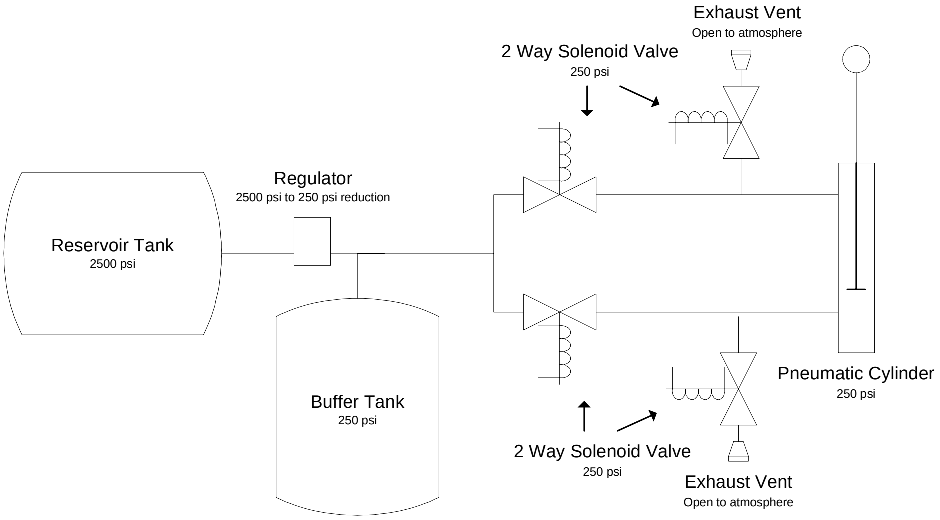


Figure 9.3 – Pneumatics setup using four 2-way valves

To operate the 2-way valve setup, the inlet valve on the first cylinder port branch would open, while the exhaust valve remains closed, while the inlet valve on the second cylinder port branch would be closed, with its exhaust valve open. Using the 4 2-way valves, two valves, an inlet and an opposing exhaust, would always remain open; the combination of the two keeping the arm either extended or retracted.

9.4 Testing

After placing the arm assembly and pneumatic components in the robot chassis, it was observed that the overwhelming weight of the steel arm caused the cylinder to quickly retract when Port A was allowed to exhaust. Since the cylinder could passively retract, the two valves on the Port-A branch of the pneumatics setup were eliminated and the port was simply left to exhaust directly to the atmosphere, Figure x.4. The removal of those two 2-way valves not only simplified the pneumatics setup, but the controls setup as well. No longer was it necessary to run wiring for 2 extra valves or draw the current from the battery. The elimination of the two valves also reduced weight and conserved space within the BattleBot.

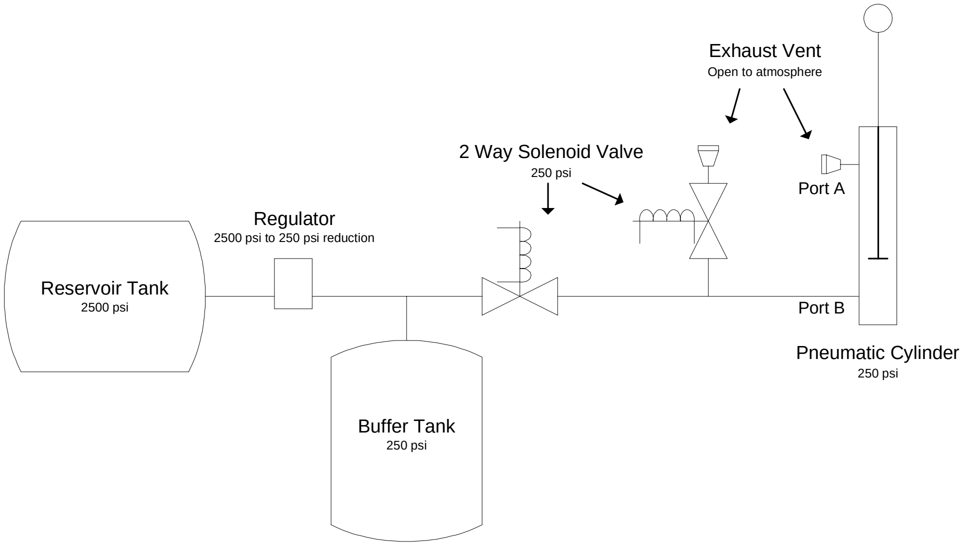


Figure 9.4 – Pneumatic Setup Using Two 2-way Valves

9.5 Final Design

The final setup of the pneumatics system begins with the Luxfer Cylinders SCUBA Tank S13S used as the nitrogen gas reservoir, pressurized at 2500 psi. Two 2- way 24V solenoid valve from Parker and gauges from Capital Rubber are placed in series with the valve opening and have a 3/8 NPT hose leading out. The 3/8 NPT line goes to a Tescom regulator, Model BB-1, which reduces the nitrogen gas pressure from 2500 psi to 250 psi. A 3/8 NPT line leads out from the regulator to a 3/8 NPT T-junction which places a buffer tank, Luxfer Cylinders Medical Cylinder M004, in parallel with the remainder of the pneumatic circuit. The second outlet of the T-Junction leads to the first branch of the pneumatic cylinder on Port B. Between the T-Junction and Port B of the cylinder are two 2-way valves. The first 2-way valve is placed in line with the branch and allows the control of nitrogen to that branch. The second 2-way valve is placed on a T-Junction in parallel to the cylinder port and is used to exhaust gas on the return stroke of the cylinder. The remaining cylinder port, Port B is left open to the atmosphere to vent exhaust gas. Pictures of the pneumatic system can be seen in Figure 9.5.

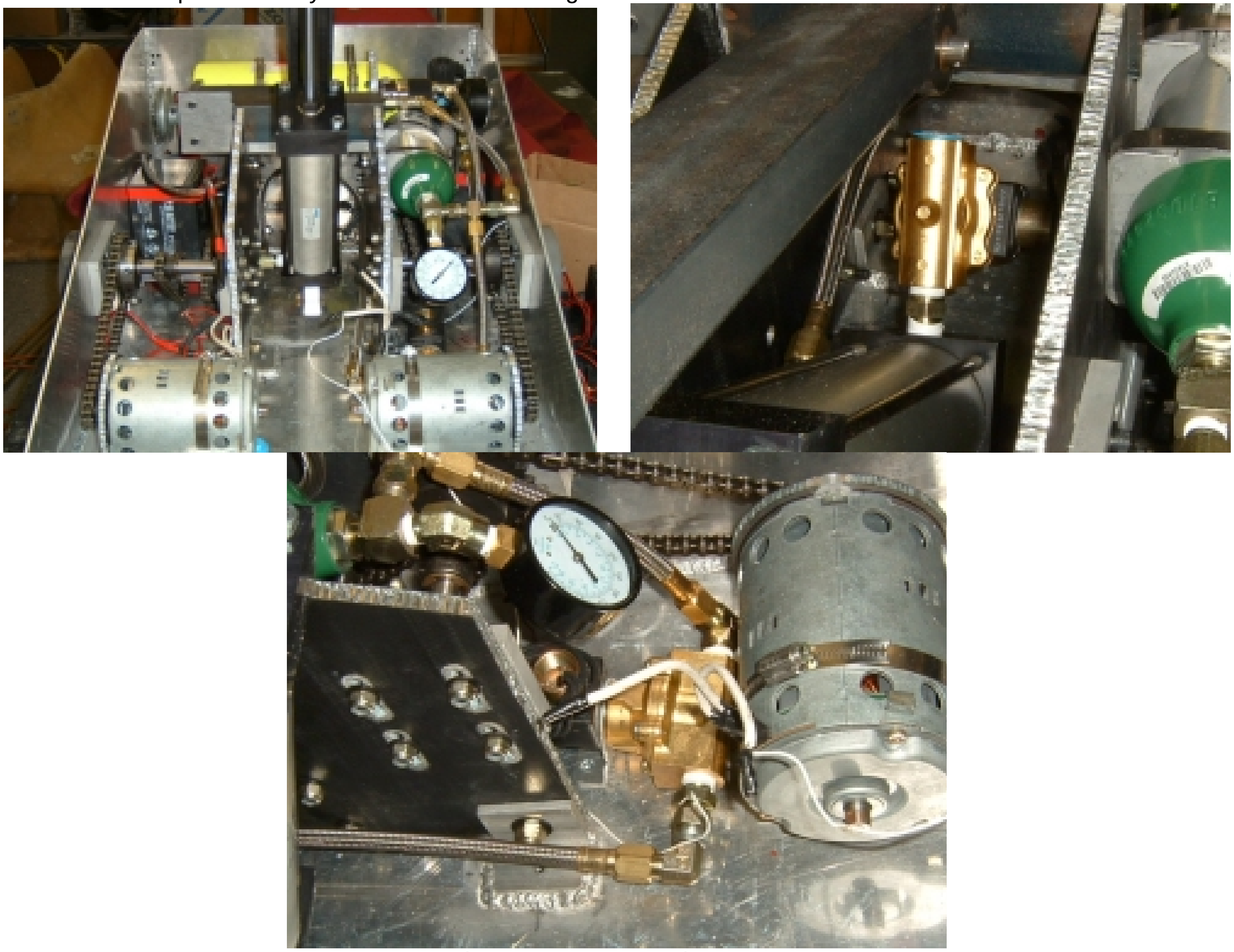


Figure 9.5 – Pneumatic System

10.0 SECONDARY WEAPON

The existing Secondary Weapon System consists of a 25-inch rotating steel drum armed with two horizontal edges mounted on the rear of the robot. The rotating drum is designed to inflict damage on opponents much like a saw. The drum is mounted on two large Aluminum (6061) brackets and is driven 1/3-hp 24-V Dayton Motor (4200rpm) on slipping V-Belt as seen in Figure 10.1.

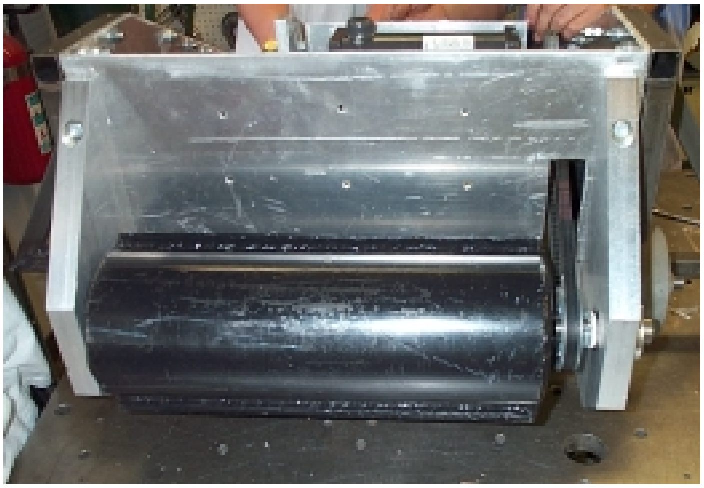


Figure 10.1 – Secondary Weapon System

The design of the existing Secondary Weapon System was determined to be very effective on the previous BattleBot and primarily remains the same. The only aspects of the Secondary Weapon System that have been reworked are the mounts for the drum motor and the drum itself. The mounts for the motor were reworked to slightly reposition the motor within the robot assembly. The mounts for the rotating drum were redesigned to optimize the strength to weight ratio and is discussed in detail in Section 11.1 below.

The construction of the mounting blocks was completed using sophisticated computerized milling equipment. Because of the amount of material that was to be cut and the shape it had to be cut with, it was decided that the best way to do it was on the CNC mill. This would lead to cutting out exactly the desired amount of material and in the same shape with each side of the two brackets. Instead of writing a program on the CNC, a file from the CAD software Pro-Engineering was transferred to other software that can come up with the NC code that the CNC can use. Once this was achieved the computer was linked to the CNC directly to input the data. Then all there was to do was to fasten the part to the CNC table and let the machine work. When it finished one side the part would then just be flipped over and the machine would cut the same pattern on the opposite side. The same thing was done on the other part. That is what was great about having access to a CNC mill, it can cut out complex shapes as well as repeat the pattern as much as desired.

11.0 STRUCTURAL ANALYSIS

11.1 Drum Bearing Bracket

One of the main problems of last year was that the Bot was overweight. So weight reduction became a very important aspect of the design. The drum bearing blocks and the interior bulkheads were one of the main focus points for the weight reduction. With the aid of Pro-Engineering CAD software and ALGOR FEM package these parts were modeled and analyzed. Then different designs and materials were implemented and the results were compared.
With the drum bearing blocks material was cut from the bulky brackets to make them lighter without loosing their rigidity. The final selection is shown in Figure 11.1. Even though this one had

the biggest displacement it was still extremely small and having the extra weight off was worth it. The details of the structural analysis can be seen in Appendix E.

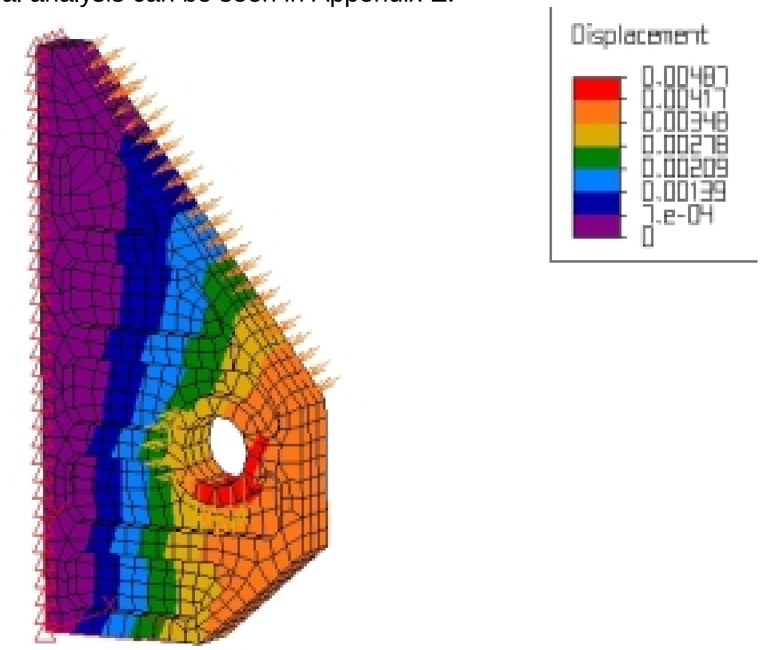


Figure 11.1: Final Drum Bearing Block Design

11.2 Bulkhead

For the bulkhead the decision was to leave the design the way it was because all the mounting points for different components were needed plus the flipping arm will attach to them. No strength could be sacrificed, so instead their material was looked into. Instead of Aluminum Alloy that has a tensile strength of 33ksi a high modulus carbon fiber with a tensile strength of 110 ksi was chosen. Because of the strength difference a smaller thickness was used from .5” to .375”. Here is where a big chunk of weight was reduced. With the aluminum the two bulkheads weighed a combined 16.757 pounds, with the carbon fiber the weight dramatically reduces to approximately 1 pound. This was due to the differences in density (aluminum alloy 6061 .0975 lb/in^3). The carbon fiber bulkheads had an aluminum honeycomb core which greatly increases the strength for a given weight. Bulkheads can be seen in Figure 11.2.

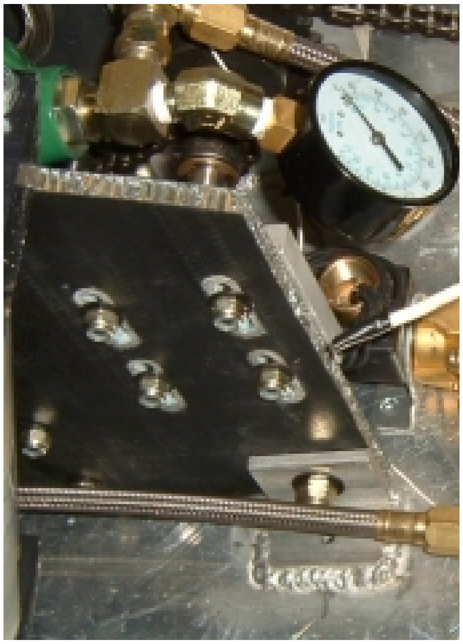


Figure 11.2 – Carbon Fiber Bulkheads

11.3 Body

After analyzing the body of the Bot, it was determined that the sides and bottom of the body could be made from a thinner material. This decision was made to make the panels out of 5/32 plate, instead of 1/4", because the armor struts that bolt onto the sides of the body give it strength. The panels themselves do not need to be as strong because the armor struts act like a frame. After analyzing the model in Pro/E, it was determined that a weight savings of 10.5 pounds would be realized from this modification.

12.0 3-D DESIGN AND DRAFTING

Many details of the BattleBot design had to go beyond pure calculations. Many issues, such as availability of parts, packaging, and weight all had large impacts on this design. 3-D modeling in Pro/E was invaluable in solving these problems. The entire BattleBot was created in the computer, down to the last detail, as seen in Figure 12.1.

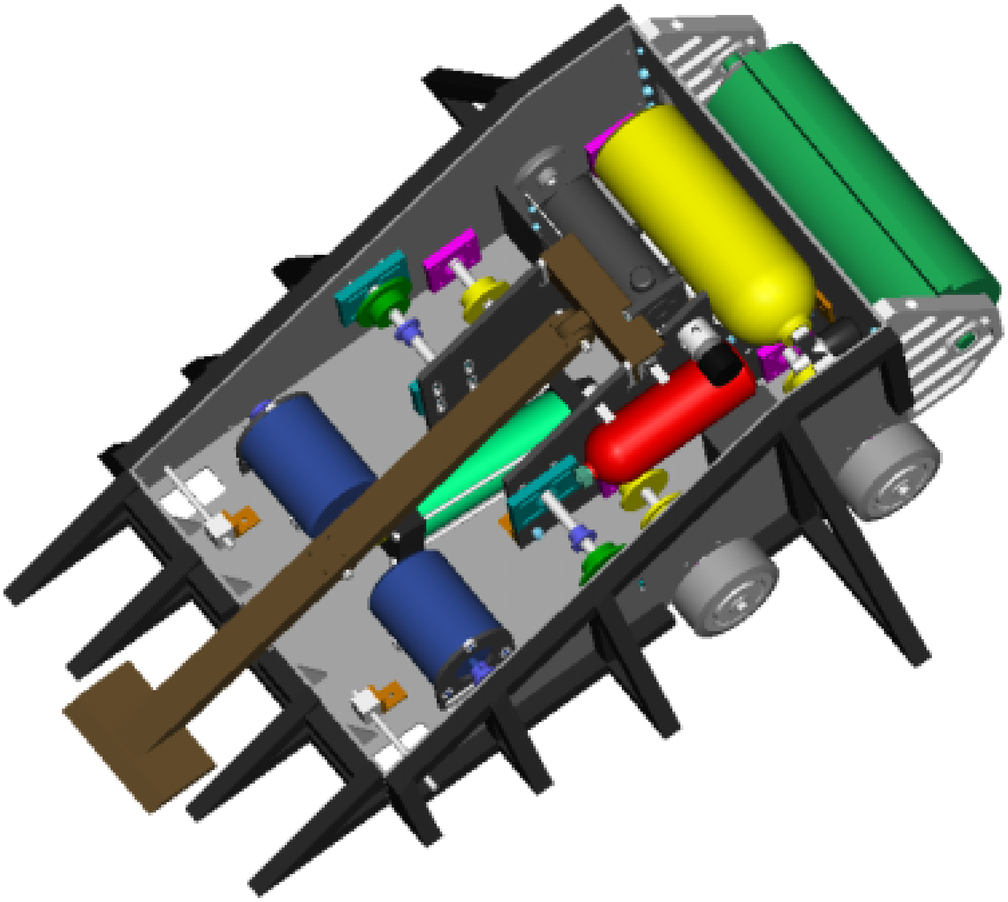


Figure 12.1 – Assembly of BattleBot

All of the practical considerations were examined, such as securing sprockets to shafts, mounting motors and holding tanks.

12.1 Drive Train Design

Many of the aspects of the original design were left as is, some were totally removed and some were modified. The main chassis of the robot was left mainly untouched. The armor struts, seen on the front and sides in black were left mostly alone. The front armor strut required slight modification to allow the lifting arm to extend to the front of the robot (not pictured here). The body shell, made of 1/4 inch and 5/32 inch aluminum retained the same shape but was created anew for greater strength and lighter weight.

The drive train was totally redesigned, except for the motors and wheels. The old belt system was totally removed and replaced with a chain drive. The locations of the wheels remained the same as well as the rough placement of the motors and shafts as seen in Figure 12.2.

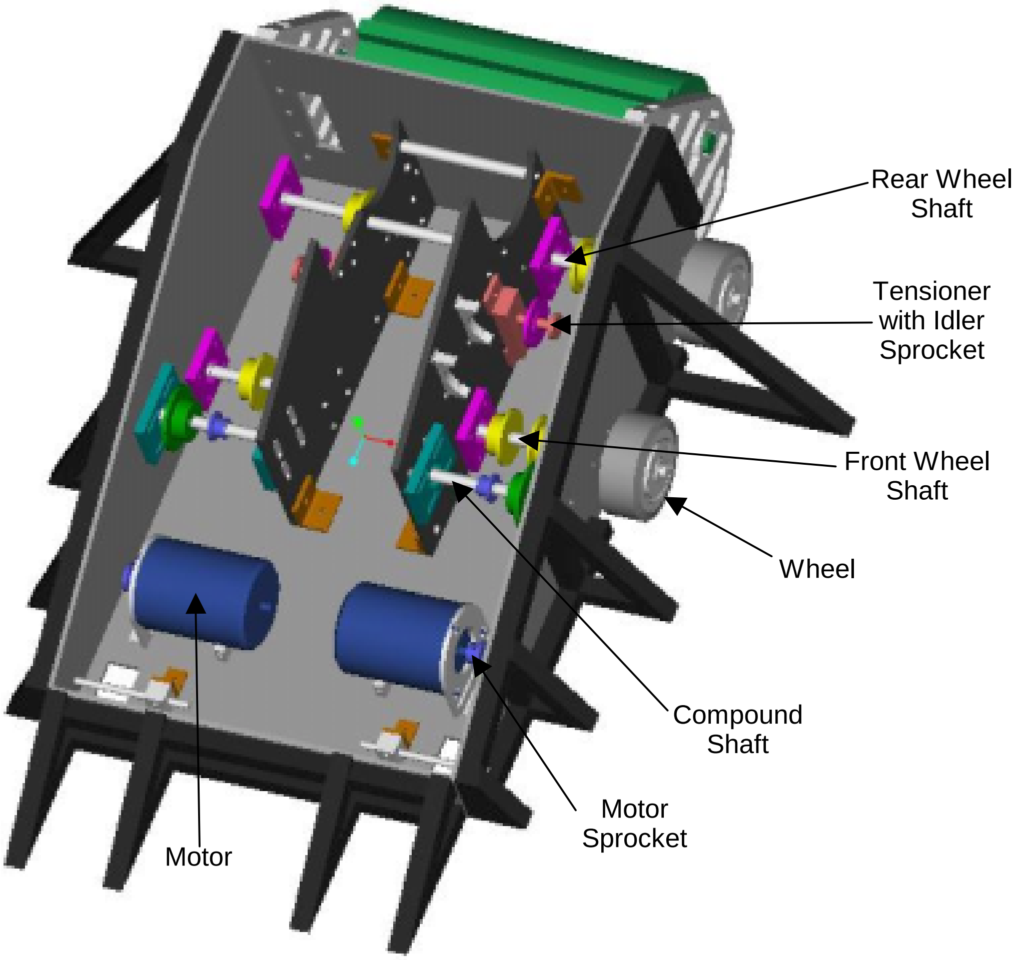


Figure 12.2 – Drive Train Components

The motor has a 10 tooth sprocket which is attached via the chain to a 25 tooth sprocket on the compound shaft (green sprocket). The 10 tooth sprocket on the compound shaft (blue) rotates with the green sprocket and is connected to a 21 tooth sprocket on the front wheel shaft (yellow). The front and rear wheel shafts are finally connected together by a 21 tooth sprocket on each shaft (yellow).

Tensioning the chain was a very important problem to solve. If the chain was too loose, it could fall off or cause severe rhythmic vibrations. Many different tensioning mechanisms were explored. One of the first ideas was to make one of the shafts moveable like on a bicycle rear tire. The shaft could be slid back until the chain was tight and then bolted down. The first problem encountered with this design was that the two wheel shafts could not be moved easily. However, this idea did seem to work well for the compound shaft or motor. The motor could either slide or rotate to tension the chain between it and the compound shaft. This did however present problems with mounting the motor securely and was discarded. The next idea was to move the compound shaft by cutting slots into its bearing blocks as seen in Figure 12.3.

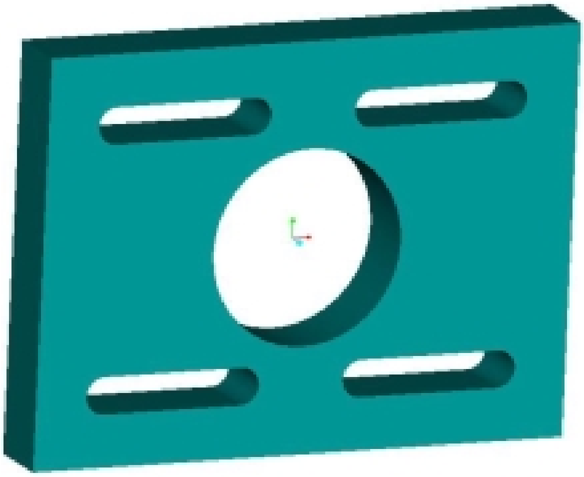


Figure 12.3 – Bearing Block to Allow Compound Shaft to Tension Chain

This would allow the whole compound shaft to slide up to tension the chain. This idea worked well for the chain between the motor and the compound shaft but made the chain between the compound shaft and front wheel shaft looser.

The next idea for the chain between the compound shaft and front wheel shaft was to let the adjustable bearing block slide in grooves vertically as well as horizontally as seen in Figure 12.4.

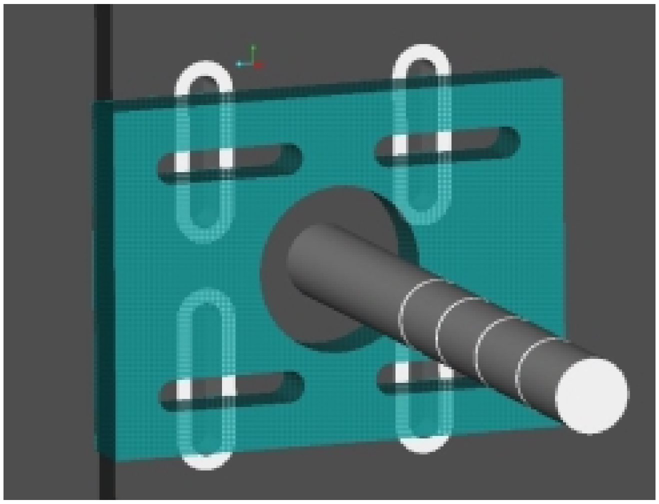


Figure 12.4 – Two-Way Adjustable Bearing Block

Thus, tension could be applied to both chains at the same time without adding extra weight or parts. Simply by giving the compound shaft two degrees of freedom, both chains could be tightened at once. Details of the bearing blocks can be found in Drawing 5 Sheet, 1.

This solution could not be applied to the chain between the two wheel shafts. The next idea for those shafts was to use a tensioner and idler sprocket as seen in Figure 12.5 to take up the slack in the chain.

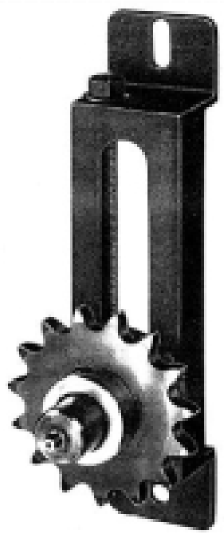


Figure 12.5 – Tensioner with Idler Sprocket

This particular tensioner applied force to the chain by screwing the bolt on the top which moved the idler up or down. Other types of tensioners work using springs or simply by having grooved mounting holes, but this seemed to be the most rugged and easiest to adjust. This tensioner worked well for the chain between the two wheel shafts but added weight to the design.

All of the drive train components can be seen in Figure 12.6.

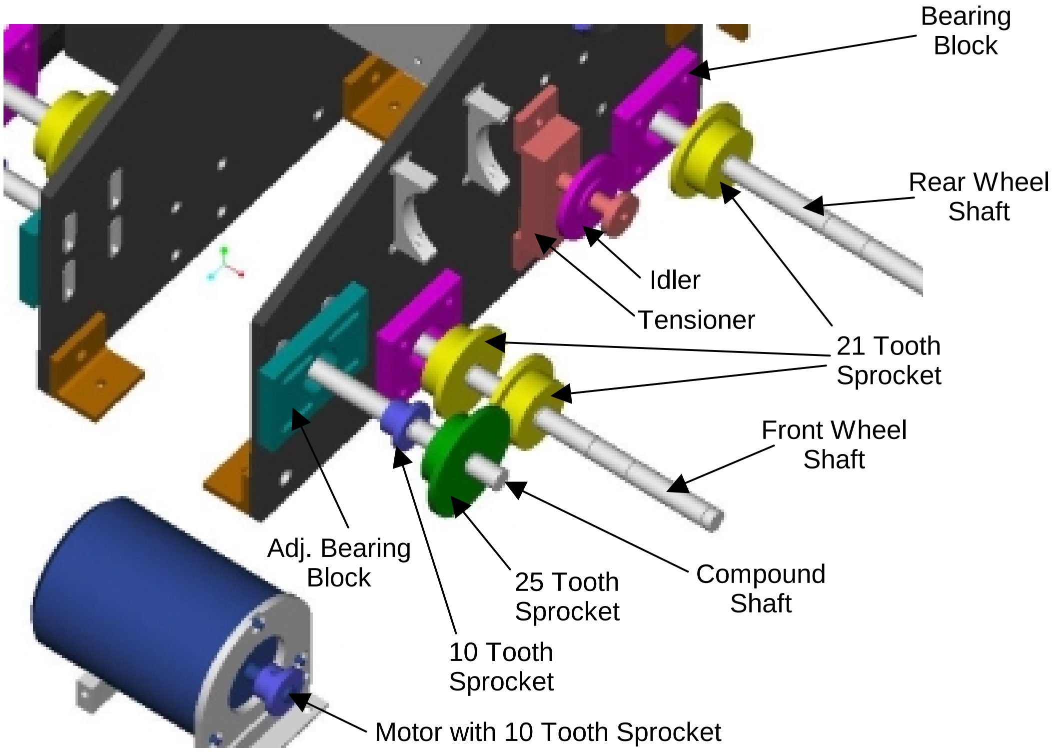


Figure 12.6 – All Final Drive Train Components

12.2 Shaft Design

Attaching the sprockets to the shafts and securing the sprockets into the bearings was a problem for the BattleBot last year. The sprockets were attached to the shafts using set screws and flats on the shafts. This was acceptable for normal driving, but the high impacts and constant direction changes made the set screws become loose. This resulted in one of the sprockets becoming misaligned and breaking the belt. For this years design, a much more rugged design was needed.

The diameter of the wheel shafts was 5/8 inch and was not a problem last year. This year, all three shafts were made the same diameter to cut down on different sizes of materials and parts. The shafts rode in bearings seated in bearing blocks. The inner bearing block was bolted to the bulkhead and the outer was bolted to the body. As seen in Figure 6. The wheel shafts were captured in place on the inside by the bulkhead wall, which was not cut out behind the bearing block. On the body side, an E-ring was used to secure the shaft. Dimensions for the E-rings can be found in Appendix B.

The compound shaft was captured on one side by the bulkhead and on the other by the body. Since neither the bulkhead nor the body was cut out behind the adjustable bearing blocks, the shaft could not slide.

Multiple methods were used to secure the sprockets to the shafts. For the motor sprocket, two set screws offset at 90º secured the sprocket to the shaft as seen in Figure 12.7.

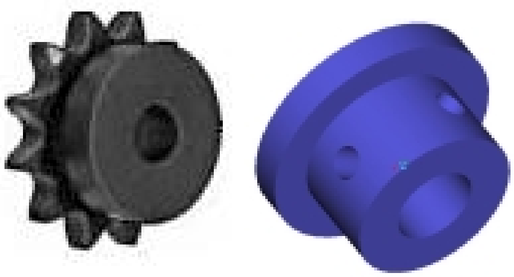


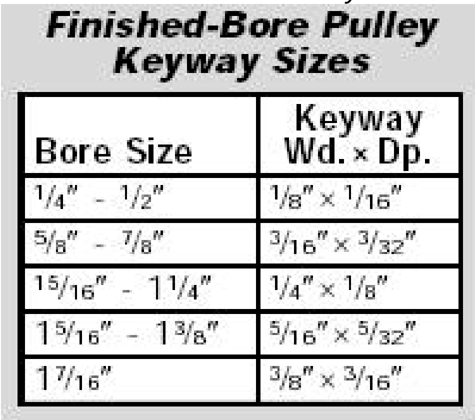
Figure 12.7 – Plain Bore Sprocket as Purchased and Finished Motor Sprocket with Bored Out Center and Two 90º Set Screws

Since the shaft diameter of the motor was metric (12mm), a plain bore sprocket was selected to be bored to the correct diameter. The set screw holes would then be tapped as seen in Drawing 5, Sheet 1. For all other sprockets, a keyway, E-rings and set screws were used. The sprockets chosen can be seen in Figure 12.8.

Figure 12.8 – Finished Bore Sprockets

Standard square keys were used for each sprocket. These standard sizes are based on shaft diameter and can be found in Table 12.1.

Table 12.1 – Standard Key Sizes



Finished-Bore Pulley Keyway Sizes

Bore Size	Keyway Wd. × Dp.
1/4" - 1/2"	1/8" × 1/16"
5/8" - 7/8"	3/16" × 3/32"
15/16" - 1 1/4"	1/4" × 1/8"
1 5/16" - 1 3/8"	5/16" × 5/32"
1 7/16"	3/8" × 3/16"

Since the key is square, half of the key protrudes into the shaft and the other half into the sprocket. Thus, the depth of the cut is half the width of the key. The keyway dimensions can be found in Drawing 5, Sheets 1 and 2.

The sprockets also come with two 90º offset set screws. These will be tightened for two reasons. First, it will help secure the sprocket from sliding laterally on the shaft. Also, it will take up any tolerance between the key and the slot, and help reduce backlash.

To further secure the sprockets and shafts, and E-ring will be placed 0.025 inches from either side of the sprocket as seen in Figure 12.9. The dimensions for the E-ring Slots can be found in Drawing 5, Sheets 1 and 2. Also, the manufacturers design information can be found in Appendix F.

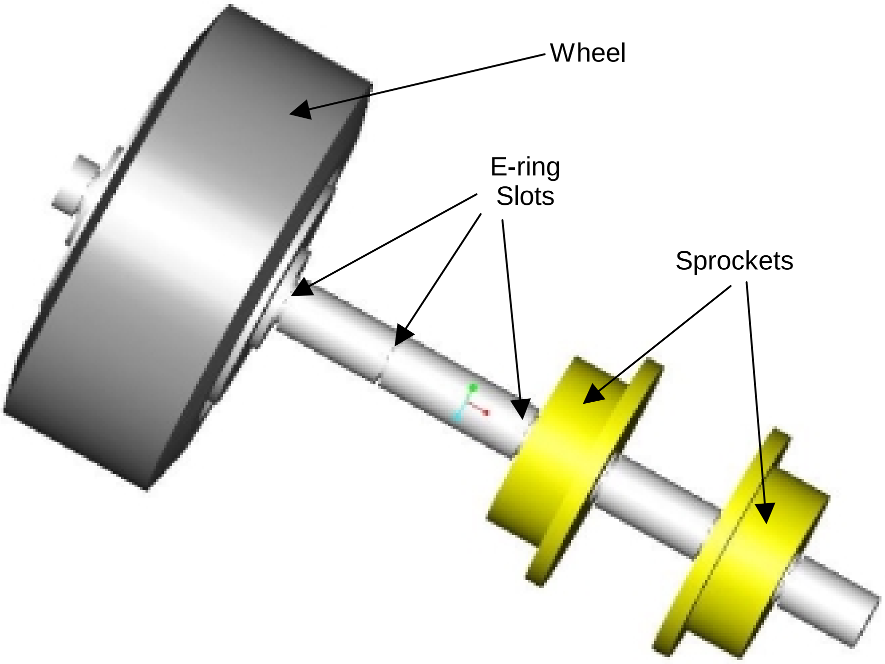


Figure 12.9 – Shaft Assembly Showing Sprocket and E-Ring Slots

Finally, wheels had to be secured to the shafts. Last year, a Woodruff key was used to keep the wheel from rotating. It was decided to eliminate the Woodruff key and use the same size keys throughout to keep the tooling and parts cost low. To keep the wheel from sliding laterally, the end of the shaft was threaded and the wheel secured with a nut. This idea was also scrapped because of the high machining costs and the fact that some of the threads were damaged during the match and made removing the nut very difficult. This year, the wheels were secured with an E-ring on each side as seen in Figure 12.9.

12.3 Bulkhead and Body Design

The Bulkheads, shown in Figure 1 were very important to the design of the BattleBot. Almost everything in the robot was attached to these two structures. Last year, they were made of 1/2 inch this aluminum plate. This year, to save weight, they will be made of carbon fiber sheet which is 3/8 inch thick. This alone caused some design problems. The carbon sheet could be crushed by the force of the bolts when they are tightened, so every screw hole in the bulkhead had to have an aluminum insert to keep the carbon fiber from collapsing. This can be seen in Figure 12.10.

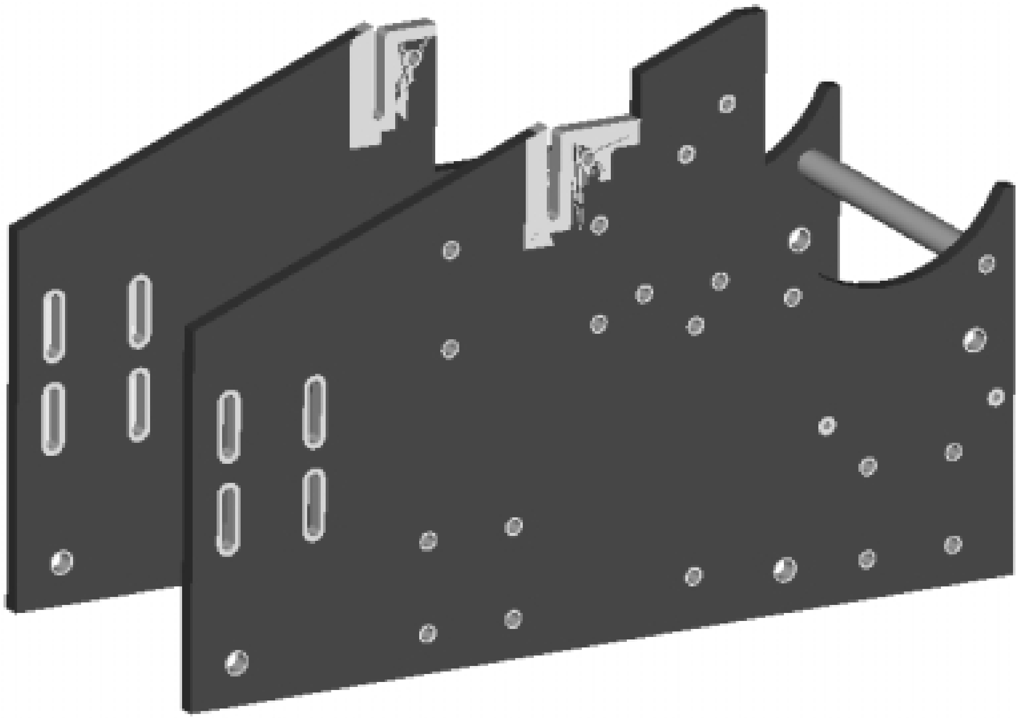


Figure 12.10 – Carbon Fiber Bulkheads with Inserts

3-D modeling was invaluable in designing the locations of all the screw holes on each bulkhead. All the parts that were attached were brought into the model and alignment of the screw holes was checked. Details of the bulkheads can be found in Drawing 4, Sheets 1-4. The bulkheads were secured to the body by 3/8 inch bolts that passed through tabs welded to the body as seen in Figure 12.11.

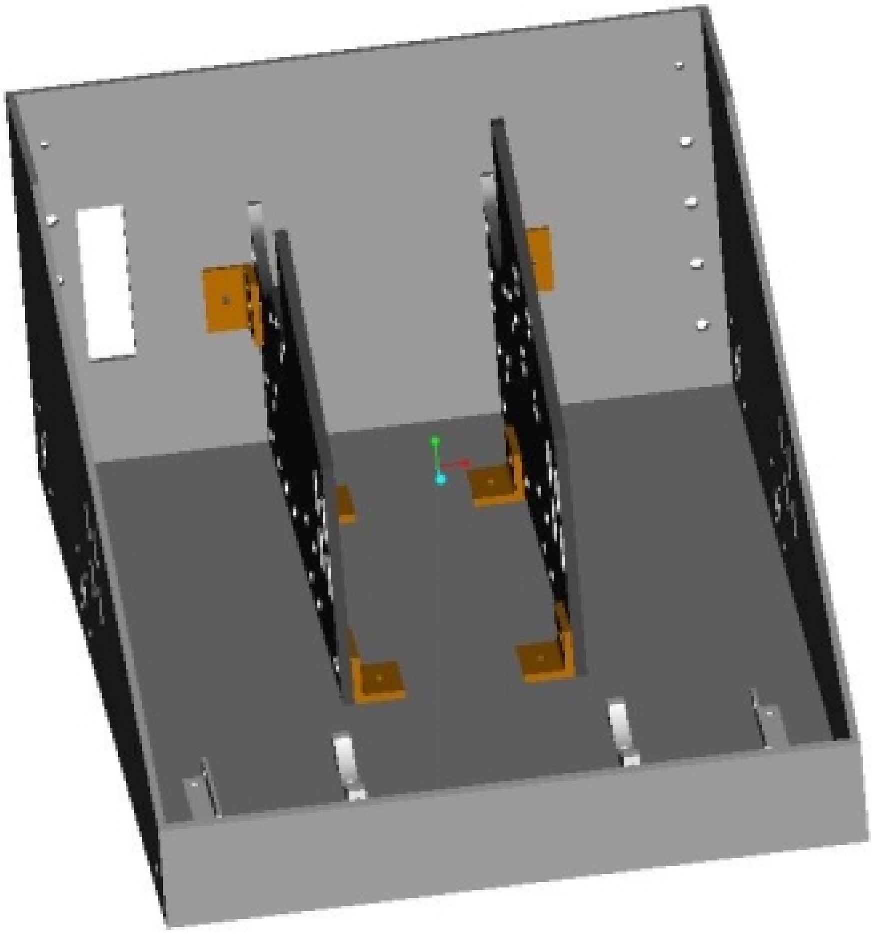


Figure 12.11 – Bulkheads Secured to Body by Tabs

Welding the tabs to the body was an improvement over last years design because it eliminated bolt heads on the bottom side of the BattleBot. Some of the bolt heads were severely damaged due to hazards and impacts and had to be drilled out. They could also catch the BattleBot on obstacles and stop it. The current design has eliminated all bolt heads from the bottom side. There are, however, still bolt holes to secure the tabs to the body. This was done so that the tabs could be bolted in place during welding, ensuring an accurate fit. After welding, they will be removed. Details of the body and tabs can be found in Drawing 3, Sheets 1-4.

12.4 Rotating Drum Design

The rotating drum system was left largely alone. The drum motor was left in its same place as last year with only minor modifications to fit it to the carbon fiber bulkheads as seen in Figure 12.12. The details of the drum motor mounts can be found in Drawing 6, Sheet 2.

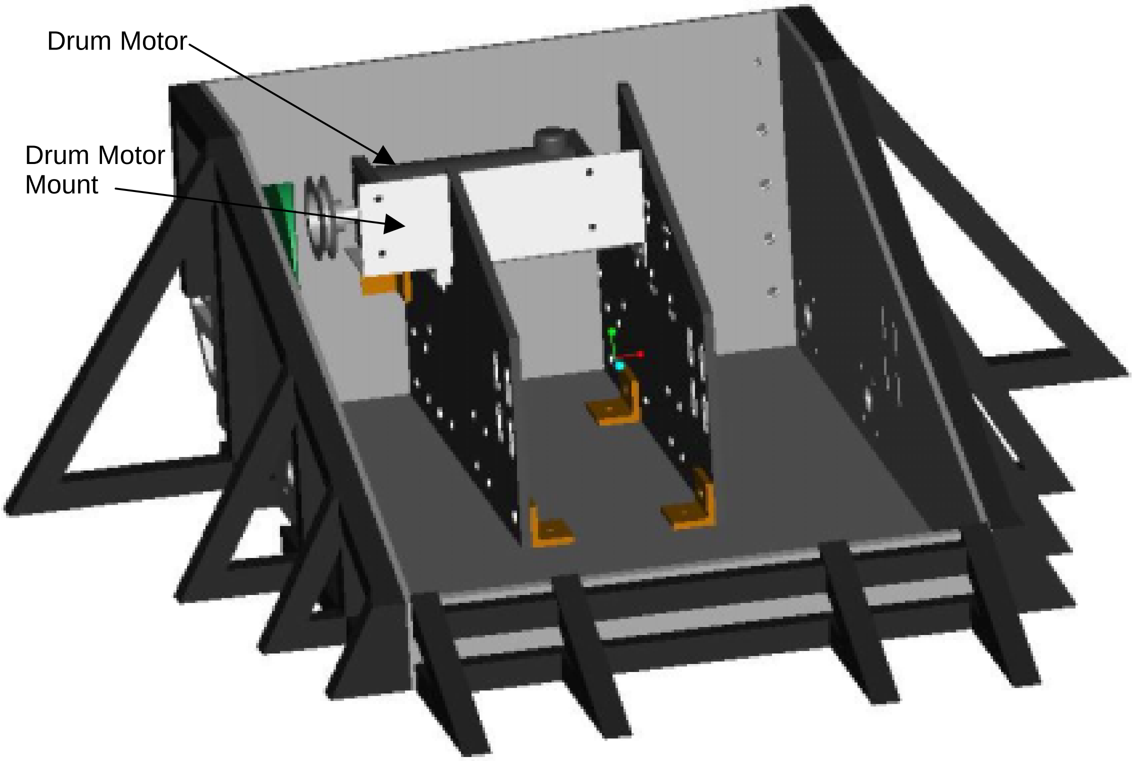


Figure 12.12 – Drum Motor Mounted in BattleBot

The drum itself was mounted to the body with two large drum mounts as seen in Figure 12.13.

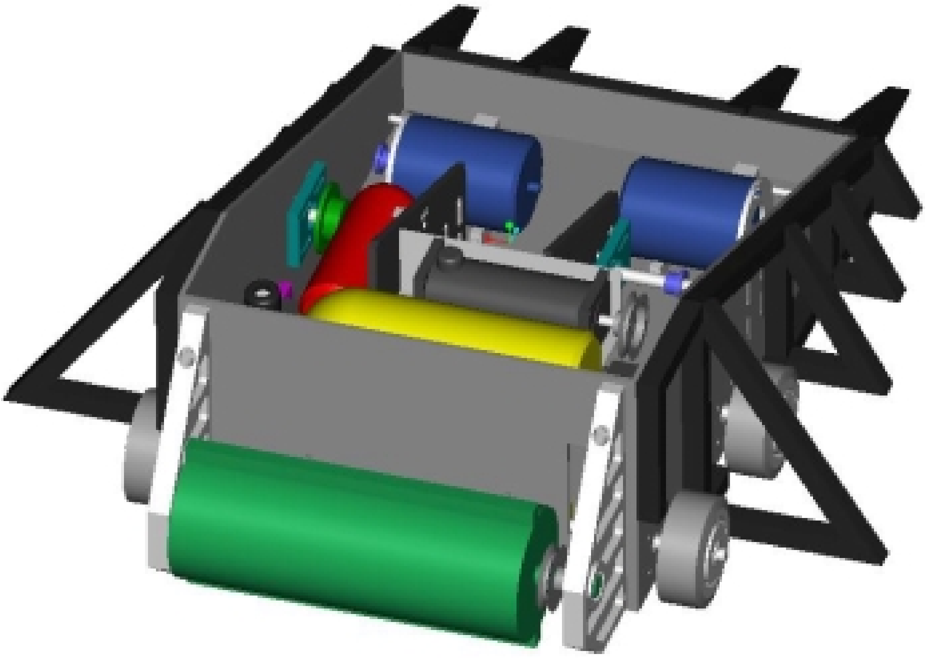


Figure 12.13 – Drum with Mounts

The only modification made to this setup was to try to reduce weight. The original drum mounts were made of 1 inch thick aluminum and weighed 4.7 pounds. After many different designs were examined with FEM analysis, the final design was created as seen in Figure 12.14.

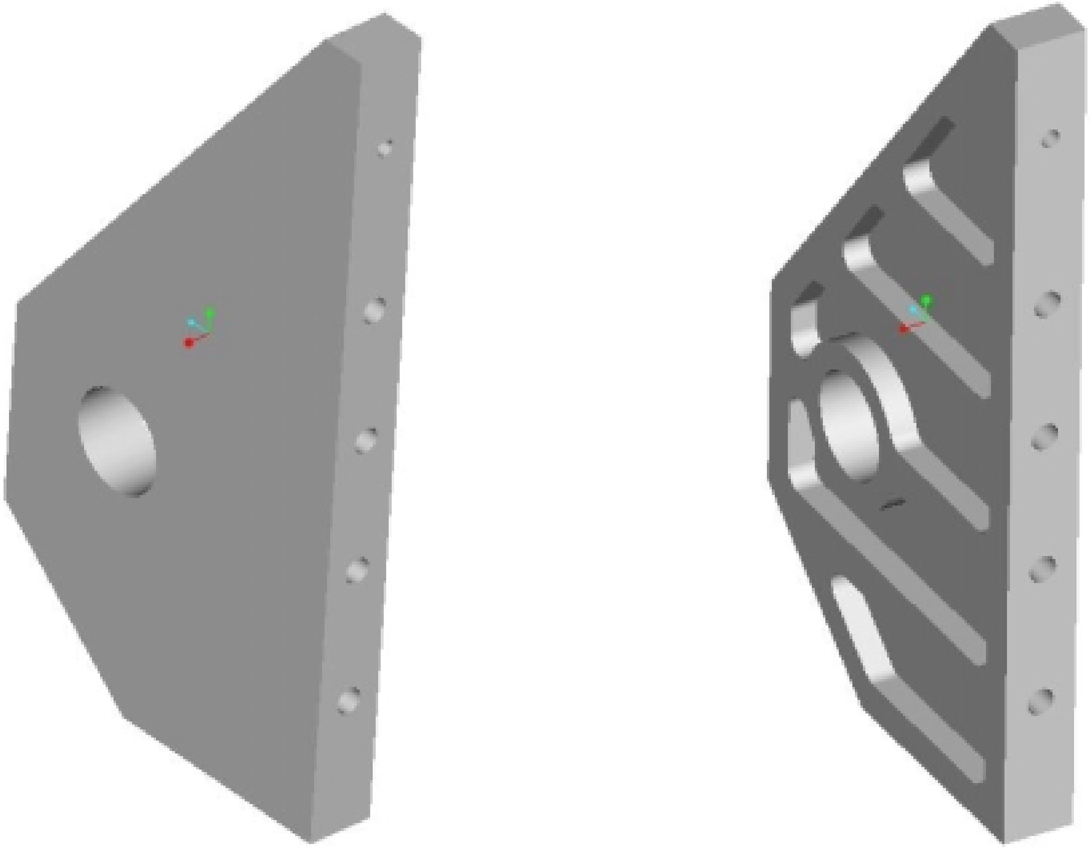


Figure 12.14 – Original Drum Mount and Modified Drum Mount

Material was cut out 3/8 inch deep on either side resulting in a weight reduction of 2.9 pounds. By creating the 3-D model, the ribs were able to be placed directly over the screw holes without worry of interfering with and threads. Also, the exact weight of each part was accurately approximated. The details of this mount can be found in Drawing 6, Sheet 1.

12.5 Internal Components

The BattleBot's systems have many internal components that had to be secured inside the body. Two of the most important were the nitrogen tank and buffer tank. The location of the nitrogen tank was kept the same as last year, but the method of securing it was changed. Last year it was enclosed in a box made of aluminum sheet. For this design, we decided to secure it with the bulkheads by pulling it down into a cradle as seen in Figure 12.15.

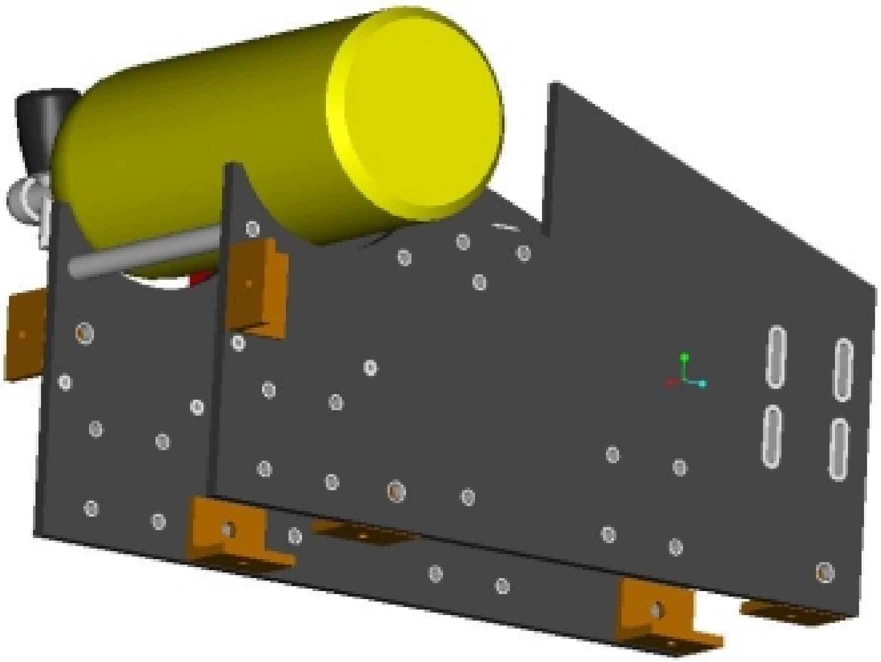


Figure 12.15 – Nitrogen Tank in Cradles

To keep the tank from damaging the bulkheads, the diameter of the cradles was made 1/4 inch greater than the tank. This allowed for a rubber lining to fit between the tank and the bulkheads, thus preventing damage.

To pull down in the tank, many different ideas were explored including a split circle that could be bolted around the tank, to securing it with a simple sheet metal strap. It was finally decided that two large pipe clamps, as seen in Figure 12.16, would be wrapped around two bars under the tank, as seen in Figure 12.17, and then over the tank itself. The clamp could then be tightened to secure the tank.

Figure 12.16 – Large Diameter Hose Clamps for Securing Nitrogen Tank

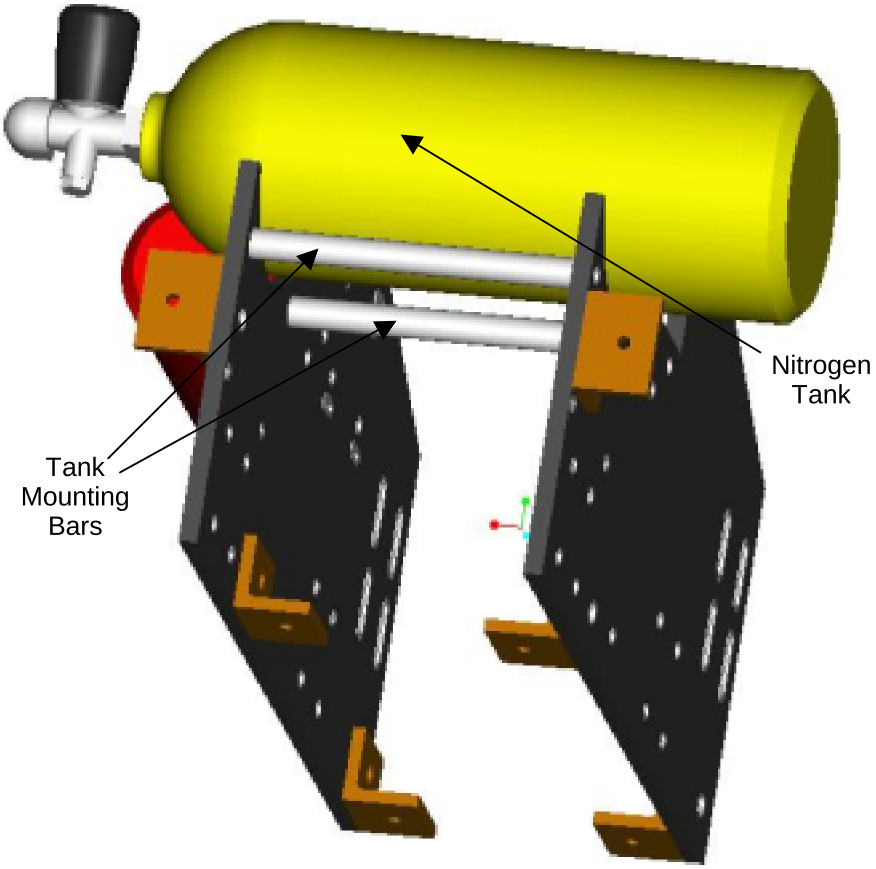


Figure 12.17 – Nitrogen Tank with Mounting Bars

This was an advantageous design because it was very light and also added stiffness and strength to the bulkheads. The details of these parts can be found in Drawing 6, Sheet 2.

The buffer tank was added to last years design, so no place existed for it in the robot. Using 3-D modeling, space for it was found on the right bulkhead above the chain drives as seen in Figure 12.18.

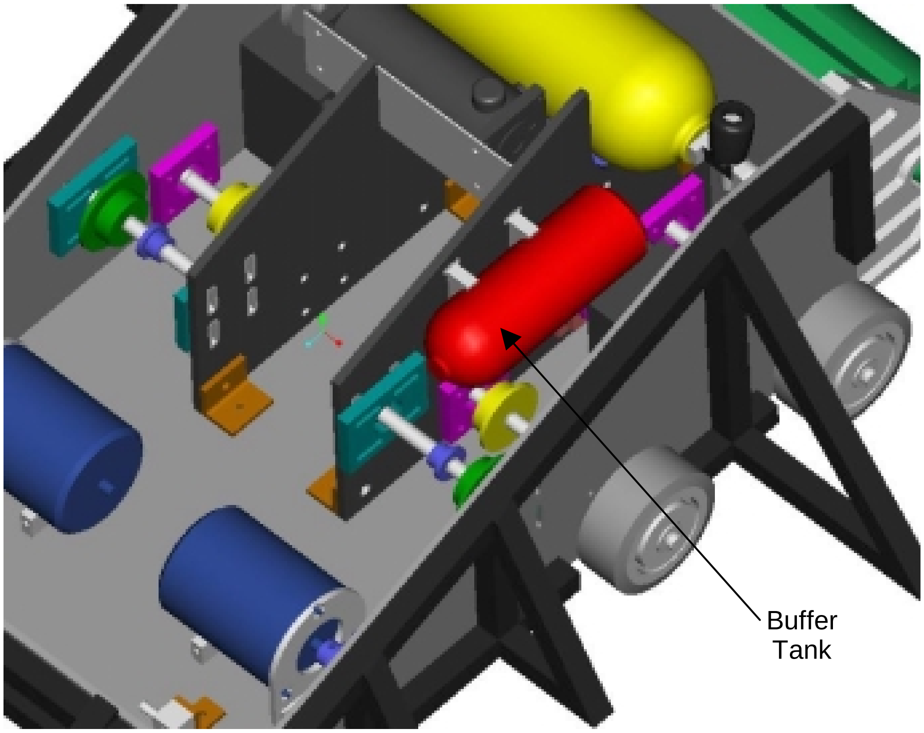


Figure 12.18 – Buffer Tank Location

This tank presented some problems for mounting because the round tank had to be mounted to the flat surface. Many of the same ideas were explored but a similar design to the nitrogen tank was designed. Two cradles were made from aluminum and screwed to the bulkhead. Then, hose clamps would pass between the cradles and the bulkhead and wrap around the buffer tank. When the hose clamps were tightened, the buffer tank would be pulled securely into the cradle as seen in Figure 12.19.

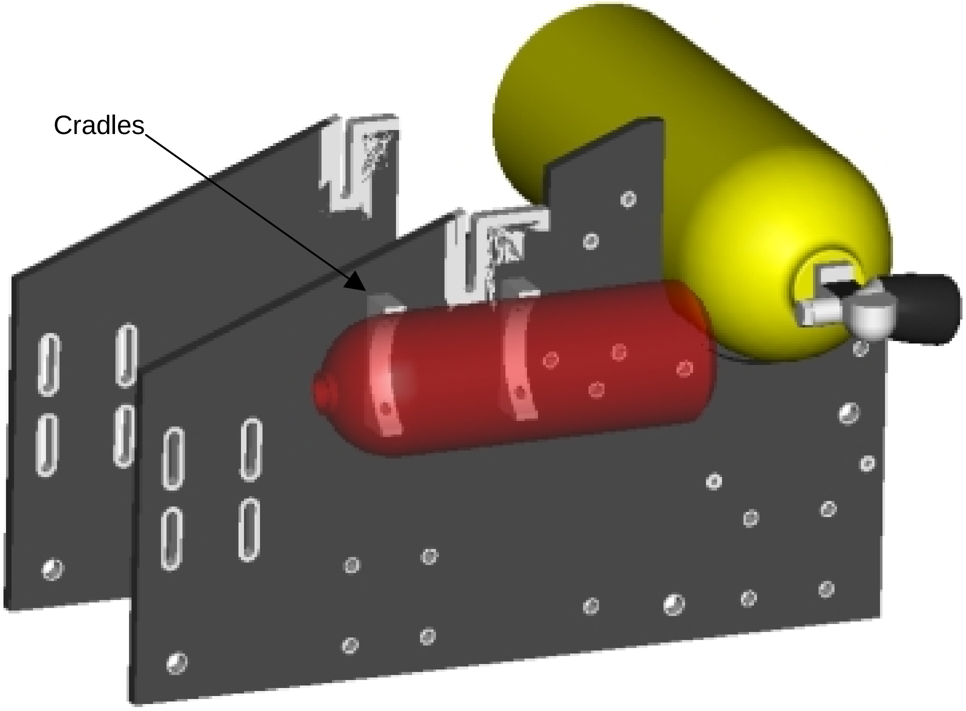


Figure 12.19 – Buffer Tank Mounting System

Another important component was the batteries. Two 12 volt batteries were required to power all the motors. Their location was not changed from last year and can be seen in Figure 12.20.

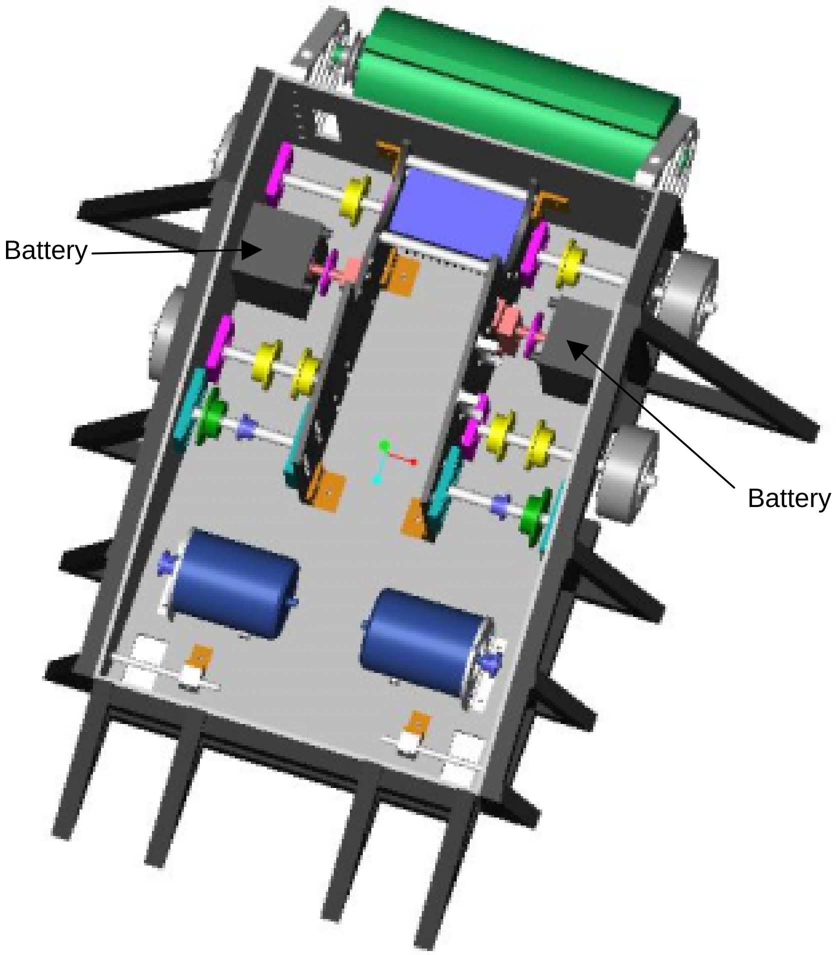


Figure 12.20 – Battery Mounting Location

The mounting system consisted of sheet metal straps and was deemed satisfactory to leave as is. The chain drives were designed to not interfere with the battery locations.

The brain of the drive system was the motor speed controller. This box full of electronics took inputs from the transmitter and output voltage to the motors. This controlled both the speed and the steering of the BattleBot. The location of this was not changed but the mounting design was changed slightly. The original design had the bulkheads spaced so the speed controller fit exactly between them. Bolts were screwed through the bulkheads into tapped holes in the speed controller. By using thinner bulkheads, a 1/8 inch gap was created on either side of the speed controller. This space was used to place a rubber washer between the bulkhead and speed controller to attenuate the vibration from shocks. Another washer was also placed under the screw head on the other side of the bulkhead to further reduce energy transfer. This helped to protect the electronics from damage when the BattleBot suffered impacts. The speed controller location can be seen in Figure 12.21.

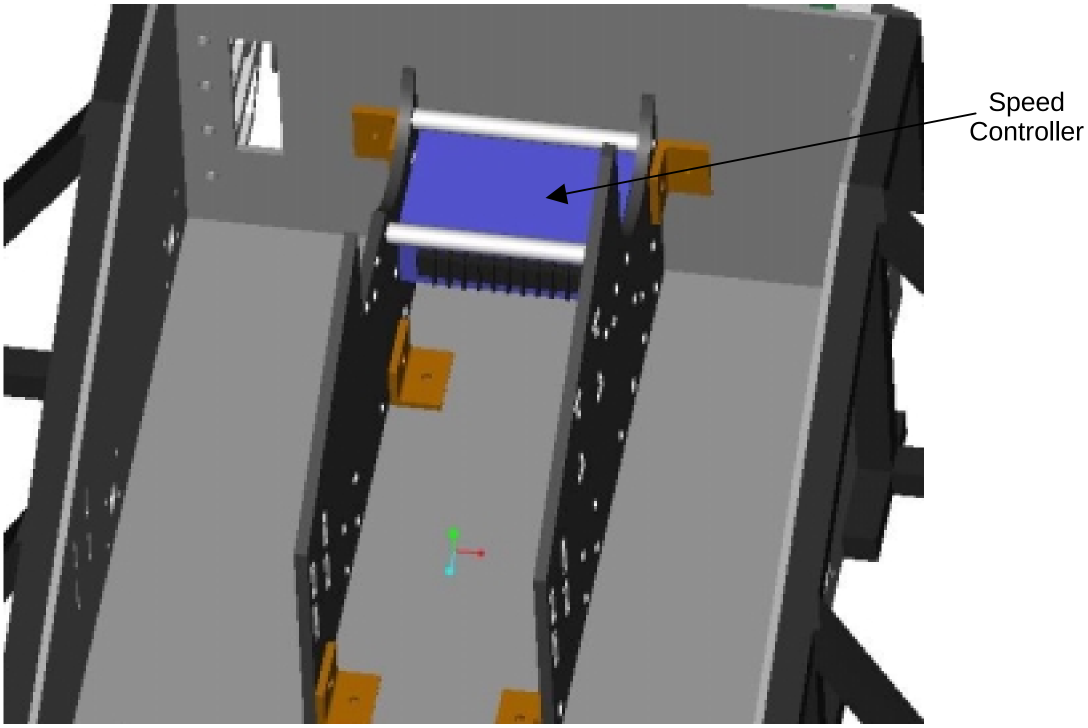


Figure 12.21 – Speed Controller Location

Assembling the lifting arm in 3-D was invaluable in manufacturing the system correctly on the first try. The lifting arm and piston were modeled in the up and down position as seen in Figure 12.22. The saddle piece, which holds the pivot bracket was also assembled in 3-D to check clearances.

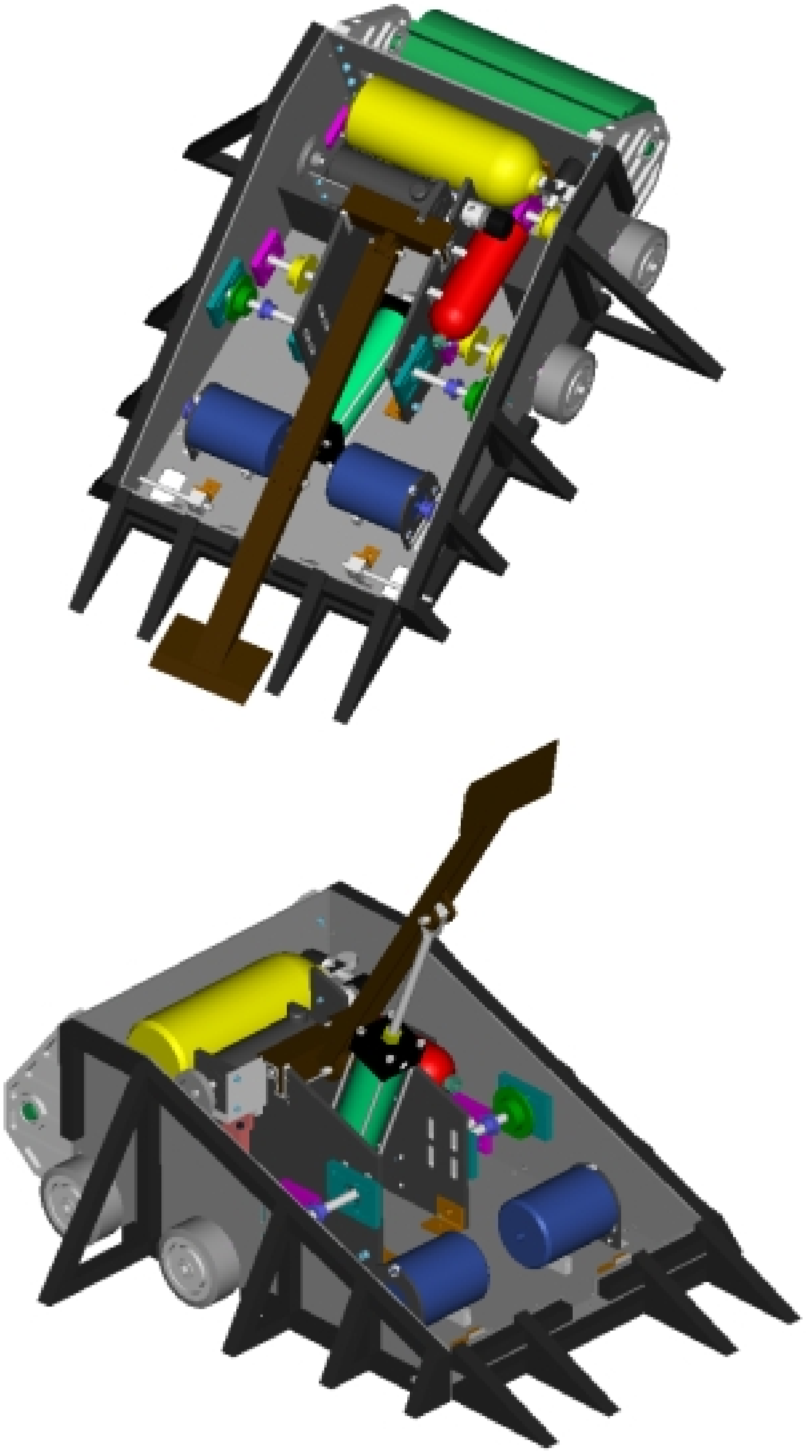


Figure 12.22 – Lifting Arm in Up and Down Positions

The clearances were checked and all interferences were eliminated prior to manufacturing. The design was so good in fact, that no parts needed to be modified after being fabricated and assembled.

13.0 ELECTRICAL SYSTEM

In this section, the electrical components, remote controls, wiring, power calculations, and some of the problems that were encountered will be discussed. There are several operations needed to make the BattleBot move both forward and backward. Also the BattleBot has two ways to damage and destroy the other bots. The first weapon is a lifting arm, designed to flip or disable the other battle bots. The secondary weapon is a drum roller, designed to roll over and disable the opposing bots. Previous parts from other groups were good for two reasons. First, the drum roller and lift-arm are good weapons of destruction. Second, these particular weapons were available to the design group for no extra cost.

13.1 Main Power Schematic

There were two main schematics considered for the electronic portion of the BattleBot. The main problem in developing these schematics was testing them. Once the Bot was on the testing table wiring problems, and malfunctioning parts became key issues. The main idea behind pre-testing was that if a part did not work or there were problems with the design, it could be fixed before the parts were permanently mounted. There was one main design difference between the two schematics: the position of the switch. When looking at the final schematic, shown in Figure 13.1, the position of the switch had been modified. In the previous schematic the switch was after a relay. That meant that even when the switch was off, current flowed through the relay. In the current schematic, the switch becomes a main power switch. As a result, no current flows in the BattleBot when the switch is off. However, when dealing with a 24-volt source and the current associated with it, the shock given can be quite painful. When using the old schematic, a person can be shocked if wiring the relay even if the switch is closed. The current design, shown in Figure 13.1 was determined to be the most effective circuit.

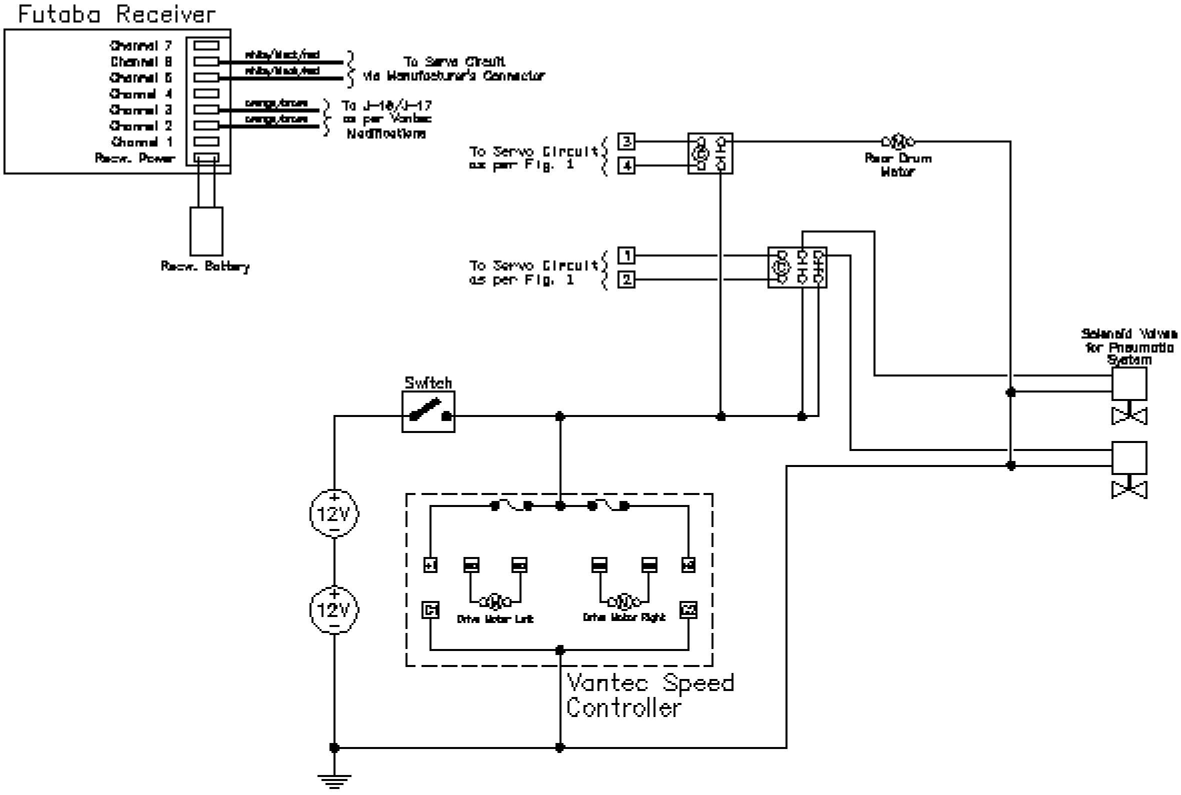


Figure 13.1 – Electrical System Schematic

Aside from safety concerns, the rest of the circuit is fairly simple. There are two 12-volt batteries connected in series. The negative terminal of one battery is connected to the positive terminal of the other. The negative terminal is designated with a black wire and the positive terminal by a red wire. There is a splitting contact attached to the negative terminal. The positive wire is attached to the main power switch. The switch then is split three ways with wires going to the speed controller and two separate relays. The speed controller received inputs from the remote control and sends the appropriate amount of power to each of the drive motors. The two relays control the drum motor both solenoid valves that actuate the lifting arm as discussed in the Pneumatics Section. Channels 3 and 4 of the receiver are used to control the speed controller and channels 5 and 6 control the drum motor and lifting arm. The design of these systems will be elaborated later. The schematic in Figure 13.1 can be seen in the Drawing Package.

13.2 Power Calculations

An intricate part of our design entailed selecting a battery system with the capability to produce the desired amount of power to make it possible for the BattleBot and its weapons to operate for the entire match. Though choosing the right amount of battery capacity was an important part of designing the BattleBot, there were several other things that had to be considered, such as cost. Some important decisions to be considered were:

1. You must decide on what type of battery to be used. The choices were sealed lead acid (SLA), Nickel cadmium or Metal nickel hydride. Each type of battery has different weight per Amp Hr. rating which is important if weight is a consideration. Sealed lead acid types are the least efficient and the heaviest of the three types, but are the cheapest. Nickel Cadmium are a lot lighter than Sealed Lead Acid and are a lot more efficient and they can be recharged several times faster, of course there are a lot more expensive. Metal Nickel Hydride batteries are even more efficient than Nickel Cadmium and of course the most expensive because of the weight saving reason and the capability to recharge much faster.

2. Batteries are rated by a scale called Amp Hour rating. In theory this rating is the maximum current the battery can supply for one hour in a perfect world. Unfortunately batteries have internal resistance which reduces their efficiency. Different types of batteries are more efficient than others. Even batteries of the same type from different manufactures can behave differently. Of course this complicates the choice of a battery.

3. Another consideration when choosing a battery size is how much load will be applied by the motors. This is why it is good to use as low of a drive gear ratio as possible because lower gearing reduces the time that the motors will be at stall. If a high gear ratio is used for more speed, a higher capacity set of batteries will be required, as would be expected.

The battery which we are using to operate our battle robot is a sealed lead acid (SLA). As mentioned above, this the cheapest of the three but least efficient. However, it was determined that it would suffice.

To power the BattleBot, two 12 volt batteries were wired in series to be able to produce a total output voltage of 24 volts. To find the maximum current draw from the batteries, Equation 13.1 was used where P is the power measured in Watts, V is the voltage measured in volts, and I is the amount of current measured in Amperes.

$$I = \frac{P}{V} \tag{13.1}$$

Using Equation 13.1, it was determined that the maximum current draw was 87.7 Amps. The details of the power calculations can be seen in Appendix G.

All matches leading up to the final match in the "Battle Bots" show are scheduled for three minutes, with the final or championship round being scheduled for five minutes of intense fighting. Thus, it was determined that the batteries needed to survive for at least 5 minutes. By multiplying the maximum current draw of 87.7 Amps and the required time of five minutes, the required Amp minutes were calculated as seen in Equation 13.2.

$$AmpMin = 87.7\ Amps * 5\ min = 438.5\ Amin \qquad (13.2)$$

Next the amp minutes were converted into amp hours. It was determined that 7.308 amp hours were required for the match.

In order to see how much of the battery is actually being used in the five minutes that robot will be operated the Amp hour rating of the battery was converted to Amp minutes, and then divided the Amp minutes by the required five minutes of the match. The power needed for one match was determined to be 144 Amps.

Finally in order to see how long the fully powered batteries can operate while producing its maximum current draw, the total Amp minutes was divided by the maximum current draw. It was determined that the battery would operate for 8.21 minutes. Since the robot only needs to operate for a maximum of five minutes during a match it is safe to conclude that the batteries used will be able to provide the necessary output power to keep the robot running for a full five minutes.

13.3 Remote Control

The remote control and receiver are very important to the battle-bot design. Battle-bot remotes are not usually built, so an airplane remote control was used. The Futaba FP-T6XAS remote was chosen. The FP mean Futaba Product, the T means a transmitter, the 6 means the remote has 6 channels, X is for the series, A is for aircraft, and the S is for super edition. The receiver is a product that is compatible with the FP-T6AS remote. It is a model FP-R138DP. The FP means Futaba Product, the R is for receiver, the 1 is for J-plug style, the 3 is the series number, 8 is for the number of channels, and the D is for duel conversion. A picture of the remote control is shown in Figure 13.2.

Figure 13.2 – Futaba Remote Control

The specs for the remote control transmitter and receiver are listed below in Table 13.1

Table 13.1 – Specifications for remote Control and Receiver

Transmitter Specifications:

Operating system: 2-stick, 6 channels,
PCM1024 system
Modulation: FM/PPM or PCM, switchable
Power supply: 9.6V Ni-Cd battery
Current drain: 250mA

Receiver Specifications

Type: FM, Dual conversion
Intermediate frequencies: 455kHz, 10.7MHz
Power requirement: 4.8V or 6V Ni-Cd battery
Current drain: 14mA @ 4.8V
Size: 1.39x2.52x0.82" (35.3x64.0x20.8mm)
Weight: 1.5oz (42.5g)

The remote control must be programmed for it to function properly. The instructions for programming the remote can be found in Appendix H. When programming the remote controller, keep in mind that the controls are not controlling what the instructions say they are. The design team denoted Channel 3 as right and left and Channel 4 for forwards and back. Channel 5 is for the turning on/off the lift arm. The flap is for Channel 6, but that knob controls the drum motor.

The receiver is a seven-channel receiver but our remote only works with six of these. A picture of the receiver is shown in Figure 13.3.

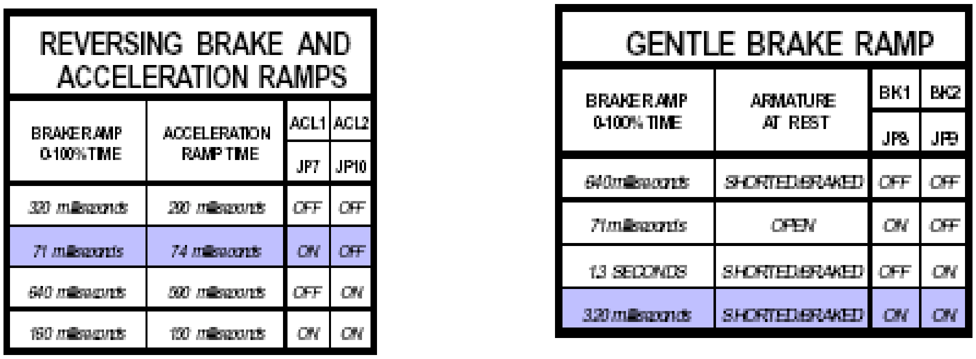
Figure 13.3 – 7 Channel Futaba Receiver

A battery is placed in the B/B channel. The 4-cell NR-4J battery powers the receiver. If the battery is not charged, the receiver will not work and the BattleBot will not move or respond to any of the commands. There are relays attached to channels 5 and 6 which will only trip when the switch is flipped and/or the knob is turned. If the receiver should become damaged any time during the competition, the whole receiver must be replaced. To replace the receiver, turn off all the power switches, starting with the main power switch, then the receiver power switch, and finally the control power. Detach all of the wires from the receiver and remove the receiver. Replace with either a R127DF, R116FB, R138DP, or R148DP. When replacing, make sure the receiver is on the right frequency.

13.4 Speed Controller

The Vantec RDFR32 was the only considered option for the BattleBot because of the availability and price limitations. The Vantec speed control has many great features. The RDFR speed controller performs speed, direction and steering functions for vehicles powered by two independent electric motors employed as a right drive and a left drive, all from only two channels. Employing tank style maneuvering, the speed controller allows for separate drive wheels. When used with a single spring centered joystick, hands off is stop, up stick gets straight ahead, and down yields backwards. Pure right or left twirls the vehicle as the motors turn opposite directions. In between stick positions are completely proportional, including reverse. RDFRs eliminate heavy-duty steering servos yet the steering signal is available. In twin-screw boats or subs differential props combined with rudder steering enhance maneuverability. RDFRs have also been used to command proportional hydraulic valves to control hydraulic motors.

When adjusting gain selection, most users prefer HI gain to achieve the maximum possible speed with the stick straight up, when the vehicle turns at full speed the wheel on the inside slows down but the outside wheel can't go any faster because it's already at top speed. Gain calibration is based upon a Futaba FP-6XAS with 100% ATV, 100% Dual Rate, no trim, centered at 1.53 ms, and factory defaults. This gain works well with other popular radios. Adjustment of gain may also be made at the transmitter using the ATV function or servo travel adjustment potentiometer. Sequenced electro-dynamic braking shunts the motor by modulating both top legs of the bridge. With a command to "stop" the brake is gently ramped from 0 to 100% duty cycle. When a remote control command that changes direction is received the brake is quickly sequenced to first bring the motor to a halt, then the reversing power is ramped up to the commanded speed. This forced sequencing minimizes motor "plugging" and stress on mechanical components. The implementation and timing of these functions is user selectable through jumpers indicated by 'JP' on the figure 3. The times for the braking and accelerating are shown in Figure 13.4.



REVERSING BRAKE AND ACCELERATION RAMPS

BRAKE RAMP 0-100% TIME	ACCELERATION RAMP TIME	ACL1	ACL2
		JP7	JP10
320 milliseconds	290 milliseconds	OFF	OFF
71 milliseconds	74 milliseconds	ON	OFF
640 milliseconds	580 milliseconds	OFF	ON
160 milliseconds	150 milliseconds	ON	ON

GENTLE BRAKE RAMP

BRAKE RAMP 0-100% TIME	ARMATURE AT REST	BK1	BK2
		JP8	JP9
640 milliseconds	SHORTED/BRAKED	OFF	OFF
71 milliseconds	OPEN	ON	OFF
1.3 SECONDS	SHORTED/BRAKED	OFF	ON
320 milliseconds	SHORTED/BRAKED	ON	ON

Figure 13.4 – Times for Braking and Accelerating of Motors

The wiring schematic of the speed controller is shown in Figure 13.5.

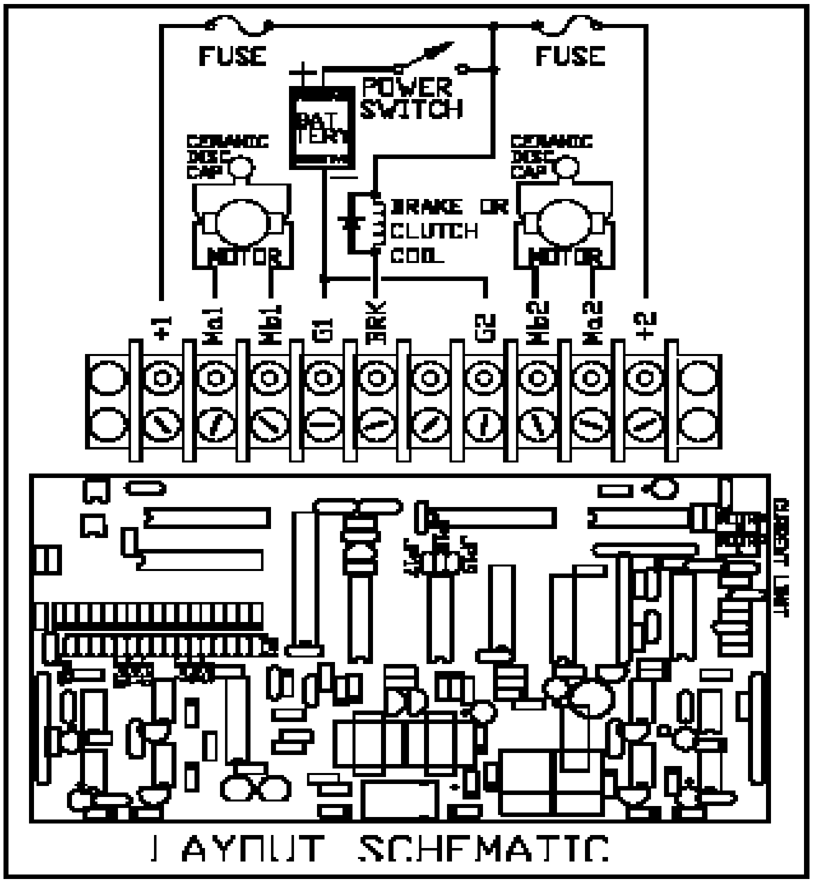


Figure 13.5 – Wiring Schematic of Speed Controller

There are two motors in the BattleBot. When looking at Figure 13.5, one motor is connected at Ma1 and Mb1 while the other is connected at Mb2 and Ma2. G1 is grounded to the negative battery terminal. The positive battery terminal is connected to both +1 and +2. Servo command pulse: The inputs plug into the receiver like a servo and the connectors are engraved: Steering = S, and Throttle = T. Only the receiver common and your servo command pulse signal wires are required to drive the optical isolators within the RDFR. The RDFR neither takes power from nor supplies power to the R/C receiver; thus the plus (red) wire is not used. Available with Futaba J or G, Airtronics, Deans, or JR connectors, it works with FM or PCM radios. The full length supplied R/C antenna should be used and located away from other wires and metal structures. When mounting, do not mount the unit directly adjacent to the remote control receiver. Simultaneous operation of both halves at max ratings may require cooling air or mounting the RDFR side-opposite-the-terminal-block to additional heat sinking; usually the metal frame of the vehicle is sufficient. No special heat sinks are required. The mounting screws should not thread into the case more than 1/8". If the RDFR becomes too hot to hold, cease operation and investigate the cause. In the popular tank steering mixed mode both servo connectors must be plugged in for the unit to operate even one motor. Use transmitter trims of both channels to set motors off dead band. Assignment of right/left motors to #1 or #2 outputs, motors polarity, and transmitter servo reversing switches have numerous combinations. Select the correct combination experimentally but never reverse the motor battery polarity. Noise in sound systems is due to a poor power distribution scheme. Output current through the MOSFET transistors is compression limited above a threshold by PWM duty cycle limiting. The threshold adjustment trim pot for each output is factory set.

13.5 Servo Motor Modifications

The original circuit or servomotor came with the remote control package and is a Futaba s3004 servomotor as seen in Figure 13.6 below. The Futaba s3004 servomotor is made to use with a variety of Futaba controllers and can be obtained from most hobby stores or hobby catalogs.

Figure 13.6 – Futaba Servomotor

The s3004 servomotor is a standard lightweight single ball bearing servomotor controlled by a servo control pulse signal. The servomotor weighs only 38 grams (approx. 1.3 ounces) and is capable of producing 44.4 inch-ounces of torque. This servomotor and circuitry is actually an electromechanical device using both circuitry and tiny plastic gears to control its position. This servomotor is made to be controlled by a pulse width modulated signal. This means that a small square wave signal is sent to the servo, the width of that pulse corresponds to the servomotor being in a certain position. The circuitry inside compares the pulse sent to the position of the servo and if they do not match then it moves the servo to the desired position. This brings up the question of, “How does it know whether it is in the right position”? Well, as the servomotor turns, it also turns attached gears inside of the black box, which turn a potentiometer. This potentiometer is connected in such a way that it feeds back into the circuit providing a feedback signal to be compared with the incoming signal. When the two signals, the feedback signal and the control signal, match the servo stops turning.

In the original design of the BattleBot from last year, built by team R.A.D., one of each of these s3004 servo motors were used to control the pneumatic lifting arm and the rear drum motor. This was done by using the servomotor as is and connecting it to a channel on the Futaba R127DF receiver. Then, to actually control the switch, which engaged either the lifting arm or the rear drum motor, there was small strip of aluminum screwed to the wheel on the servo and also screwed to a bracket, which held a switch. The original control system using the servomotor is shown below in Figure 13.7.

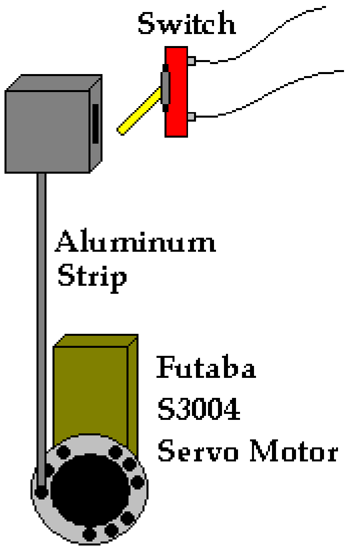


Figure 13.7 – Original Control System

The electrical engineering team felt this was not a good design for many reasons. First of all, the aluminum strip had to be very small in order to connect it to the servomotor. This made this a weak point in the BattleBot, for if this tiny strip became bent for any reason, the weapons system would not work. Secondly, this whole system was mounted on small brackets protruding from the bulkhead making it easy to bounce and therefore, easier to bend something vital or cause something to become misaligned. Finally, this did not seem like an electrical solution to the problem, it seemed more like a mechanical shortcut to solving the electrical problem at hand.

An improved circuit was designed to eliminate the problems with the old system. Our first main concern was with the servo control pulse that controlled this servo. This servo control pulse, as it is commonly referred to as by Futaba, is transmitted across three wires. The three wires were red, black, and white. One, the red wire, seemed to be a simple DC voltage that was used as a carrier signal. The black wire was a ground wire. The white wire seemed to be the pulse carrying wire that actually sent the pulses of the pulse width/code modulated signal to the servo.
After researching in the lab, we found that across the red and black wires there was a steady 0.2 to 0.4 volt signal. The original design idea was to amplify this signal using op amps, bipolar junction transistors, and resistors to some sort of control signal that could pull in the coil on a relay and engage our 24VDC rear drum motor or our 24VDC solenoid valves. However, this is a very small signal and this is a very small difference between on and off. It was determined that simple noise can cause fluctuations in voltage from 0.2 to 0.4 volts and since all of this circuitry is mounted in a tight space near large motors that this would not work. At this point we went back to the beginning of the design process and started looking for some other way to control our weapons.

The second time around in the design process, we looked for a way to decode the pulse code modulated signal and use it so that any signal other than the current position signal would engage our weapon. We found that this was a bigger problem than expected. First of all, in order to decode this signal we also needed a feedback from whatever we were controlling which would have to be encoded and sent back as feedback. Second, when Futaba was called about the servomotors, it was discovered that how all the circuitry works and how the signal was decoded and/or encoded was proprietary information. As a result, the idea had to be abandoned. However, after researching how the servo motors worked from other sources, another possibility arose.

In the lab, it was determined that the servomotor mounted in the servo circuitry was a 5VDC motor meaning that when it had 5VDC across the two terminals on the circuit board, it spun one direction and when the polarity was reversed it spun the other direction. This seemed to be the most valid signal to be used as a control voltage. Furthermore, it was discovered that by manually adjusting the potentiometer on the circuit, which was turned via gears in normal operation, the motor could be spun in either the clockwise, counter-clockwise direction, or even stop. When the switch on the remote control was turned off and the potentiometer was set for the motor to stop and then the switch was switched on, the motor would spin one direction via the 5VDC signal being sent to it. This voltage provided the control source needed for the weapon systems.

Our research produced a 5VDC signal at the terminals where the motor was soldered into the servo circuitry. Instead of bypassing this circuitry or trying to decode the servo control pulse signal, the servo circuitry was allowed to decode this signal and output the 5VDC voltage. A schematic of the servo circuitry and modifications that were made can be seen in Figure 13.8.

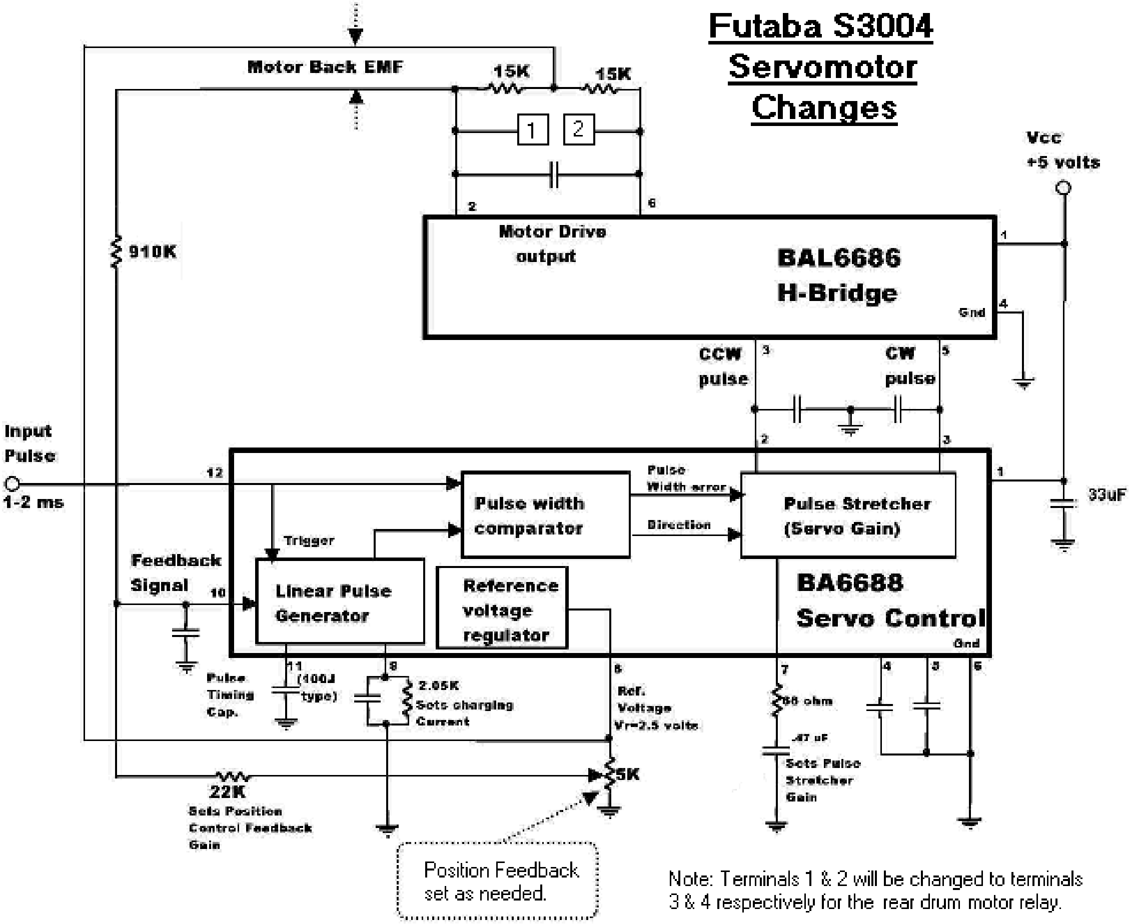


Figure 13.8 – Schematic of Modified Servomotors

In order to change this circuitry, the servomotor had to be disassembled and the circuitry removed. Next, the motor was unsoldered from the circuit board and a set of wires was re-soldered in its place. In order to mount the circuit back into the servo casing, all the gears had to be removed from inside the servomotor casing. Then the wheel was removed from the front.

Finally, an extra hole had to be drilled in the front of the servo casing in order to run the wires out of the servo casing.

The key function that makes the design work is setting the potentiometer to a neutral position when the switch on the remote is in the off position. This means that the voltage across the motor terminals is zero. Now when the switch is switched to ON or 100% we have 5VDC across the motor terminals in the circuit. Of course, this cannot be set until the coil for the relay is attached and the motors are in place due to the fact that the relay coil has a different resistance than the motor and is used as feedback thru the potentiometer. Also, it would have been better to have taken out the potentiometer and soldered in a specific resistor once we found the final value it needed to be set to, however, the servo circuitry was too small to safely unsolder and re-solder the potentiometer terminals without causing damage to the other components or causing a short circuit. Instead, in order to keep the potentiometer from being bumped or moved during battle we a strong epoxy was used to hold the potentiometer in place.

Once the servo was modified, the leads were run out of the front of the servo casing and spade lugs were used, with a crimping tool, so that we could push the wires easily on the relay. The relay was a 5VDC coil relay with contacts rated at 20amps/28VDC. This relay was selected based on the needed coil voltage coming from the servo circuitry. This relay also had a nominal current rating that was equal to the nominal current rating of the actual motor originally in the servomotor circuit. No other modifications were done to the servomotor and with the exception of removing the motor from the servo circuit board and replacing it with two wires we did not change anything in the servo circuit. The functionality of the servo circuit changed in that the potentiometer was set to one setting so, that the circuit supplies either 0 VDC or 5VDC. If the motor was still there it would either stop or spin constantly depending on whether the switch is in the off or on position. In our case, the coil on the relay either engaged the relay and closed the contacts or didn’t do anything. This seemed to be a better design than the original electromechanical design from last year and also had a faster response time since the weapons were being turned on or off with a circuit instead of a mechanical system.

14.0 FABRICATION OF BODY PARTS AND MOUNTS

14.1 Bulkheads

To keep the carbon fiber from crushing when parts were tightened down to it, inserts had to be made. On a lathe, round aluminum stock of different sizes was drilled. Different size insets were made to fit the diverse assortment of screws that were used. All of the inserts were sandblasted to provide a rough surface, which is ideal for epoxying.

The bulkheads were cut out of an aluminum honeycomb cored carbon fiber sheet. The desired outer shape was cut by using a jig saw. Since the bulkheads are where all the drive system would be connected it was very important that the holes drilled would be accurately placed. To assure this the CNC mill was used. The part was fastened to the table and extra care was used to make sure it was lined up straight. Then the part was located by the machine so that each hole would end up exactly where it needed to be as seen in Figure 14.1.

Figure 14.1 – Fabricating Bulkheads on CNC

The inserts were epoxied into the holes in the bulkheads using West System Epoxy. A 404 filler was used to help the epoxy settle in the holes. After the epoxy cured overnight, the inserts were securely attached to the bulkheads.

14.2 Body

The body panels of the shell were machined on the CNC mill because of the accuracy needed for the holes. The size of the panels made it near impossible to do on a conventional mill, so that was another reason why the CNC with a big 3’×5’ table was used.

Welding was used to hold the body together. To ensure that the panels all lined up exactly so that the holes ended up aligned, small jig blocks were made. This allowed the body to be screwed together so that when it was welded everything would be in the right place. The same was done with all the aluminum brackets that were attached to the body. All the brackets were screwed in and then welded. This also allowed us to remove the screws holding the brackets. Therefore leaving a smooth bottom free of nut and bolts heads that could be damaged in battle.

14.3 Front Motor Mounts

For the front motor mounts carbon fiber was also used. In the center of the mount there needed to be a large hole for the center of the motor to fit correctly. The CNC was used to make this since it can precisely make large holes as seen in Figure 14.2. Also, an exact replica was needed for the opposite side. The aluminum inserts where the motor attached were glued as mentioned in Section 14.2.

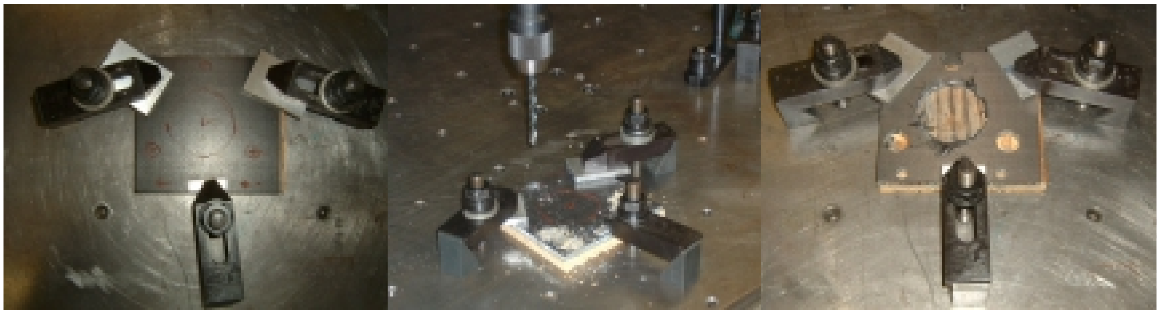


Figure 14.2 – Front Motor Mount on the CNC Mill

15.0 ASSEMBLY

The BattleBot was assembled in stages. First, parts were fabricated and as the parts for one system were finished, they were put together. Once the Body was welded, the parts were assembled and the integration of the many systems began as seen in Figure 15.1.

Figure 15.1 – Assembly of Major Systems into Body

Slight modifications to some parts, such as grinding a clearance on the bulkhead to fit over the welds were performed, but no major alterations were required. Once all systems were installed, the BattleBot was taken to Capital Rubber to have the plumbing for the pneumatic system installed.

Figure 15.2 – Plumbing of Pneumatic System

Working with one of the technicians, the gages, regulator, tanks and valves were plumbed using 3/8" stainless steel braided hose. After the plumbing was finished, the entire BattleBot was disassembled and welds were sanded and the body was polished. All the components were reinstalled and the electrical system was hard mounted inside the BattleBot. Finally, the armor was installed and the assembly was finished as seen in Figure 15.3.

Figure 15.3 – Assembled BattleBot

16.0 TESTING

The BattleBot's systems were tested rigorously during assembly as well as after. Fit checks were performed on all components and system tests were performed to fix problems with individual systems before they were all integrated. Very few problems with the individual system were discovered. Once the body was completed, the systems were all installed together for the first time. Most of the problems were electrical but they were solved relatively quickly.

After the bugs were worked out of the system, the BattleBot performed its first tests. The speed was taken by recording the time over a measured distance as seen in Figure 16.1.

Figure 16.1 – Measuring the BattleBot's Speed

The top speed was found to be 8 mph, just as predicted during the design phase. No excessive wear or other problems was found on the chain system. The electrical system also faired well with no major problems. The secondary weapon worked flawlessly after the bearing on the drum were removed, cleaned and repacked. The armor also worked well resisting repeated blows from ball peen hammers and having things thrown at the robot as it sped by.

The lifting arm also worked as designed. The arm extended out faster than last year and with much greater force as seen in Figure 16.2.

Figure 16.2 – Lifting Arm Motion

If the BattleBot was inverted, it was able to flip itself back over by actuating the arm. No significant damage was done to any of the internal components during this violent maneuver. The lifting arm was also able to throw a cinder block into the air which was a great improvement over the previous design.

Some other observations made during testing were that all of the internal components were very well mounted and secured. During the violent impacts, nothing broke loose or rattled. The motor mounts last year were not very secure which resulted in the mounting bolts getting bent. This design had no such problems. All of the tanks, valves and other components did not shaft, interfere or show any signs of mounting difficulties, which is very important. The design has performed everything it was designed to do and has also proven to be very rugged and durable.

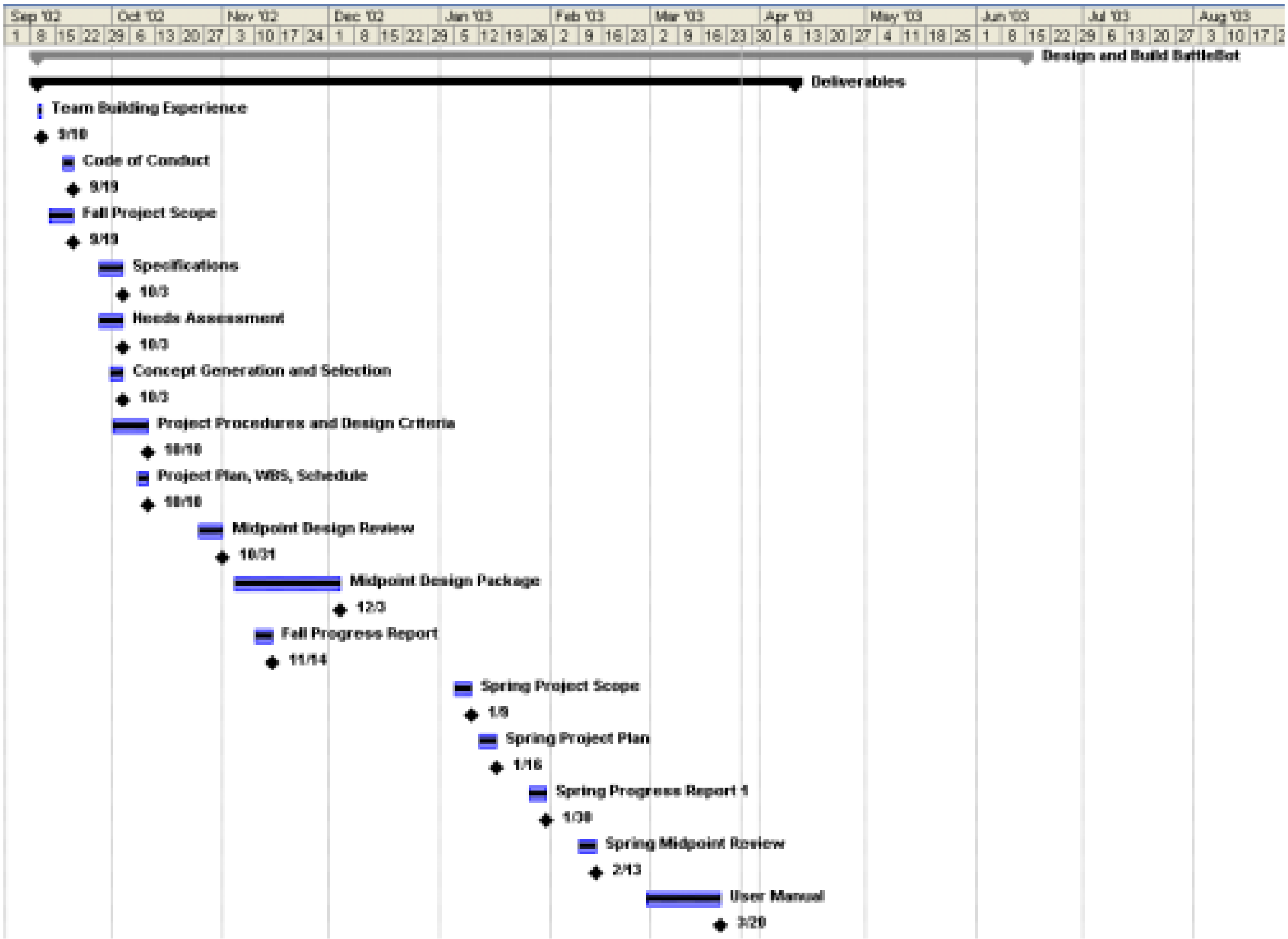
17.0 BILL OF MATERIALS

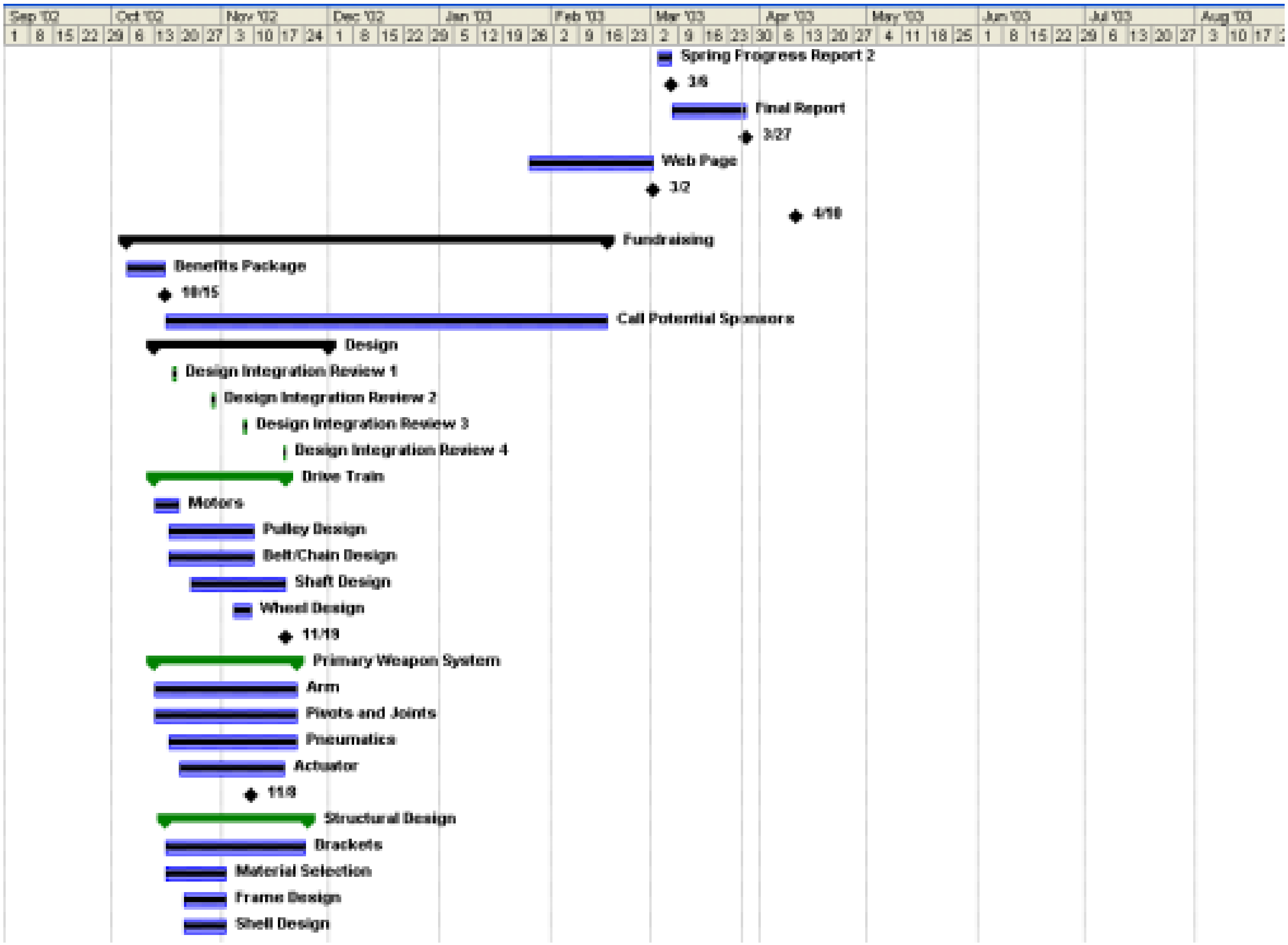
The Bill of Materials for this project and can be seen in Appendix H. All of the parts for the BattleBot, including screws and nuts have been compiled and parts that were donated have a 0 dollar amount.

18.0 CONCLUSIONS

The design of the 2002-2003 BattleBot has been a complete success. Last years design was improved in every aspect and every singe design objective has been met or exceeded. The effectiveness of the weapons has been improved by redesigning the lifting arm. The drive train has been made more durable and reliable by changing it to chain drive and making the motors, shafts and sprockets more secure. Most importantly, however, even with the improvements to the systems, the overall weight has been reduced substantially. Nearly thirty pounds was removed from the BattleBot while increasing the strength and effectiveness. Novel materials and a greater understanding of the structure has greatly contributed to decreasing the weight. Overall, the extremely complex systems and advanced materials and manufacturing techniques came together without many problems or redesigns due to the rigorous attention to detail by the design team early in the design process. The BattleBot senior design project fulfilled all of its objectives on time and for about one tenth the cost of the previous project, making this design a complete success.

APPENDIX A – SCHEDULE

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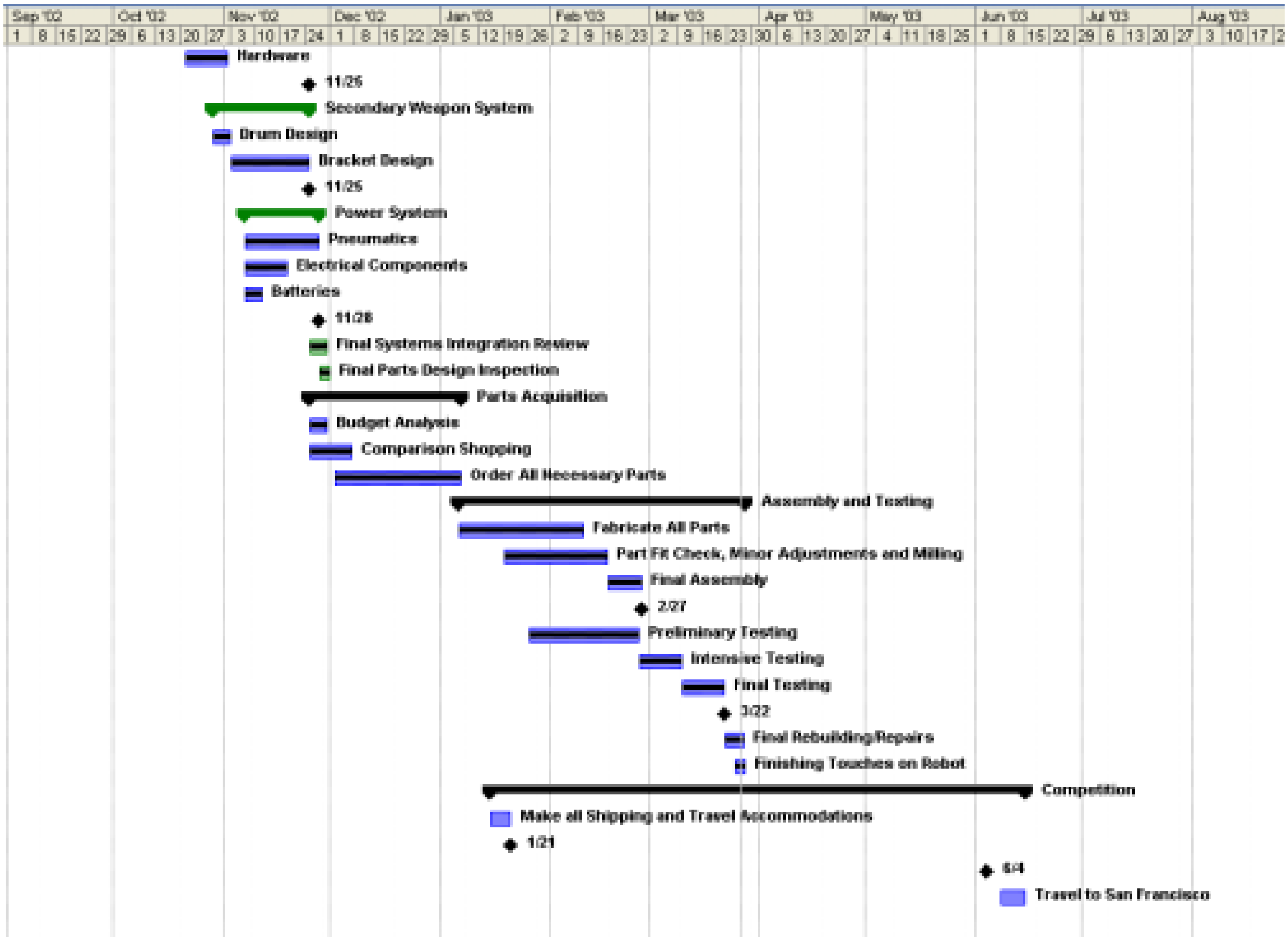
Jan '03
Feb '03
Mar '03
Apr '03
May '03
Jun '03
Jul '03
Aug '03
Spring Progress Report 2
3/6
Final Report
3/27
Web Page
3/2
4/10
Fundraising
Benefits Package
10/15
Call Potential Sponsors
Design
Design Integration Review 1
Design Integration Review 2
Design Integration Review 3
Design Integration Review 4
Drive Train
Motors
Pulley Design
Belt/Chain Design
Shaft Design
Wheel Design
11/19
Primary Weapon System
Arm
Pivots and Joints
Pneumatics
Actuator
11/8
Structural Design
Brackets
Material Selection
Frame Design
Shell Design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Jun '03
Jul '03
Aug '03
Hardware
11/26
Secondary Weapon System
Drum Design
Bracket Design
11/26
Power System
Pneumatics
Electrical Components
Batteries
11/28
Final Systems Integration Review
Final Parts Design Inspection
Parts Acquisition
Budget Analysis
Comparison Shopping
Order All Necessary Parts
Assembly and Testing
Fabricate All Parts
Part Fit Check, Minor Adjustments and Milling
Final Assembly
2/27
Preliminary Testing
Intensive Testing
Final Testing
3/22
Final Rebuilding/Repairs
Finishing Touches on Robot
Competition
Make all Shipping and Travel Accommodations
1/21
6/4
Travel to San Francisco

APPENDIX B – NEEDS/SPECS/CONCEPTS

1.0 NEEDS ASSESMENT

The BattleBot must meet the following Customer Needs:

- Move fast
- Quick acceleration
- Be able to push competitors around arena
- Agile and maneuverable
- Improve weapon effectiveness
- Improve durability
- Armor must protect Bot from other Bots and hazards
- Easy assembly/disassembly and battery recharging
- Must meet heavyweight division requirements
- Self righting

To confirm and validity and completeness of the customer needs and specifications, the needs and metrics were compared to ensure all needs were accounted for the all metrics were necessary. Table 1.1 shows that all the needs are associated with at least one metric and there are no metrics that do not relate to a customer need.

Table 1.1.– Needs/Metrics Matrix

	Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	Needs	High top speed	Powerful drive train	Drive system must withstand constant direction and acceleration changes	Bearings must last through entire competition without needing replacement	Must operate at full power for entire match	Tires must resist punctures and cuts	Tires must have high traction	Must be highly maneuverable	Drive train must function under the weight of another Bot	Primary weapon must be able to function under weight of another Bot	Impact solid immoveable wall repeatedly at full speed and be fully functional	Must survive being tossed through the air	Armor must resist puncture from repeated blows by sharp object	Armor must protect entire robot	Armor must resist temporary encounters with saws	All repairs must be able to be made between matches	Power systems must be ready for each match	Entire Bot must make weight with all components installed	Self righting quickly
1	Move fast	•	•						•											
2	Quick acceleration		•					•	•											
3	Be able to push competitors around arena		•	•				•		•										
4	Agile and maneuverable			•				•	•											
5	Improve weapon's effectiveness									•	•									
6	Improve durability			•	•		•			•	•	•	•							
7	Protect Bot from other Bots and hazards						•							•	•	•				
8	Easy assembly/disassembly and recharging					•											•	•		
9	Must meet heavyweight division requirements					•								•	•	•	•		•	
10	Self righting																			•

2.0 SPECIFICATIONS

2.1 Target Specifications

The Target Specifications for the BattleBot are shown in Table 2.1. Specification importance (Imp,) is on a scale of 1 to 5 with 5 being the highest.

Table 2.1 – Target Specifications

	Metric	Imp.	Ideal Value	Acceptable Values	
				+	-
1	High top speed	4	10 mph	3	3
2	Powerful drive train	5	10 hp	2	4
3	Drive system must withstand constant direction and acceleration changes	5	100 cycles	40	20
4	Bearings must last through entire competition without needing replacement	3	10 matches	2	1
5	Must be highly maneuverable	5	turn within 1 length	0	0.5
6	Drive train must function under the weight of another Bot	3	300lbs	10	80
7	Must operate at full power for entire match	5	5 mins	0	2
8	Tires must resist punctures and cuts	4	75% functional at end of match	25	10
9	Tires must have high traction	4	full power from drivetrain w/o slip	0	10%
10	All repairs must be able to be made between matches	4	20 mins	0	5
11	Power systems must be ready for each match	4	20 mins	0	5
12	Entire bot must make weight with all components installed	5	220 lbs	0	10
13	Self righting quickly	3	7 secs	3	2
14	Primary weapon must be able to function under weight of another Bot	4	300lbs	50	80
15	Impact solid immoveable wall repeatedly at full speed and be fully functional	5	15 times	5	2
16	Must survive being tossed through the air	4	3 ft high drop	2	0
17	Armor must resist puncture from repeated blows by sharp object	4	20 times	10	2
18	Armor must protect entire robot	4	6 sides	0	1
19	Armor must resist temporary encounters with saws	3	3 secs, 4 times	2, 5	0

2.2 Final Specifications

The final specifications for BattleBot design are given in Table 2.2

Table 2.2 – Final Specifications

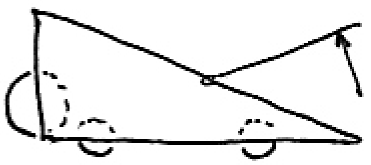
	Metric	**Ideal Value**
1	High top speed	8 mph
2	Powerful drive train	Two 1 hp
3	Drive system must withstand constant direction and acceleration changes	100 cycles
4	Bearings must last through entire competition without needing replacement	10 matches
5	Must be highly maneuverable	turn within 30 inches
6	Drive train must function under the weight of another Bot	300lbs
7	Must operate at full power for entire match	5 mins
8	Tires must resist punctures and cuts	75% functional at end of match
9	Tires must have high traction	full power from drivetrain w/o slip
10	All repairs must be able to be made between matches	20 mins
11	Power systems must be ready for each match	20 mins
12	Entire bot must make weight with all components installed	220 lbs
13	Self righting quickly	7 secs
14	Primary weapon must be able to function under weight of another Bot	300lbs
15	Impact solid immoveable wall repeatedly at full speed and be fully functional	15 times
16	Must survive being tossed through the air	3 ft high drop
17	Armor must resist puncture from repeated blows by sharp object	300 lbs, 20 times
18	Armor must protect entire robot	6 sides
19	Armor must resist temporary encounters with saws	3 secs, 4 times

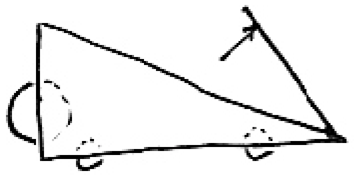
3.0 CONCEPT GENERATION AND SELECTION

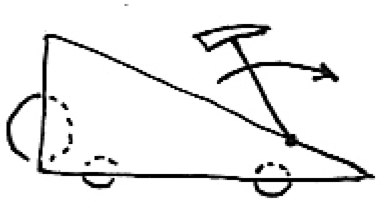
3.1 Concept Generation

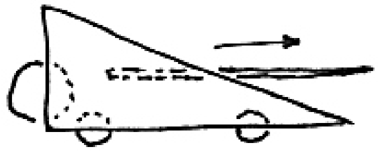
The primary weapon system is mounted on the front of the Bot and will serve and the main method of attack. The concepts generated for the primary weapon system can be seen in Table 3.1.

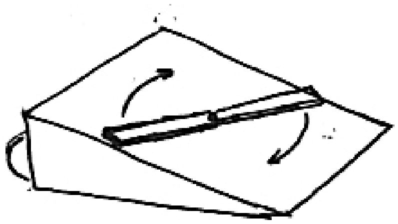
Table 3.1 – Primary Weapon System


Flipper 1


Flipper 2

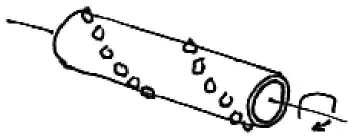

Hammer Spike

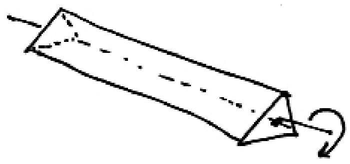

Projectile Spear

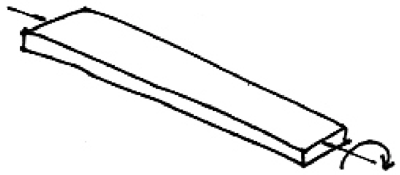

Spinning Blades of Death

The secondary weapon system will serve as another means of attack. It will also facilitate attack from multiple angles and directions as well as greater feasibility in attacking different types of Bots. The concepts generated for the secondary weapon system can be seen in Table 3.2

Table 3.2 – Secondary Weapon System


Helical Spikes

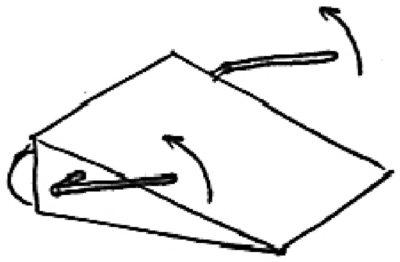

Triangular Bar


Rectangular Bar

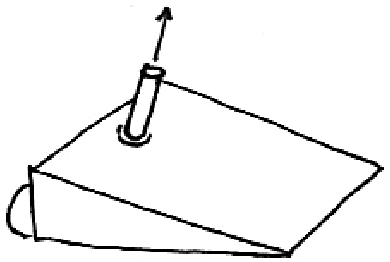

Existing Drum

In the event that the Bot is flipped, either by a hazard or another Bot, the self-righting mechanism will flip the Bot back on its wheels so it is not immobilized and therefore eliminated. Table 7.3 shows the concepts generated for the self righting mechanism.

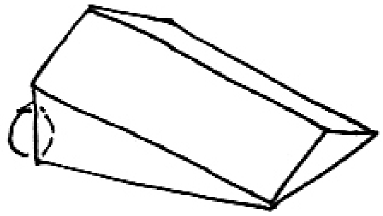
Table 3.3 – Self Righting Mechanism



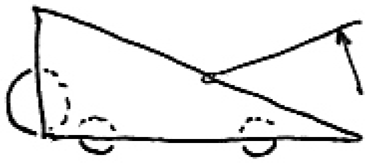
Flipping Arms



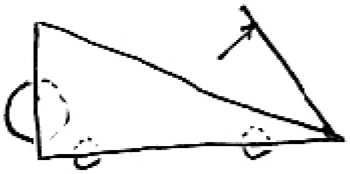
Flipping Rod



Geometric Balance



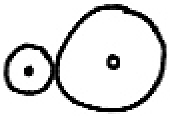
Flipper 1



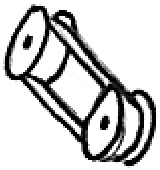
Flipper 2

The drive train must transmit power to the wheels and be able to stand up to the high loads and shocks from other Bots and the hazards in the arena. Concepts generated for the drive train can be found in Table 3.4.

Table 3.4– Drive Train

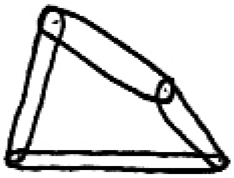


Gears



Belts

Chains



Linkages

3.2 Concept Selection

A rough comparison was made of the concepts in order to eliminate as many unfeasible solutions as possible. Each concept was given a plus (+), minus (-) or zero (0) according to whether it fulfilled the specification or not. By summing the pluses and minuses, the feasibility of each concept was determined. After careful consideration, some were eliminated. Table 3.*5* shows the comparison matrix for the primary weapon system.

Table 3.5 – Phase 1 Matrix for Primary Weapon System

	Concepts				
Selection Criteria	**Flipper 1**	**Flipper 2**	**Hammer Spike**	**Projectile Spear**	**Spinning Blades**
Move fast	0	0	0	0	0
Quick acceleration	0	0	0	0	0
Be able to push competitors around arena	+	+	-	-	-
Agile and maneuverable	0	0	0	0	0
Improve weapon effectiveness	0	0	0	0	0
Improve durability	0	0	0	0	0
Armor must protect Bot from other Bots and hazards	+	+	-	-	0
Easy assembly/disassembly and battery recharging	0	0	0	0	-
Must meet heavyweight division requirements	+	+	-	-	-
Self righting	+	-	+	-	-
Low cost	-	-	-	-	-
Ease of machining	+	+	+	-	0
Feasibility of timely production	+	+	+	0	0
Use existing parts	+	+	-	-	-
Sum +'s	7	6	3	0	0
Sum 0's	6	6	6	7	8
Sum -'s	1	2	5	7	6
Net Score	6	4	-2	-7	-6
Rank	1	2	3	5	4
Continue?	yes	yes	no	no	no

After careful consideration, the Hammer Spike, Projectile Spear and Spinning Blades were eliminated. To narrow the selection further, the remaining two possibilities were tested by assigning a weight and value to the fulfillment of each specification and summing the numbers to get a total score. If it seemed that the concept with the highest score was the best, all other concepts were eliminated. If not, a more rigorous selection would have to be performed. Fortunately, this more rigorous selection process was not necessary. Table 3.*6* shows the final concept selection for the primary weapon system.

Table 3.6 – Phase 2 Matrix for Primary Weapon System

		Concepts			
		Flipper 1		**Flipper 2**	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Move fast	3%	2	0.06	2	0.06
Quick acceleration	4%	2	0.08	2	0.08
Be able to push competitors around arena	12%	4	0.48	3	0.36
Agile and maneuverable	7%	4	0.28	4	0.28
Improve weapon effectiveness	11%	5	0.55	3	0.33
Improve durability	12%	3	0.36	3	0.36
Armor must protect Bot from other Bots and hazards	6%	3	0.18	4	0.24
Easy assembly/disassembly and battery recharging	5%	3	0.15	3	0.15
Must meet heavyweight division requirements	9%	4	0.36	4	0.36
Self righting	10%	5	0.5	3	0.3
Low cost	11%	3	0.33	3	0.33
Ease of machining	4%	2	0.08	2	0.08
Feasibility of timely production	3%	3	0.09	3	0.09
Use existing parts	3%	2	0.06	2	0.06
Net Score	100%		3.56		3.08
Rank			1		2
Continue?			yes		no

The Flipper 1 was determined to be the best concept and will be developed.

The same procedure was used to determine the concepts for all other categories. Table 3.*7* shows the rough selection matrix for the secondary weapon system. It was determined that even though there was a difference in the scores, no concepts could be eliminated at this phase because they all showed possible merit.

Table 3.7 – Phase 1 Matrix for Secondary Weapon System

	Concepts			
Selection Criteria	**Helical Spikes**	**Triangular Bar**	**Rectangular Bar**	**Existing Drum**
Move fast	0	0	0	0
Quick acceleration	0	0	0	0
Be able to push competitors around arena	0	0	0	0
Agile and maneuverable	0	0	0	0
Improve weapon effectiveness	+	+	-	0
Improve durability	-	0	0	0
Armor must protect Bot from other Bots and hazards	0	0	0	0
Easy assembly/disassembly and battery recharging	0	0	0	0
Must meet heavyweight division requirements	0	+	+	0
Self righting	0	0	0	0
Low cost	0	0	0	+
Ease of machining	-	+	+	-
Feasibility of timely production	0	+	+	0
Use existing parts	-	-	-	+
Sum +'s	1	4	3	2
Sum 0's	8	9	9	10
Sum -'s	3	1	1	1
Net Score	-2	3	2	1
Rank	4	1	2	3
Continue?	yes	yes	yes	yes

All four concepts were ranked in the weighted matrix as seen in Table 3.8. After careful consideration, including cost and use of existing parts, the existing drum was decided upon as the best concept.

Table 3.8 – Phase 2 Matrix for Secondary Weapon System

		Concepts							
		Helical Spikes		**Triangular Bar**		**Rectangular Bar**		**Existing Drum**	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Move fast	3%	3	0.09	4	0.12	4	0.12	4	0.12
Quick acceleration	4%	1	0.04	3	0.12	3	0.12	1	0.04
Be able to push competitors around arena	12%	3	0.36	3	0.36	3	0.36	4	0.48
Agile and maneuverable	7%	2	0.14	3	0.21	3	0.21	2	0.14
Improve weapon effectiveness	11%	4	0.44	4	0.44	4	0.44	5	0.55
Improve durability	12%	3	0.36	3	0.36	3	0.36	3	0.36
Armor must protect Bot from other Bots and hazards	6%	2	0.12	2	0.12	2	0.12	2	0.12
Easy assembly/disassembly and battery recharging	5%	3	0.15	3	0.15	3	0.15	4	0.2
Must meet heavyweight division requirements	9%	2	0.18	4	0.36	2	0.18	2	0.18
Self righting	10%	1	0.1	1	0.1	1	0.1	1	0.1
Low cost	11%	2	0.22	3	0.33	3	0.33	5	0.55
Ease of machining	4%	1	0.04	2	0.08	2	0.08	3	0.12
Feasibility of timely production	3%	3	0.09	3	0.09	3	0.09	3	0.09
Use existing parts	3%	1	0.03	1	0.03	1	0.03	5	0.15
Net Score	100%		2.36		2.87		2.69		3.2
Rank			4		2		3		1
Continue?			no		no		no		yes

The rough selection matrix for the self righting mechanism is shown in Table 3*.9*. It was determined that using either of the flippers as the self righting mechanism was the best of the concepts.

Table 3.9– Phase 1 Matrix for Self Righting Mechanism

	Concepts				
Selection Criteria	**Flipping Arms**	**Flipping Rod**	**Geometric Balance**	**Flipper 1**	**Flipper 2**
Move fast	0	0	0	0	0
Quick acceleration	0	0	0	0	0
Be able to push competitors around arena	0	0	0	0	0
Agile and maneuverable	0	0	0	0	0
Improve weapon effectiveness	0	0	0	0	0
Improve durability	0	0	0	0	0
Armor must protect Bot from other Bots and hazards	-	-	+	+	+
Easy assembly/disassembly and battery recharging	-	-	+	0	0
Must meet heavyweight division requirements	-	-	-	0	0
Self righting	+	+	+	+	+
Low cost	-	-	-	-	-
Ease of machining	-	-	-	0	0
Feasibility of timely production	0	0	0	0	0
Use existing parts	-	-	-	0	+
Sum +'s	1	1	3	2	3
Sum 0's	7	7	7	11	10
Sum -'s	6	6	4	1	1
Net Score	-5	-5	-1	1	2
Rank	4	5	3	2	1
Continue?	no	no	no	yes	yes

The two flipping arms were carried over to the weighted matrix as seen in Table 3.10. The Flipper 1 concept was determined to be the best concept. Fortunately, the Flipper 1 concept was also determined as the best primary weapon system. Had this not been the case, the selection of both systems would have been revaluated.

Table 3.10– Phase 2 Matrix for Self Righting Mechanism

		Concepts			
		Flipper 1		**Flipper 2**	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Move fast	3%	2	0.06	2	0.06
Quick acceleration	4%	3	0.12	3	0.12
Be able to push competitors around arena	12%	2	0.24	2	0.24
Agile and maneuverable	7%	2	0.14	2	0.14
Improve weapon effectiveness	11%	4	0.44	2	0.22
Improve durability	12%	2	0.24	2	0.24
Armor must protect Bot from other Bots and hazards	6%	4	0.24	4	0.24
Easy assembly/disassembly and battery recharging	5%	2	0.1	2	0.1
Must meet heavyweight division requirements	9%	4	0.36	4	0.36
Self righting	10%	5	0.5	3	0.3
Low cost	11%	2	0.22	2	0.22
Ease of machining	4%	4	0.16	4	0.16
Feasibility of timely production	3%	4	0.12	4	0.12
Use existing parts	3%	3	0.09	3	0.09
Net Score	100%		3.03		2.61
Rank			1		2
Continue?			yes		no

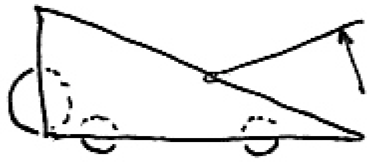
Finally, the drive system was evaluated using the rough selection matrix as seen in Table 3*.11*. It was determined that chains would make the best drive system even though it did not win out decisively over belts. This decision was made due to the fact that the belts failed in the 2002 competition and that chains could be more durable.

Table 3.11 – Phase 1 Matrix for Drive Train

	Concepts			
Selection Criteria	**Gears**	**Belts**	**Chains**	**Linkage**
Move fast	0	0	0	0
Quick acceleration	0	0	0	0
Be able to push competitors around arena	0	0	0	0
Agile and maneuverable	0	0	0	0
Improve weapon effectiveness	0	0	0	0
Improve durability	+	-	+	-
Armor must protect Bot from other Bots and hazards	0	0	0	0
Easy assembly/disassembly and battery recharging	+	-	+	-
Must meet heavyweight division requirements	-	+	+	-
Self righting	0	0	0	0
Low cost	-	+	+	-
Ease of machining	-	+	+	-
Feasibility of timely production	0	+	+	-
Use existing parts	-	+	-	-
Sum +'s	2	5	6	0
Sum 0's	8	7	7	7
Sum -'s	4	2	1	7
Net Score	-2	3	5	-7
Rank	3	2	1	4
Continue?	no	no	yes	no

The final concept selections for all systems can be seen in Table 3.12

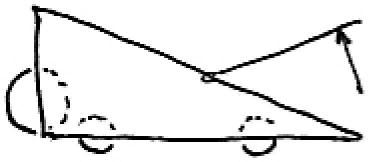
Table 3.12 – Final Concept Selections for all Systems



Primary Weapon - Flipper 1

Secondary Weapon – Existing Drum

Drive Train - Chains



Self Righting Mechanism – Flipper 1

APPENDIX C – DRIVE TRAIN CALCULATIONS

Team 9 BattleBot

Florida State University
Tallahassee, FL

DATE 12/02/02	**DOCUMENT NAME**	Drive Train Calculations	REV -

TITLE:

Drive Train Calculations

TEAM MEMBERS:

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Rafael Bonnelly	Will Resnick	Jay Wells	David Leddy

REVISIONS							
LTR	DESCRIPTION	DATE	APPROVAL	LTR	DESCRIPTION	DATE	APPROVAL
-	Initial release	12/02/02					

PAGE				
REVISION	-	-	-	
PAGE				PAGE 1 OF 12
REVISION				

Team 9 BattleBot

Florida State University
Tallahassee, FL

DATE 12/02/02	**DOCUMENT NAME**	Drive Train Calculations REV -

TABLE OF CONTENTS

1.0 THEORY 78

2.0 DESIGN CALCULATIONS 80

- 2.1 MATERIAL SELECTION 81
- 2.2 SPROCKET SIZE CALCULATIONS 81

REFERENCES 85

APPENDIX A – MATHCAD 86

1.0 THEORY

Chain drives transmit power from one shaft to another through a chain made of links, connected by rollers which are in mesh with teeth on sprockets attached to each shaft. Chain size is denoted by the chain pitch, or the distance between each link as seen in Figure 1[1].

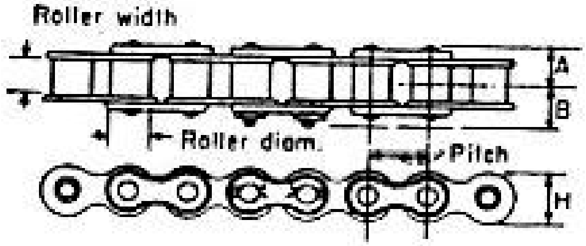


Figure 1 – Chain Pitch

Standard have been created by ANSI to describe each size of chain. For example, a #35 ANSI chain has a pitch of 3/8 inches. These standards can be found in ANSI document numbers JIS 1801 and JIS 1802.

Chain can also be single, double, triple or more stranded as seen in Figure 2[2].

Figure 2 – Single and Double Strand Chains

This is done to increase the power transmitted but using double strand chain does not mean the twice the power can be transmitted. Due to the construction and added friction, the increase in power transmission is only 1.7 times that of single chain. Table 1 shows the power factors for single double and triple chain[3].

Table 1 – Service Factors

Number of strands	Service Factor
2	1.7
3	2.5
4	3.3

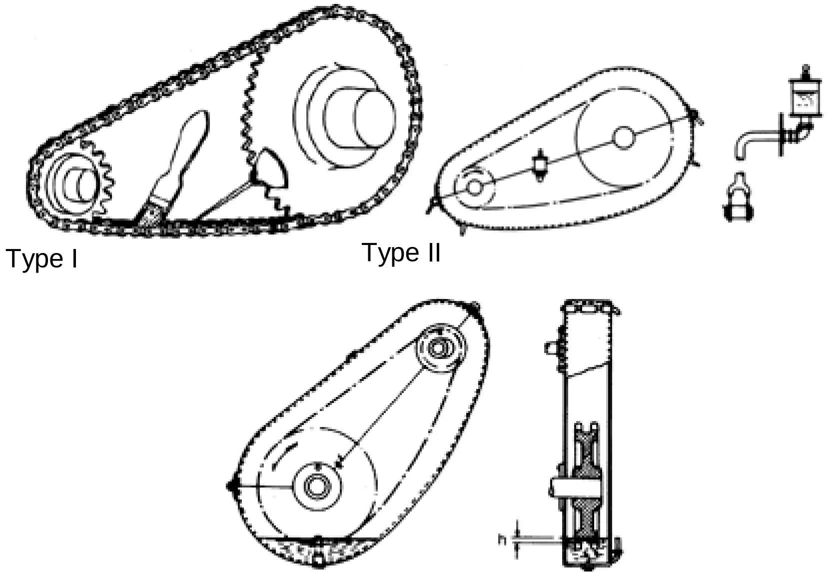
The limiting factor on the design of the chain drives is the number of teeth on the small sprocket. This is based on the horsepower being transmitted and the RPM of the small sprocket. The more teeth there are on the small sprocket, the higher the power that can be transmitted. Manufactures of chain drive components have tabulated this data as seen in Table 2[1].

Table 2 – Table for Sprocket Sizing Based on Horsepower and RPM

ANSI Pitch No.	**No. Teeth on Small Sprocket**	**Small Sprocket RPM**									
		50	**500**	**1200**	**1800**	**2500**	**3000**	**4000**	**5000**	**6000**	**8000**
25	11	0.03	0.23	0.50	0.73	0.98	1.15	1.38	0.99	0.75	0.49
	15	0.04	0.32	0.70	1.01	1.36	1.61	2.08	1.57	1.20	0.78
	20	0.06	0.44	0.96	1.38	1.86	2.19	2.84	2.42	1.84	1.20
	25	0.07	0.56	1.22	1.76	2.37	2.79	3.61	3.38	2.57	1.67
	30	0.08	0.68	1.49	2.15	2.88	3.40	4.40	4.45	3.38	2.20
	40	0.12	0.92	2.03	2.93	3.93	4.64	6.00	6.85	5.21	3.38
35	11	0.10	0.77	1.70	2.45	3.30	2.94	1.91	1.37	1.04	0.67
	15	0.14	1.08	2.38	3.43	4.61	4.68	3.04	2.17	1.65	1.07
	20	0.19	1.48	3.25	4.68	6.29	7.20	4.68	3.35	2.55	1.65
	25	0.24	1.88	4.13	5.95	8.00	9.43	6.54	4.68	3.56	2.31
	30	0.29	2.29	5.03	7.25	9.74	11.50	8.59	6.15	4.68	3.04
	40	0.39	3.12	6.87	9.89	13.30	15.70	13.20	9.47	7.20	4.68
		Type I		Type II					Type III		

The RPM and horsepower are known, thus the number of teeth on the small sprocket can be read directly from the chart. It can be seen that heavier chains can not run at as high RPMs as smaller chains. Also, as the RPM increases, the power transmitted increases as would be expected. However, as the RPM gets higher, there is a point where the rollers impact the sprocket teeth so hard that the bushings are galled, resulting in a dramatic reduction in power transmitted. Thus, operating at the below this maximum power transmission will lead to the most efficient chain drive with the longest life.

Lubrication of chain drive systems is also very important. There are three types of lubrication as seen in Figure 3[4].



Type I

Type II

Type III

Figure 3 – Type I (Manual), Type II (Oil Bath) and Type III (Oil Spray) Lubrication

Type I lubrication is brushed or dripped on manually and simply is replenished as needed. This is typically used for low speed or low torque applications. Type II lubrication is an oil bath where the chain is in a case and it runs through a sump filled with oil. This is used for moderate speed and torque application. Type III lubrication is dripped or sprayed by a pump directly between the links of the chain and is used for high speed and torque applications.

The type of lubrication required is determined by the power transmitted and RPM of the small sprocket. This information is on the same table used to size the small sprocket as seen in Table 3[1].

Table 3 – Lubrication Requirements

ANSI Pitch No.	**No. Teeth on Small Sprocket**	**Small Sprocket RPM**									
		50	**500**	**1200**	**1800**	**2500**	**3000**	**4000**	**5000**	**6000**	**8000**
25	11	0.03	0.23	0.50	0.73	0.98	1.15	1.38	0.99	0.75	0.49
	15	0.04	0.32	0.70	1.01	1.36	1.61	2.08	1.57	1.20	0.78
	20	0.06	0.44	0.96	1.38	1.86	2.19	2.84	2.42	1.84	1.20
	25	0.07	0.56	1.22	1.76	2.37	2.79	3.61	3.38	2.57	1.67
	30	0.08	0.68	1.49	2.15	2.88	3.40	4.40	4.45	3.38	2.20
	40	0.12	0.92	2.03	2.93	3.93	4.64	6.00	6.85	5.21	3.38
35	11	0.10	0.77	1.70	2.45	3.30	2.94	1.91	1.37	1.04	0.67
	15	0.14	1.08	2.38	3.43	4.61	4.68	3.04	2.17	1.65	1.07
	20	0.19	1.48	3.25	4.68	6.29	7.20	4.68	3.35	2.55	1.65
	25	0.24	1.88	4.13	5.95	8.00	9.43	6.54	4.68	3.56	2.31
	30	0.29	2.29	5.03	7.25	9.74	11.50	8.59	6.15	4.68	3.04
	40	0.39	3.12	6.87	9.89	13.30	15.70	13.20	9.47	7.20	4.68
		Type I		Type II					Type III		

The table is divided into sections of Type I (blue), II (yellow), and III (red) lubrication. Which ever section the horsepower, RPM and number of teeth on the small sprocket meet is the type of lubrication required.

The life of the chain is heavily dependent on the type and quality of lubrication. A properly maintained chain is expected to last 15000 hours. Lack of lubrication, foreign particles, dirt, and metal shavings can damage the chain and reduce its life.

The distance between the shafts is also important. As the distance decreases, the wrap of the chain around the larger sprocket increases while the wrap of the smaller sprocket decreases. Since it is better to have more teeth in mesh with the chain at one time, the center distance should be as great as possible. The recommended distance is 30-50 pitches[5].

2.0 DESIGN CALCULATIONS

An overall gear reduction of between 5:1 and 6:1 was used last year and was satisfactory, so the chain drive was designed with this reduction. It quickly became apparent that a compound reduction would be necessary. With a minimum of 10 teeth recommended on the small sprocket, the large sprocket would have to have at least 50 teeth to accomplish the reduction directly. This meant that for #35 ANSI chain, the large sprocket would have to be approximately 7 inches in diameter. Since the wheels are only five inches in diameter, this would mean that the sprocket would stick out of the bottom of the robot and hit the ground. Thus, a compound reduction was necessary to keep the size of the large sprocket on the wheel shaft to a minimum.

The chain and sprockets for the drive train needed to be as light as possible while retaining high strength. In addition, the space constraints meant that the diameter of the sprockets could not be much larger than 3 inches. The power to be transmitted was approximately 1 horsepower.

2.1 Material Selection

The objective of the design is for the drive train to be as strong as possible. It must, however, do this while being light weight. Last year's BattleBot was overweight by about 7 pounds and strengthening the drive train was definitely going to add weight. Thus, choosing the correct material was very important.

The belt drive system was clearly not strong enough to take the loads imposed upon it by the impacts and constant direction changes. To ensure that the chain drive would be strong enough, a factor of safety of between 1.5 and 2 was set for the system. This factor would be applied to the maximum power the drive train could generate, which was when the wheels were stopped and the motors were at full power. Although this factor of safety is not very high, the drive train would not see this stress very often and would most often operate well below this point.

Since the chain and sprockets were going to be bought from a manufacturer, the list of available materials was quite small. Fortunately, the strength and weight information for the complex shapes and materials had already been calculated and tabulated for the different sizes of sprockets and chains. The materials available included steel, stainless steel, cast iron, nylon, and fiberglass reinforced nylon.

Cast iron was eliminated immediately because all of these sprockets were designed to transmit much more than 1 horsepower and where far larger than was necessary. For the remaining sprockets, the power transmission capability of the different material was compared for a 21 tooth sprocket. A 21 tooth sprocket was chosen because it was the largest sprocket that could fit onto the wheel shaft without hitting the bottom of the BattleBot. It was determined that a steel or stainless steel sprocket were the only choices that could carry the load while still being small enough to fit into the BattleBot. Steel was chosen because the environment was not excessively corrosive, steel was slightly stronger and stainless steel was about 5 times as expensive as steel.

For the chain, the tensile strengths for #35 ANSI chain for each material, as well as weight per foot, were compared. The steel chain had the highest tensile strength but also the greatest weight. However, steel chain was chosen because it was the only one that could handle the load.

2.2 Sprocket Size Calculations

After deciding on steel chain, the size was determined by examining the horsepower capacity as well as the size. As the size of the chain increased, the diameter of the sprockets did also. In addition, as the size increased, the maximum RPM decreased. The sizes near the operating range were #25, #35, and #40 ANSI chain. Using the information seen in Table 1[1], #35 ANSI chain was chosen because it gave plenty of strength, could operate at the high RPM at the motor, but was small enough that the sprockets would fit into the BattleBot.

Table 1 – Sprocket Sizing Table with Approximate Operating Ranges of Drive Train Highlighted

ANSI Pitch No.	**No. Teeth on Small Sprocket**	**Small Sprocket RPM**									
		50	**500**	**1200**	**1800**	**2500**	**3000**	**4000**	**5000**	**6000**	**8000**
25	11	0.03	0.23	0.50	0.73	0.98	1.15	1.38	0.99	0.75	0.49
	15	0.04	0.32	0.70	1.01	1.36	1.61	2.08	1.57	1.20	0.78
	20	0.06	0.44	0.96	1.38	1.86	2.19	2.84	2.42	1.84	1.20
	25	0.07	0.56	1.22	1.76	2.37	2.79	3.61	3.38	2.57	1.67
	30	0.08	0.68	1.49	2.15	2.88	3.40	4.40	4.45	3.38	2.20
	40	0.12	0.92	2.03	2.93	3.93	4.64	6.00	6.85	5.21	3.38
35	11	0.10	0.77	1.70	2.45	3.30	2.94	1.91	1.37	1.04	0.67
	15	0.14	1.08	2.38	3.43	4.61	4.68	3.04	2.17	1.65	1.07
	20	0.19	1.48	3.25	4.68	6.29	7.20	4.68	3.35	2.55	1.65
	25	0.24	1.88	4.13	5.95	8.00	9.43	6.54	4.68	3.56	2.31
	30	0.29	2.29	5.03	7.25	9.74	11.50	8.59	6.15	4.68	3.04
	40	0.39	3.12	6.87	9.89	13.30	15.70	13.20	9.47	7.20	4.68
		Type I		Type II					Type III		

The #40 chain, with a 1/2" pitch was not chosen because it was operating nearer to the maximum RPM allowed for that size chain. In addition, the sprockets would have been too large to fit into the BattleBot.

The #25 chain was not chosen because for it to handle the load, the sprockets would have had to have more teeth, and consequently, would be too large to fit.

Once the #35 chain was chosen, the next step was to size the sprockets. Since a compound train was to be used, the size of the sprockets, as well as the individual reductions of each train could be manipulated. The overall reduction was calculated using Equation 1 where $N_1 - N_4$ are the number of teeth on each sprocket and M_1 and M_2 are the reduction ratios.

$$M_{total} = (M_1)(M_2) = \frac{N_2}{N_1}\frac{N_4}{N_3} \qquad (1)$$

The gear locations are shown in Figure 1.

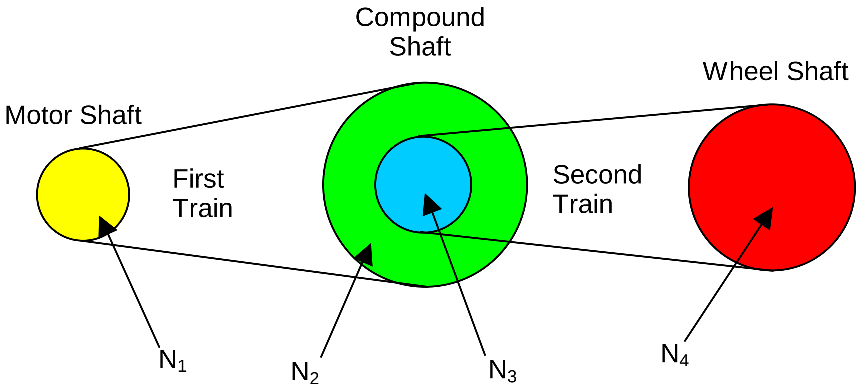


Figure 1 – Compound Gear Train

Using MathCad, many combinations of gear ratios and numbers of teeth were explored. From the geometry of the BattleBot, it was determined that the wheel sprocket could not be larger than 21 teeth. If it was any larger, it would hit the bottom of the body. This helped to reduce the number of variables in the problem. After many iterations, it was determined that the more even the reduction ratios were between the two trains, the better the overall design. This was due to the fact that as the first ratio was increased, the RPM of the second train's small sprocket was reduced, resulting in less power capacity as seen in Table 1. These calculations can be found in Appendix A.

After many iterations, the sprockets were finally sized and it was determined that they would fit into the BattleBot. The sizes are shown in Table 2.

Table 2 – Sprocket Sizes

Sprocket Number	Number of Teeth	OD (in)
1	10	1.38
2	25	3.19
3	10	1.38
4	21	2.71

The factors of safety for each train were also calculated. Since the weakest part of the drive train was the small sprocket, the factor of safety of each train was based on that part. Using Table 1, the factor of safety was calculated using Equation 2 where n was the factor of safety.

$$n = \frac{load_{capacity}}{load_{applied}} \tag{2}$$

The load capacity was obtained from Table 1 and the load applied was equal to the horsepower of the motor, or 1 hp. The factor of safety for Train 1 was 2.5, and was 1.7 for Train 2. These calculations can be seen in Appendix A.

Sprockets 1 and 3 were made the same size to reduce the number of different parts required. The overall ratio, calculated using Equation 1, was found to be 5.25:1 which was within the tolerance.

Next, the length of chain needed to be calculated. This was done using Equation 3 where L is the length of chain in pitches, C is the center distance in pitches, N_1 is the number of teeth on the small sprocket, and N_2 is the number of teeth on the large sprocket.

$$L = 2C + \frac{N_2 + N_1}{2} + \frac{(N_2 - N_1)^2}{4\pi^2 C} \tag{3}$$

To obtain the center distances, the exact layout of the drive train in the BattleBot was needed. This was modeled in 3-D using Pro/E which will be examined later. The basic layout of the drive train can be seen in Figure 2.

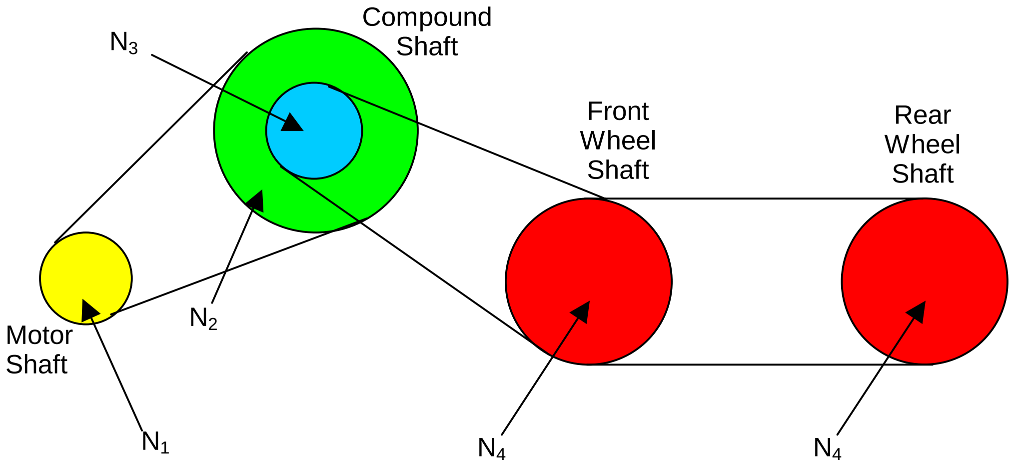


Figure 2 – Basic Layout of BattleBot Drive Train

The center distances were obtained from Pro/E and used to calculate the length of chain. Equation 4 was used to convert inches to pitches and vice versa where p is the chain pitch (3/8 inch for #35 chain).

$$l_{in} = l_{pitches}\, p \tag{4}$$

The length of chain between the motor and compound shafts was found to be 23.25 inches, between the compound and front wheel shafts was 16.5 inches and between the front and rear wheel shafts was 27.375 inches. These detailed calculations can be found in Appendix A.

REFERENCES

1. Mark's Standard Handbook for Mechanical Engineers, 10th Ed.; Euegene A. Avallone, Theodore Baumeister III; McGraw Hill; 1996
2. McMaster Carr Online Catalog; http://www.mcmaster.com
3. Machine Elements in Mechanical Design; Robert L. Mott; Prentice Hall; New Jersey; 1999
4. Ustsubaki Corp.; The Complete Guide to Chain; http://www.ustsubaki.com/section7.html#0009
5. Design and Application of Small Standardized Components; Stock Drive Products; New York; 1983

APPENDIX A – MATHCAD

design horsepower = 1 hp.

Gear Train 1

$\omega_1 := 3300$ $N_1 := 10$ $N_2 := 25$

$M_1 := \frac{N_2}{N_1}$ $M_1 = 2.5$ $factor\_of\_safety_1 := 2.5$ from Table

Gear Train 2

$\omega_2 := \frac{3300}{M_1}$ $\omega_2 = 1.32\times 10^3$

$N_3 := 10$ $N_4 := 21$ fixed by size of BattleBot

$M_2 := \frac{N_4}{N_3}$ $M_2 = 2.1$ $factor\_of\_safety_2 := 1.7$ from Table

Overall Gear Ratio

$M := M_1 \cdot M_2$ $M = 5.25$

Center distance between motor and compound shaft

$C_{in} := 8.29$ inches from Pro/E model

$C := \frac{C_{in}}{\frac{3}{8}}$ convert to pitches $C = 22.107$ pitches

$C := \mathrm{round}(C, 0)$ round to even number of pitches $C = 22$

Length of Chain (pitches)

$n := 10$ $N := 25$ $L := 2C + \frac{N+n}{2} + \frac{(N-n)^2}{4\pi^2 C}$ $L = 61.759$

$L := \mathrm{round}(L, 0)$ $L = 62$ pitches

$L_{in} := \frac{3}{8} \cdot L$ $L_{in} = 23.25$ inches

initialize counting variable

$L_{total} := 0$

sum counting variable

$L_{total} := L_{total} + L$

Center distance between compound shaft and front wheel shaft

$C_{in} := 5.3$ inches from Pro/E model

$C := \dfrac{C_{in}}{\dfrac{3}{8}}$ convert to pitches $C = 14.133$ pitches

$C := \mathrm{round}(C, 0)$ round to even number of pitches $C = 14$

Length of Chain (pitches)

$n := 10$ $N := 21$ $L := 2C + \dfrac{N + n}{2} + \dfrac{(N - n)^2}{4\pi^2 C}$ $L = 43.719$

$L := \mathrm{round}(L, 0)$ $L = 44$ pitches $L_{total} := L_{total} + L$

$L_{in} := \dfrac{3}{8} \cdot L$ $L_{in} = 16.5$ inches

Center distance between front wheel shaft and rear wheel shaft

$C_{in} := 9.625$ inches from Pro/E model

$C := \dfrac{C_{in}}{\dfrac{3}{8}}$ convert to pitches $C = 25.667$ pitches

$C := \mathrm{round}(C, 0)$ round to even number of pitches $C = 26$

Length of Chain (pitches)

$n := 21$ $N := 21$ $L := 2C + \dfrac{N + n}{2} + \dfrac{(N - n)^2}{4\pi^2 C}$ $L = 73$

$L := \mathrm{round}(L, 0)$ $L = 73$ pitches $L_{total} := L_{total} + L$

$L_{in} := \dfrac{3}{8} \cdot L$ $L_{in} = 27.375$ inches

Total Chain Required

$L_{total} = 179$ pitches per side

$L_{in\_total} := \dfrac{3}{8} \cdot L_{total}$ $L_{in\_total} = 67.125$ inches per side

$L_{ft\_total} := \dfrac{L_{in\_total}}{12}$ $L_{ft\_total} = 5.594$ feet per side

APPENDIX D – PRIMARY WEAPON SYSTEM CALCULATIONS

Team 9 BattleBot

Florida State University
Tallahassee, FL

DATE 12/02/02	**DOCUMENT NAME**	Primary Weapon System Calculations REV -

TITLE:

Primary Weapon System Calculations

TEAM MEMBERS:

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REVISIONS							
LTR	DESCRIPTION	DATE	APPROVAL	LTR	DESCRIPTION	DATE	APPROVAL
-	Initial release	12/02/02					

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PAGE																		PAGE 1 OF 22					
REVISION																							

DATE 12/02/02	**DOCUMENT NAME**	Primary Weapon System Calculations REV -

TABLE OF CONTENTS

1.0 GENERAL CALCULATIONS 91

2.0 MATERIAL SELECTION CALCULATIONS 95

3.0 CONCLUSIONS 99

REFERENCES 100

APPENDIX A: MATHCAD CALCULATIONS 101

1.0 GENERAL CALCULATIONS

Through concept generation and selection, the senior design team established a simple design of a self-righting mechanism for the BattleBot. It will consist of a long beam-arm, a pneumatic actuator, pin joints and brackets. One end of the beam-arm will be attached to the top-front of the BattleBot and will rotate about the attachment. The pneumatic actuator connected to the beam-arm forms a four-bar linkage in the form of an inverted slider crank. A diagram of the linkage is shown in Figure 1.1.

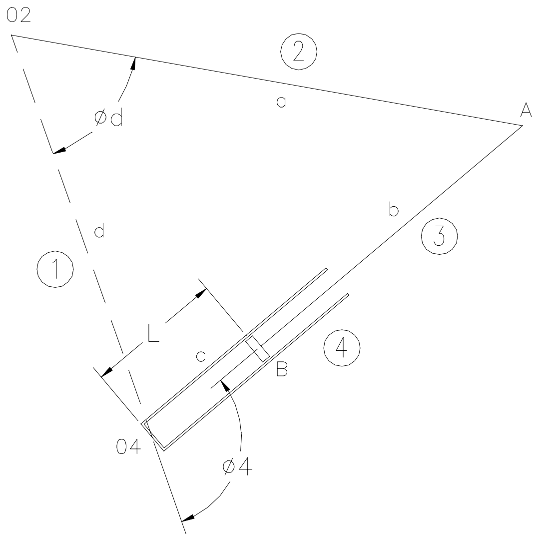


Figure 1.1: BattleBot SRM Inverted Slider Crank Four-Bar Linkage

Point 0_2 and 0_4 are joints, grounded to the body of the BattleBot. Point A is a joint where the actuator attaches to the arm. Link 1 is the distance between grounded points. Link 2 is the part of the arm between ground 0_2 and the cylinder-arm attachment. The retracted cylinder length and stroke lengths determine link lengths 3 and 4. Note that the transmission angle, between links 3 and 4, is zero.

The dimensions of the BattleBot that constrain placement of the SRM links are shown in Figure 1.2.

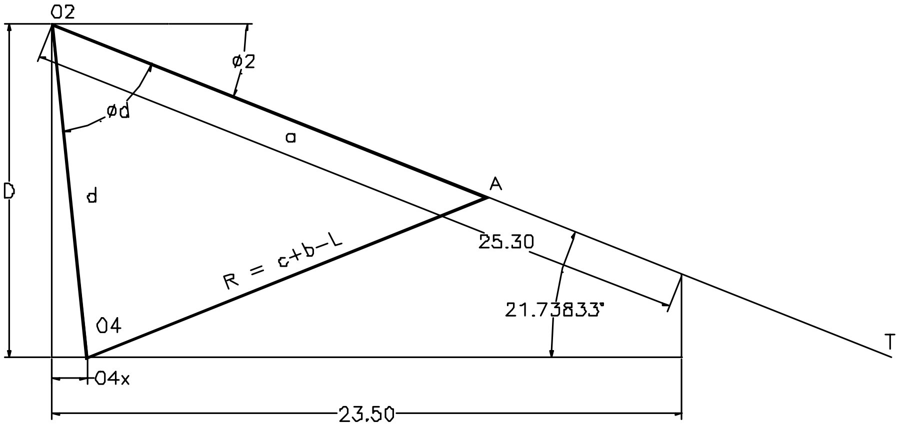


Figure 1.2: BattleBot SRM Linkage Boundary Conditions

This linkage arrangement is shown for the retracted piston condition where “R” is the piston length. The distance D is a dependant dimension set by point 0_2. Point T is located at the front of the BattleBot where the beam-arm will exert forces to flip opponents or self-right. Two factors will ensure that the piston forces will largely be given to point T: minimizing the distance from A to T and maximizing the distance from A to 0_2. This indicates 0_2 should be as far from T as possible.

Placement of 0_2 near the rear of the BattleBot is limited by the mounted position of the secondary weapon's motor. With 0_2 set back as far as possible, D is found to be 8.451 inches. Length "d", "a" and the angle ϕ_d is now determined by the placement of point 0_4. The horizontal distance of 0_4 from 0_2 is the variable "x". All calculations of the SRM ultimately depend on the value of "x". Once the location of point 0_4 is chosen with "x", the length of "d" is found with Equation 1 and the angle ϕ_d is found with Equation 2.

$$d(x) := \sqrt{x^2 + (D)^2} \qquad (1)$$

$$\theta_d(x) := 90\mathrm{deg} - \theta_2 - \mathrm{atan}\left(\frac{x}{12.5}\right) \qquad (2)$$

Here, d(x) and $\phi_d(x)$ are functions of "x". Knowing the length of "d" and "R" and the internal angle ϕ_d, the law of cosines may be used to determine the length of Link 2. The law of cosines is rearranged below in Equation 3 to solve for the length of Link 2 or distance "a".

$$a_1(x) := \frac{2\,d(x)\cdot\cos\left(\theta_d(x)\right) + \sqrt{\left(-2\,d(x)\cdot\cos\left(\theta_d(x)\right)\right)^2 - 4\left(-R_i^2 + d(x)^2\right)}}{2} \qquad (3)$$

The dimensions of the linkage, when the piston is retracted, is now defined with "d", "a" and "R". By adding the piston stroke length to the length of the retracted piston, "R", the angle of the extended arm can be found. Equation 4 gives the angle of ϕ_d, throughout the range of values of "R".

$$\theta_d(L) := \mathrm{acos}\left(\frac{R(L)^2 - a^2 - d^2}{-2\cdot a\cdot d}\right) \qquad (4)$$

Determining the forces acting on the BattleBot during the self-righting maneuver is a major step in the calculation process. The first attempt at determining these forces was through calculating the path of general plane motion. Engineering mechanics dynamics principal of work and energy was the proposed method of calculation. This method was found to be more complicated than anticipated. System boundary conditions known to be factual were the BattleBot weight, center of mass, and exterior geometry. Additional boundary conditions were needed in order to use the principal of work and energy. For example, the radius of gyration in conjunction with the coupled forces is needed to determine the rotational kinetic energy. Without the internal configuration of the interior components, the radius of gyration could only be approximated. Another complication is the fact that the force exerted at the edge of the lifting arm is variable throughout the range of motion. It was concluded that additional simplification of the system would yield inaccurate results, thus another method of determining forces was necessary.

A model of the BattleBot was developed in the Working Model simulation program. The known boundary conditions and a close but approximated linkage arrangement was used. Through trial and error, the approximate piston forces necessary for self-righting capability were determined to be about 1300 lbf. Also, for the lifting arm it was found that a large range of motion with small forces produced better results than large forces with a smaller range of motion. Therefore, what is sought after is a linkage arrangement that incorporates a large amount of perpendicular force at A as well as a large displacement of angle ϕ_d.

The amount of force a pneumatic air cylinder exerts is equivalent to the product of the surface area of the piston and the operating pressure. Equation 5 gives the piston force.

$$F_{Piston} := \left[\frac{(bore)}{2}\right]^2 \cdot \pi \cdot pressure \qquad (5)$$

At 250 psi and a 2" bore, the existing piston only provides 785 lbf. The operating pressure of standard pneumatic equipment is 150 psi while 250 psi is about as high as we want to go. A piston with a 2 ½" bore exerts 1227 lbf at 250 psi. This is a satisfactory amount of force since it is close to the approximated simulation force.

The forces exerted on Link 2 at A are parallel to the piston. Only the forces at A perpendicular to Link 2 do work. Applying a majority of the piston forces perpendicular to A and maintaining a large displacement angle has consequences. A higher level of shear and bending stresses are applied to the SRM arm. A piston with a larger bore would also be required. Keeping the location of A as close as possible to T reduces the bending stress on the arm and ensures a larger portion of direct piston forces near T. By minimizing the distance between A and T, the angular displacement of the arm can be enlarged by extending the stroke length of the piston. As the stroke length increases, the angle between the arm and the piston decreases and more of the piston forces become axial. Since the arm length will be long, it will be easier to over design for shear stresses at the pin joints than for bending stresses. So as long as enough of the piston forces are perpendicular to Link 2, the mechanism will function properly.

Vickers manufacturing company has a line of custom built tie-rod cylinders that operate at 250 psi. A Vickers VP series cylinder with an 8" stroke length is 15" long, retracted. With the previously mentioned variable "x" set to zero and "R" set to 15" the length of Link 2, distance "a", is found to be 15.912" using Equation 3. The value of "x" was chosen through iteration at the end of the calculation process. Setting "x" to zero provides an optimal linkage configuration that balances force and range of motion. Now that the geometry of the linkage has been established, the angular displacement of the arm is found with Equation 6.

$$\theta_{dtotal} := \theta_d\left(L_{stroke}\right) - \theta_d(0) \qquad (6)$$

The angular displacement of the arm is found to be 71.201 degrees with Equation 6. Angle θ_A is the angle between Link 2 and the piston, expressed with Equation 7, while the piston force perpendicular to the arm is formulated with Equation 8.

$$\theta_A(L) := acos\left(\frac{d^2 - a^2 - R(L)^2}{-2 \cdot a \cdot R(L)}\right) \qquad (7)$$

$$F_{Ay}(L) := sin\left(\theta_A(L)\right) \cdot F_{Piston} \qquad (8)$$

As the piston extends, the perpendicular forces change accordingly. Figure 4 displays this change in force at A throughout the piston extension.

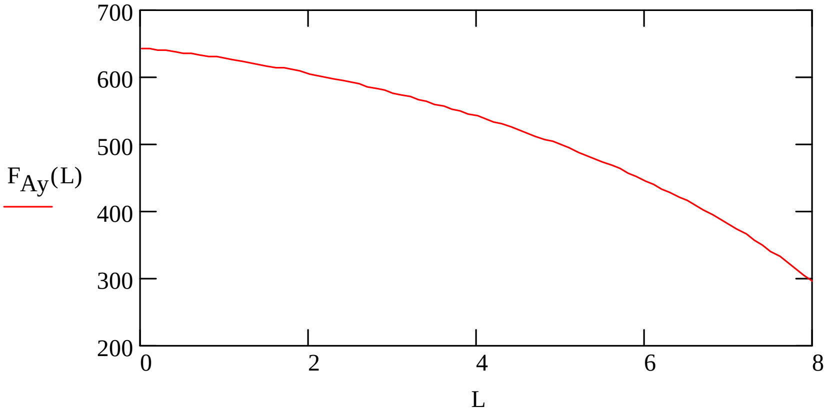


Figure 1.3: Perpendicular Forces Exerted at A Throughout Piston Extension

Figure 1.3 shows the maximum perpendicular force at A, F_{Ay}, is 642 lbf when the retracted piston begins to extend. At the end of the extension, the perpendicular force is 293lbf.

The amount of force available at T is calculated with Equation 9 and Figure 5 displays the change in force at T throughout the piston extension.

$$F_T(L) := \frac{a \cdot F_{Ay}(L)}{D_T} \qquad (9)$$

Here "a" is the length of Link 2 and D_T is 31.646", the overall length of the arm.

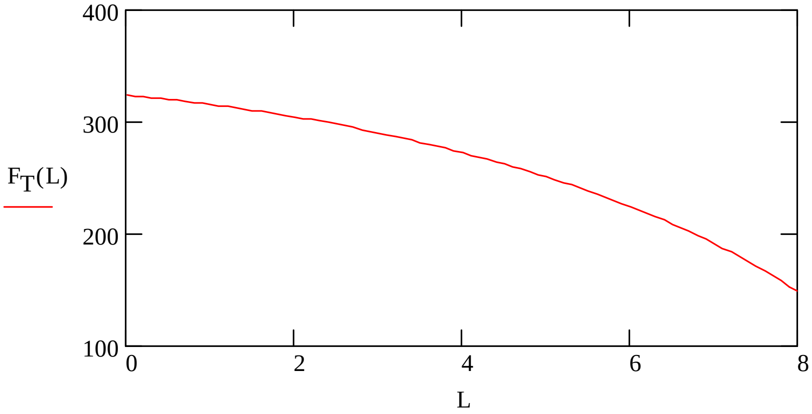


Figure 1.4: Forces Available at T Throughout Piston Extension

Figure 1.4 shows the maximum perpendicular force at T, F_T, is 323 lbf when the retracted piston begins to extend. At the end of the extension, the perpendicular force is 147 lbf. Since the maximum weight of a BattleBot in the heavyweight division is 220 lb, the lifting arm will have ample force to extend.

The average shear stresses on the pin joint 02 are mostly caused by the axial load on the arm. The axial load is found with Equation 10 and the average shear stress on the pin is Equation 11.

$$F_{Ax}(L) := \cos(\theta_A(L)) \cdot F_{Piston} \qquad (10)$$

$$\tau_{avg}(L) := \frac{F_{Ax}(L)}{2 \cdot \pi \cdot \left(\frac{Pindia}{2}\right)^2} \qquad (11)$$

The plot of average shear stresses throughout the piston extension is shown in Figure 1.5.

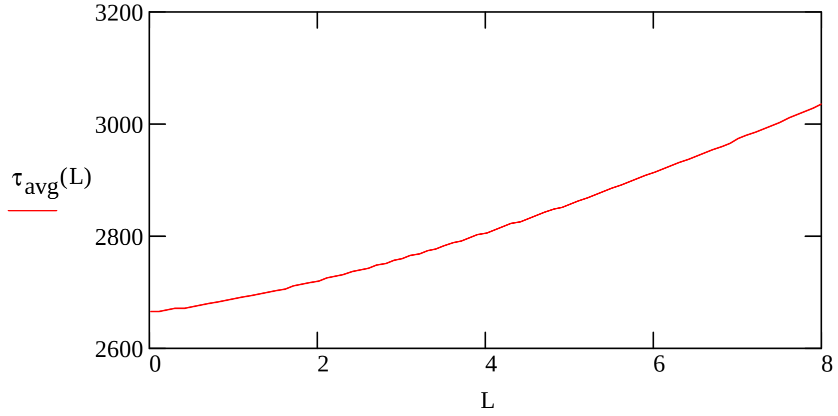


Figure 1.5: Plot of Average Shear Stresses on Pin at 02 Throughout Piston Extension

As shown in Figure 1.5, the maximum average shear stress on the pin is found to be 3035 psi at the end of the piston extension.

2.0 MATERIAL SELECTION CALCULATIONS

What is needed is a lightweight beam-arm capable of withstanding the static forces given by the pneumatic air cylinder. Four primary mathematical expressions are used to perform a material selection analysis of a system. An objective function specifies what is to be maximized or minimized. A constraint function specifies the non-negotiable conditions that must be met.

Shape factors give geometry to an abstract material formula and characterize the efficiency of a shape for a given mode of loading. The last type of material selection mathematical formula is a material index.

An equation describing the quantity to be maximized or minimized is the objective function. The mass of the beam-arm will be minimized to reduce weight. The objective function of the beam-arm is shown below in Equation 12:

$$m = \rho \cdot A \cdot L \qquad (12)$$

Where ρ is the density of the SRM material, A is the cross sectional area and L is the length of the arm.

The non-negotiable condition that must be met for the SRM arm is, the arm must not fail under bending. Equation 2 gives the constraint function for the SRM arm.

$$\sigma_{max} = \frac{M_s \cdot c}{4I} \quad \text{or} \quad F_A = \frac{4 \cdot I \cdot \sigma_{max}}{c \cdot L} \qquad (13)$$

In Equation 13, “c” is the distance from the neutral axis of bending to the outer edge of the cross section where the maximum stress is located. The variable I is the moment of inertia and the number 4 is a constant that describes the mode of loading. M_S is the moment of the arm at section s-s, see Figure 1.

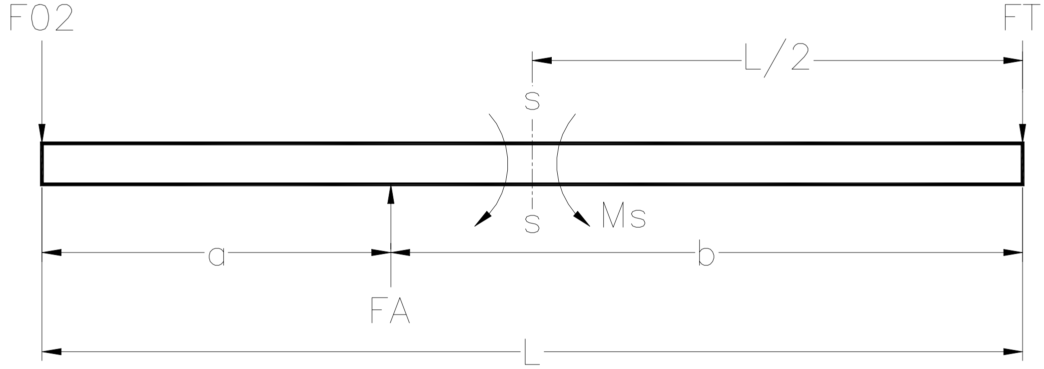


Figure 2.1: Applied Forces and Reaction Forces of the SRM Arm

Figure 1 shows the locations of F_A, F_{02} and F_T, however the relative locations are not drawn to scale. Reaction forces F_{02} and F_T are found with Equations 14 and 15 below:

$$F_{02} := \frac{F_{Ay}(0) \cdot b}{L} \qquad (14)$$

$$F_T := \frac{F_{Ay}(0) \cdot a}{L} \qquad (15)$$

Where L is D_T or the length of the SRM arm and the max value of F_{Ay} is 1227 lbf.

Since distance “a” is larger than “b”, moment M_S can be found with Equation 5.

$$M_{s1} := F_{02} \cdot \left(\frac{L}{2}\right)$$

Equation 5

The reaction force F_{02} is 319.309 lb, which makes M_S equal to 5052 in·lb.

Before the value of “c” can be found, the location of the neutral axis must be determined. For the cross sectional shape shown in Figure 2.2.

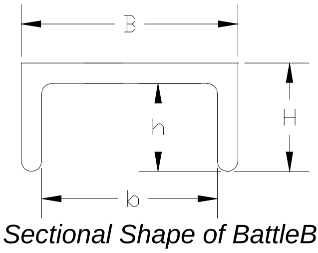


Figure 2.2: Cross Sectional Shape of BattleBot SRM Lifting Arm

The dimensions shown in Figure 2.2 are as follows: H = 1.0”, h = 0.8125”, B = 2.0”, b = 1.625”. The SRM / Primary Weapon System lifting arm will be constructed out of a c-channel shaped beam due to the strength per weight advantages described by shape factors.

Equation 66 gives the formula for the location of the neutral axis.

$$y_{NA} := \frac{B\cdot(H-h)\cdot\left(H-\frac{H-h}{2}\right)+2\cdot\left[\frac{B-b}{2}\cdot h\cdot\left(\frac{h}{2}\right)\right]}{B\cdot(H-h)+2\left(\frac{B-b}{2}\right)\cdot h} \qquad (16)$$

Using the dimensions given above, the location of the neutral axis is found to be 0.682”.

The mode of bending the SRM arm experiences causes tensional stresses to occur at the topmost edge of the cross section. With that in mind, the value of “c” can be determined with Equation 17.

$$c := H - y_{NA} \qquad (17)$$

Therefore, the distance from the neutral axis to the topmost edge of the cross section is 0.318”.

The moment of inertia is the last variable to define for Equation 2. The moment of inertia of the SRM arm is calculated with Equation 18.

$$I_2 := \left[\frac{1}{12}\cdot B\cdot(H-h)^3 + B\cdot(H-h)\cdot\left(H-\frac{H-h}{2}-y_{NA}\right)^2\right] + 2\cdot\left[\frac{1}{12}\cdot\left(\frac{B-b}{2}\right)\cdot h^3 + \left(\frac{B-b}{2}\right)\cdot h\cdot\left(y_{NA}-\frac{h}{2}\right)^2\right] \qquad (18)$$

The moment of inertia for the cross section shown in Figure 2 is found to be 0.06 in^4.

Shaped beam sections carry bending loads with as little material as possible. The shape factor is the ratio of the stiffness of a shaped section, I, to that, I^o, of a solid circular section with the same cross-section A. The shape factor for a beam in elastic bending is shown below in Equation 19.

$$\phi_B = \frac{4\cdot\pi\cdot I}{A^2} \qquad (19)$$

“A material index is a combination of material properties which characterizes the performance of a material in a given application”[1]. A material index is composed of three things that describe the design of a structural element. Functional requirements, geometric parameters and material properties are the three groups that are said to be separable when in the form given in Equation 20:

$$p = f_1(F)\,f_2(G)\,f_3(M) \qquad (20)$$

Where “p” is the parameter to be optimized and F, G and M are the three separable performance characteristics. Combining the shape factor with the objective and constraint functions by eliminating independent values of “p”, forms the material index. The material index for the SRM arm is given in Equation 21.

$$m = \underset{F}{\left(\frac{3}{2}\cdot\frac{F_A}{L^2}\right)^{\frac{2}{3}}}\cdot\underset{G}{L^3}\cdot\underset{M}{\left(\frac{\rho}{\sigma_y^{\frac{2}{3}}}\right)} \qquad (21)$$

Maximizing the material properties of the material index optimizes the mass of the SRM arm. Equation 22 shows the form of the material properties to be optimized, including the shape factor.

$$M = \frac{\left(\phi_B \cdot \sigma_{max}\right)^{\frac{2}{3}}}{\rho} \qquad (22)$$

A list of materials can now be generated for comparison and selection. These materials are chosen from the Strength–Density chart[1] shown in Figure 2.3.

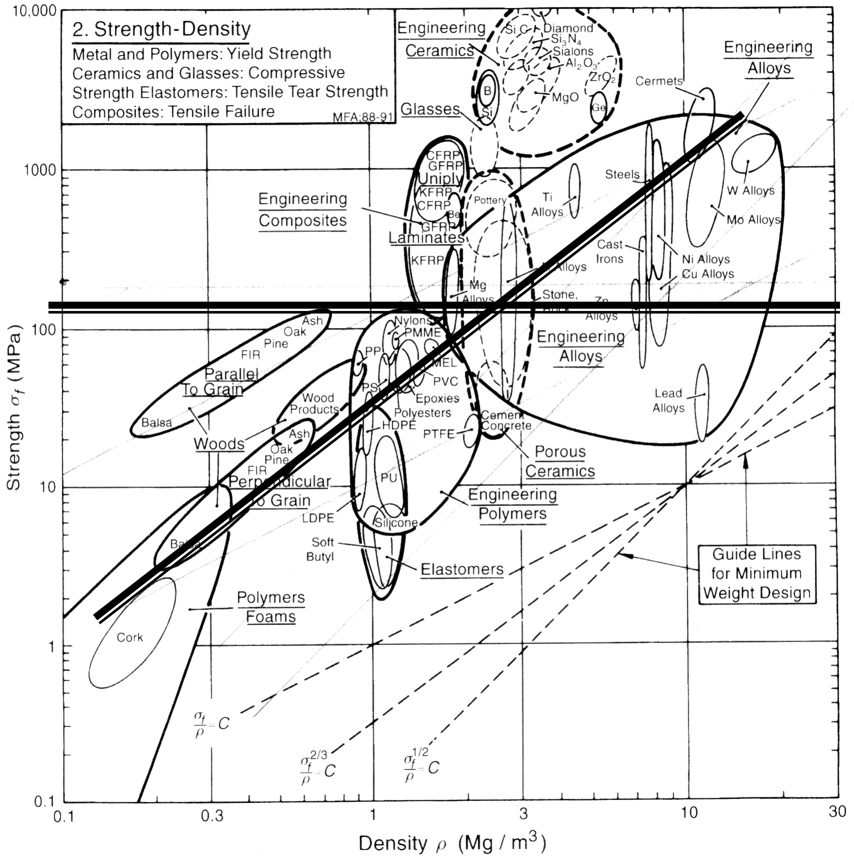


Figure 2.3: Strength-Density Chart

The maximum stress that the arm is subjected to has been calculated to be 2.682x10^4 psi or 184.9 MPa. Therefore the lower limit of yield strength is set at 185 MPa. The selection guideline slope used for minimum weight design is $(\sigma_f/\rho)^{2/3}$. The Steel Alloys are selected since their strengths exceeded the maximum tensile stress. Aluminum Alloy 6061-T6 is located inside the search region on the chart; therefore it is also a candidate for the next stage of the selection process. The materials selected from the Strength-Density chart are tabulated below in Table 2.1.

Table 2.1: Materials Selected from Strength-Density Chart, Figure 3

Material	Strength σ_f (MPa)	Density ρ (Mg/m^3)	Shape Factor ϕ_B	Index 1 $(\sigma_f/\rho)^{2/3}$	Index 2 $(\phi_B\sigma_f)^{2/3}/\rho$
Aluminum Wrought Alloy 6061-T6	255	2.71	44	20.688	257.839
Steel Alloy Structural A36	250	7.85	65	10.047	162.426
Steel Alloy Stainless 304	207	7.86	65	8.852	143.1

Aluminum Alloy displays the highest material index as shown in Table 1. Therefore aluminum seems to be the best choice to optimize the mass of the system. Unfortunately aluminum presents two unforeseen disadvantages that are not shown with this selection method. Aluminum 6061-T6 has a small ultimate strength compared to structural steel A36. While Al 6061-T6 has σ_{UT} = 290 MPa, the ultimate strength of steel A36 is 400 MPa. The additional strength of steel A36 provides an added factor of safety during the competition. The other disadvantage of Al 6061-T6 is the cost per lb is much higher than steel A36. Steel A36 is extremely inexpensive and backup parts can be fabricated with little impact on the senior design project budget. The preferred material for the SRM arm is therefore chosen to be steel alloy A36.

3.0 CONCLUSIONS

By combining range of motion and substantial piston force, an optimal linkage configuration was established. The dimensions of Links 1 and 2 were found to be 8.451" and 15.912" respectively. The designed self-righting mechanism / primary weapon lifting arm is capable of lifting 323 lbf and has an angular displacement of 71.201 degrees. A 2 ½" bore, 8" stroke pneumatic air cylinder was selected to complete this task. Through the material selection process, it was determined that the lifting arm will be constructed out of a 32" long c-channel. The material of the c-channel beam will be structural steel A36.

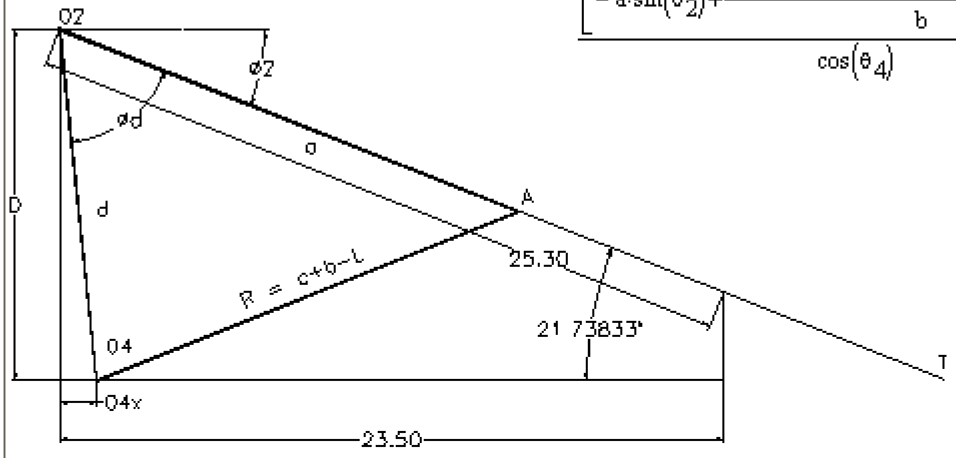
REFERENCES

1. M. F. Ashby, “Materials Selection in Mechanical Design” (1999): 70

APPENDIX A: MATHCAD CALCULATIONS

BattleBot Linkage Design Calculato

$$\frac{b_{dot}}{\dfrac{\left[-a\cdot\sin(\theta_2)+\dfrac{\left[a\cdot\cos(\theta_2-\theta_4)\cdot(b\cdot\sin(\theta_4)+c\cdot\sin(\theta_4))\right]}{b}\right]}{\cos(\theta_4)}}$$



$\theta_2 := 21.738333\text{deg}$ $D := 8.451$ $D_T := 31.646$

Independent Variables: Ri, Lstroke and O4

$O_4 := 0$ $R_i := 15$ $L_{stroke} := 8$ $b_{dot} := 10$ $\text{bore} := 2.5$ $\text{pressure} := 250$

$L := 0, 0.1 .. L_{stroke}$

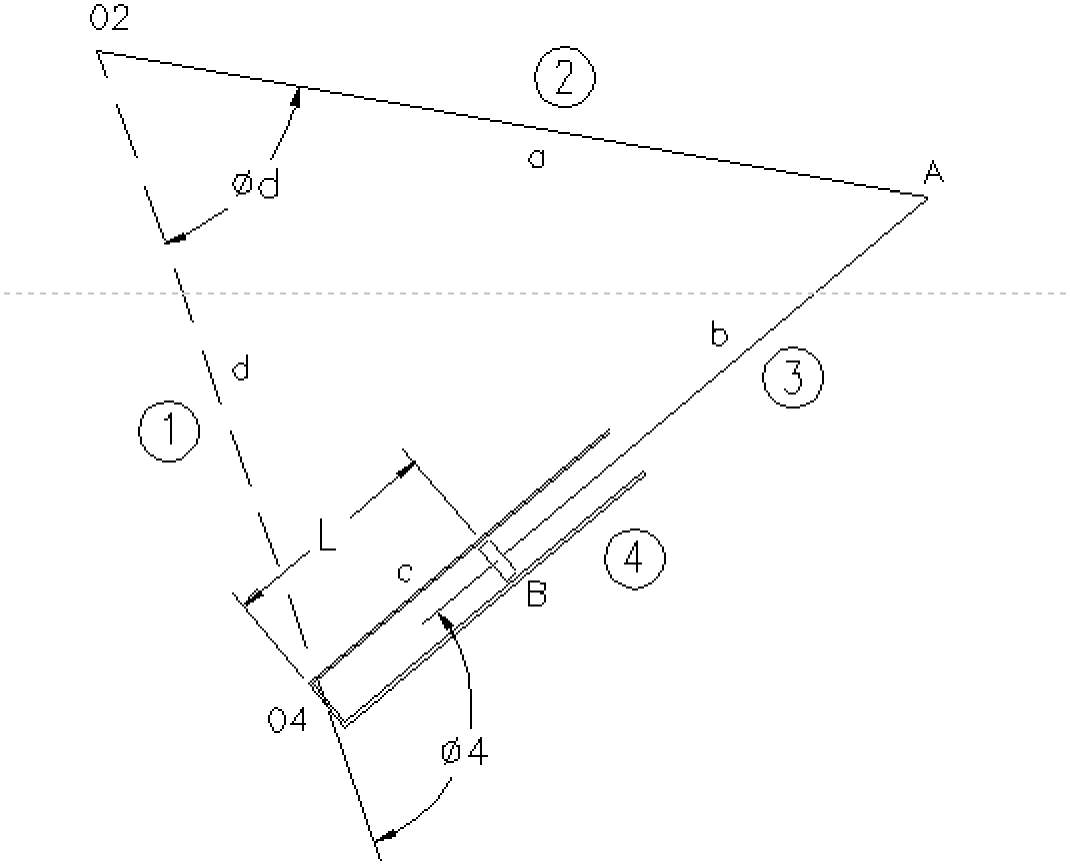
$R(l) := R_i + 1$

$d(x) := \sqrt{x^2 + (D)^2}$ $\theta_d(x) := 90\text{deg} - \theta_2 - \text{atan}\left(\frac{x}{12.5}\right)$

$d(O_4) = 8.451$ $\theta_d(O_4) = 68.262\ \text{deg}$

$$a_1(x) := \frac{2\,d(x)\cdot\cos(\theta_d(x)) + \sqrt{(-2\,d(x)\cdot\cos(\theta_d(x)))^2 - 4\left(-R_i^2 + d(x)^2\right)}}{2}$$

Fourbar Linkage: Inverted Slider Crank w/ gamma=0



Mechanical Advantage Calculations for the BattleBot Self-Righting Mechanism

Initial Condition: Piston Fully Collapsed

$$a := a_1(O_1) \qquad d := d(O_1) \quad b(I) := \frac{R(I)}{2} \quad c := b$$

$$\theta_d(L) := \operatorname{acos}\left(\frac{R(L)^2 - a^2 - d^2}{-2\cdot a\cdot d}\right)$$

$$P(L) := a\cdot\cos\left(\theta_d(L)\right) - d$$

$$Q(L) := -a\cdot\sin\left(\theta_d(L)\right)$$

$$S(L) := -Q(L)$$

$$T(L) := 2\cdot P(L)$$

$$U(L) := Q(L)$$

$$\theta_4(L) := 2\cdot\operatorname{atan}\left(\frac{-T(L) + \sqrt{T(L)^2 - 4\cdot S(L)\cdot U(L)}}{2\cdot S(L)}\right)$$

$$\omega_2(L) := \frac{b_{dot}}{\left[-a\cdot\sin\left(\theta_d(L)\right) + a\cdot\cos\left(\theta_d(L) - \theta_4(L)\right)\cdot\frac{\left(b(L)\cdot\sin\left(\theta_4(L)\right) + c(L)\cdot\sin\left(\theta_4(L)\right)\right)}{b(L)}\right]}\cdot\cos\left(\theta_4(L)\right)$$

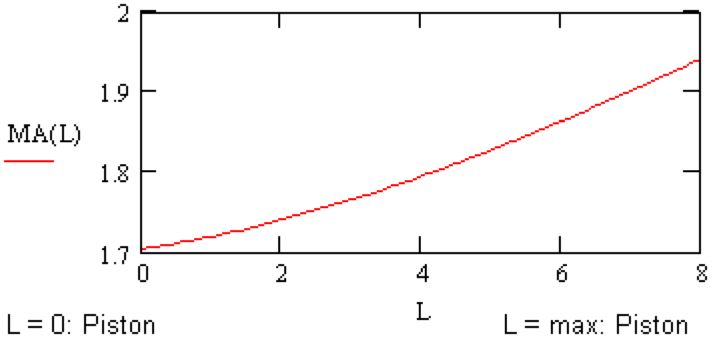
$$\omega_4(L) := \frac{a\cdot\omega_2(L)\cdot\cos\left(\theta_d(L) - \theta_4(L)\right)}{b(L)}$$

$$MA(L) := \left(\frac{\omega_4(L)}{\omega_2(L)}\right)\cdot\left(\frac{R(L)}{a}\right) \qquad MA = \frac{\omega_{in}}{\omega_{out}}\cdot\frac{r_{in}}{r_{out}}$$

$$a = 15.912 \qquad d = 8.451$$

Note: "a" cannot be greater than 25

Mechanical Advantage of Arm Throughout Piston Extension:



L = 0: Piston
Retracted

L = max: Piston
Extended

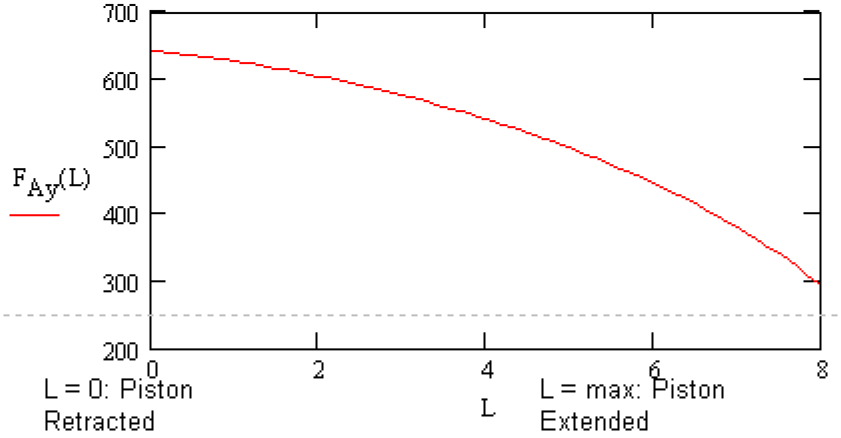
Angular Displacement of Arm at 04x Set:

$\theta_{dtotal} := \theta_d(L_{stroke}) - \theta_d(\theta_{dtotal} = 71.201\ deg$

Forces Exerted at Ay by Piston Throughout Piston Extension:

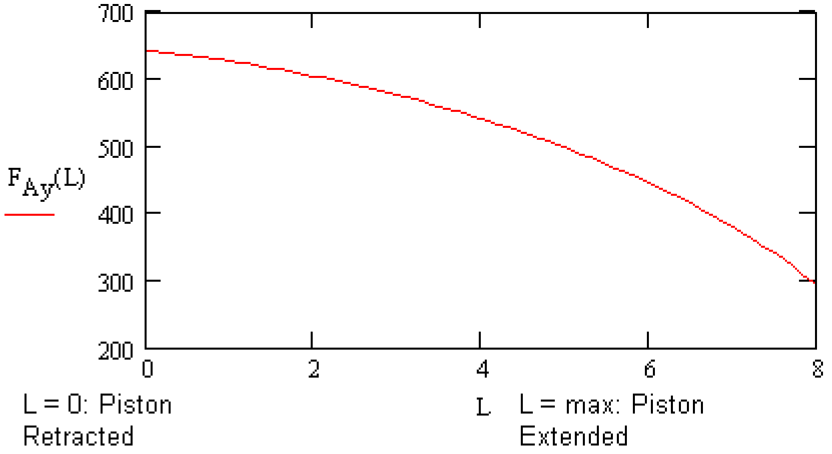
$$F_{Piston} := \left[\frac{(bore)}{2}\right]^2 \cdot \pi \cdot pressure \quad F_{Piston} = 1.227 \times 10^3$$

$$\theta_A(L) := acos\left(\frac{d^2 - a^2 - R(L)^2}{-2 \cdot a \cdot R(L)}\right) \qquad F_{Ay}(L) := \sin(\theta_A(L)) \cdot F_{Piston}$$



Forces available at T throughout piston extension:

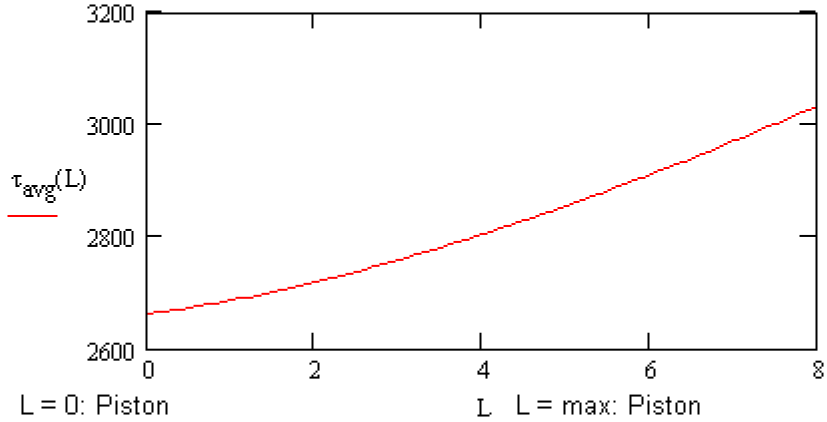
$$F_T(L) := \frac{a \cdot F_{Ay}(L)}{D_T} \qquad F_T(0) = 322.918$$



Load on pin at O2 thoughout piston extension:

$F_{Ax}(L) := \cos(\theta_A(L))\cdot F_{Piston}$ $F_{Ax}(L_{stroke}) = 1.192\times 10$ $\text{Pindia} := 0.5$

$\tau_{avg}(L) := \frac{F_{Ax}(L)}{2\cdot\pi\cdot\left(\frac{\text{Pindia}}{}\right)^2}$ average shear stress in psi $\tau_{avg}(L_{stroke}) = 3.035\times 10^3$



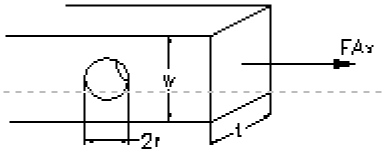
L = 0: Piston Retracted

L = max: Piston Extended

Stress concentration calculations for arm at pin O2:

Page 457 Hibbeler

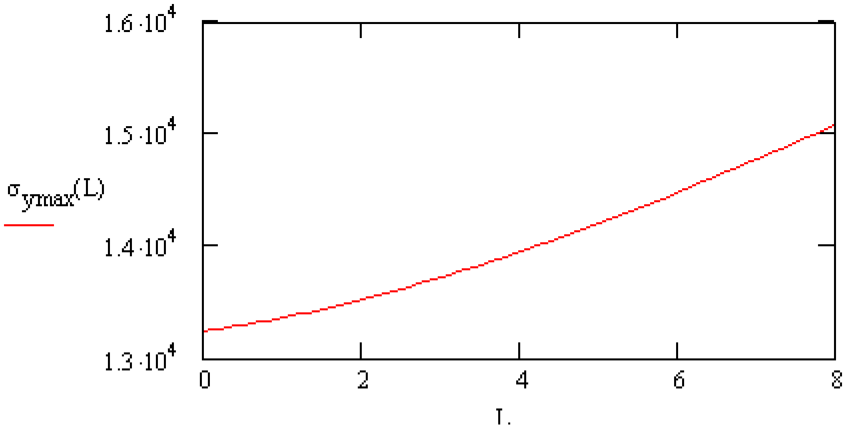
$K = \frac{\sigma_{max}}{\sigma_{avg}}$ $\sigma_{avg} = \frac{F_{Ax}}{(w - 2\cdot r)\cdot t}$



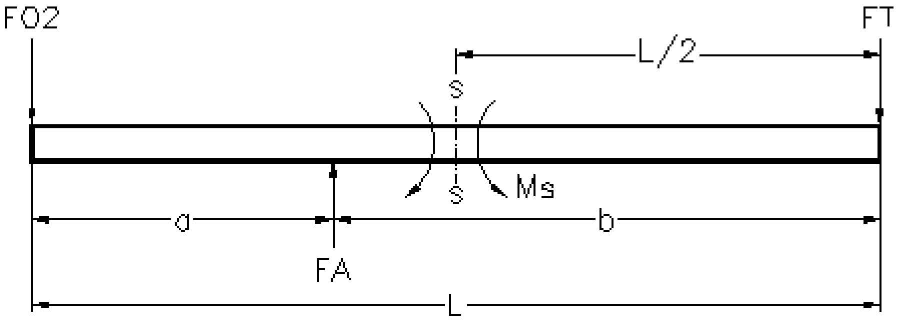
$r := 0.25$ $w := 1$ $t := 0.375$

$\frac{r}{w} = 0.25$ $K := 2.375$ $\sigma_{avg}(L) := \frac{F_{Ax}(L)}{(w - 2\cdot r)\cdot t}$

$\sigma_{ymax}(L) := K\cdot\sigma_{avg}(L)$



$1.6 \cdot 10^4$
$1.5 \cdot 10^4$
$1.4 \cdot 10^4$
$1.3 \cdot 10^4$
$\sigma_{ymax}(L)$
0
2
4
6
8
L



FO2
FT
L/2
S
S
Ms
a
b
FA
L

Materials Selection Calculations:

$a = 15.912 \quad L := D_T \quad F_{Ay}(0) = 642.227$

$b := L - a \quad b = 15.734$

$F_T := \frac{F_{Ay}(0) \cdot a}{L} \qquad F_{02} := \frac{F_{Ay}(0) \cdot b}{L}$

$M_{s1} := F_{02} \cdot \left(\frac{L}{2}\right) \qquad M_{s2} := F_T \cdot \left(\frac{L}{2}\right) - \left| F_{Ay}(0) \cdot \left(b - \frac{L}{2}\right) \right|$

$M_s := \left| \begin{array}{l} M_{s1} \text{ if } M_{s1} > M_{s2} \\ M_{s2} \text{ otherwise} \end{array} \right.$

$M_s = 5.052 \times 10^3$

Shape 1 Cross Section Variables: $\text{height}_{s1} := 1.5 \quad \text{base}_{s1} := 1$

$\sigma_{maxS1} := \frac{M_s \cdot \left(\frac{\text{height}_{s1}}{2}\right)}{\frac{1}{12} \cdot \text{base}_{s1} \cdot \text{height}_{s1}^3}$ $\qquad \sigma_{maxS1} = 1.347 \times 10^4$

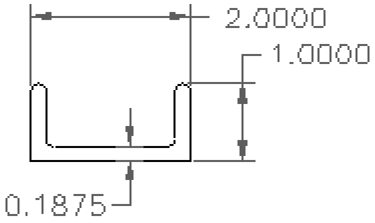
$\phi_{B.s1} := \frac{\pi \cdot \text{height}_{s1}}{3 \cdot \text{base}_{s1}}$ $\qquad \phi_{B.s1} = 1.571$

$\rho := 1100$

$\text{mass}_{s1} := M_s \cdot 2 \cdot \pi \cdot \frac{L}{\text{base}_{s1}} \cdot \frac{\rho}{\sigma_{maxS1} \cdot \phi_{B.s1}}$

$\text{mass}_{s1} = 5.222 \times 10^4$

Shape 2 cross section variables:



$H := 1 \qquad B := 2 \qquad h := 0.8125 \qquad b := 1.625$

$$A := H \cdot B - h \cdot b \rightarrow .6796875$$

$$y_{NA} := \frac{B \cdot (H - h) \cdot \left(H - \frac{H - h}{2}\right) + 2 \cdot \left[\frac{B - b}{2} \cdot h \cdot \left(\frac{h}{2}\right)\right]}{B \cdot (H - h) + 2\left(\frac{B - b}{2}\right) \cdot h}$$

location of neutral axis

$$I_2 := \left[\frac{1}{12} \cdot B \cdot (H - h)^3 + B \cdot (H - h) \cdot \left(H - \frac{H - h}{2} - y_{NA}\right)^2\right] + 2 \cdot \left[\frac{1}{12} \cdot \left(\frac{B - b}{2}\right) \cdot h^3 + \left(\frac{B - b}{2}\right) \cdot h \cdot \left(y_{NA} - \frac{h}{2}\right)^2\right]$$

$$c := H - y_{NA}$$

moment of inertia

$$\sigma_{maxS2} := \frac{M_s \cdot c}{I_2}$$

$$\sigma_{maxS2} = 2.682 \times 10^4$$

$$2.301 \cdot 10^4 \, psi = 1.586 \times 10^8 \, Pa$$

$$m = \rho \cdot A \cdot L$$

$$\sigma_{max} = \frac{M_s \cdot c}{I}$$

$$\phi_B := \frac{4 \cdot \pi \cdot I_2}{A^2} \qquad \phi_B = 1.629$$

$$p = f_1(F)\, f_2(G)\, f_3(M)$$

$$m = \underset{F}{(4 \cdot \pi \cdot M_s \cdot c)} \cdot \underset{G}{\left(\frac{L}{A}\right)} \cdot \underset{M}{\left(\frac{\rho}{\phi_B \cdot \sigma_{max}}\right)}$$

$$M := \frac{\phi_B \cdot \sigma_{max}}{\rho}$$

Summary of Calculations:

Piston bore size:	$bore = 2.5$
Piston stroke length:	$L_{stroke} = 8$
Linkage dimentions:	$a = 15.912 \quad d = 8.451 \quad R(0) = 15$
Angle of arm rotation:	$\theta_{dtotal} = 71.201\ deg$
Max force at T:	$F_T = 322.918$
Max shear stress on pin O2:	$\tau_{avg}(L_{stroke}) = 3.035 \times 10^3$
Max yeild stress of arm at O2:	$\sigma_{ymax}(L_{stroke}) = 1.509 \times 10^4$

APPENDIX E – STRUCTURAL ANALYSIS

Team 9 BattleBot

Florida State University
Tallahassee, FL

DATE 12/02/02	**DOCUMENT NAME**	Structural Analysis REV -

TITLE:

Structural Analysis

TEAM MEMBERS:

James Bernstein	Jeremiah Bullis	Oscar Garcia	Nik Hartney
Rafael Bonnelly	Will Resnick	Jay Wells	David Leddy

REVISIONS								
LTR	DESCRIPTION	DATE	APPROVAL		LTR	DESCRIPTION	DATE	APPROVAL
-	Initial release	12/02/02						

PAGE				
REVISION	-	-	-	
PAGE				PAGE 1 OF 7
REVISION				

DATE 12/02/02	**DOCUMENT NAME**	Structural Analysis REV -

TABLE OF CONTENTS

1.0 INTRODUCTION 114

2.0 ANALYSIS 114

3.0 CONCLUSION 114

REFERENCES 118

1.0 INTRODUCTION

The weight limits for the heavyweight class Battlebots is between 120 to 220 pounds. The primary weapon system had to be removed last year for the competition because the bot was overweight. One of the main goals of this year is to cut unnecessary weight to keep all the weapons and in the weight class.

2.0 ANALYSIS

The first obvious spot that was noticed where weight could be reduced was in the bearing blocks for the drum weapon system. These are two big one-inch thick aluminum blocks that were vastly over designed. In them there is a lot of material that could be cut that would not greatly affect the structural rigidity. This is due to the shape factor, an example of this can be a block compared to an “I” beam. Both of them can have nearly the same strength while the “I” beam weights a lot less. So the objective is to cut the excess material to lighten it up.

There are many different ways that material could be removed, but the goal is to remove as much weight while not loosing the strength and rigidity it contains. To go about this the CAD program Pro Engineer (Pro-E) was used to draw the part and modify it. To analyze it on the computer the program ALGOR was utilized. ALGOR uses the finite element method approach to analyze the structures and display the results graphically. By using these computer programs many different designs can be made and tested in a fast and efficient manner.

Since the part was only going to be redesigned without changing the whole part or the function of it, the original bearing block was drawn and analyzed. This became the benchmark to what all the different patterns will be compared to. To get accurate comparisons between the different designs, the same parameters and forces were used in all of them. The force that was used in the analysis was 400 lbf in the directions towards the bot and the floor to simulate obstacles hitting the drum. The magnitude of the force is not critical due to the fact that the result desired is the difference in deflection between the original part and the modified designs. As long as the force stays constant between all the tests, the magnitude does not matter. The edge of the part that fastens to the bot is where the grounds were designated in the analysis. Once the boundary conditions and the forces were assigned and a mesh of the part was implemented the computer took over. ALGOR calculated the displacement at every node and displayed the results in the form of a contour plot. This can be seen in the figures 1 trough 5 below.

To calculate the weight of the bracket, an analysis feature in Pro-E was used. After the drawing was done the only additional information needed was the density of the material used. In this case the brackets were made out of 6061 Aluminum Alloy, which has a density of 0.0975 lb/in^3 [1]. Once the density was added it calculated the weight. The calculated weight and maximum displacement of each different model designed for the drum brackets are shown in table A1.

Another place where a lot of weight could be cut was from the two bulkheads inside the BattleBot. These consist of half inch thick aluminum plates. They were also over designed, which is good for this competition, but add too much weight. To decrease the weight here a decision to go with another material was made. The reason for this was that the area was needed to attach certain parts and the pneumatic arm will also be connected to the top. This means that it is crucial that these bulkheads remain very strong. So to reduce weight and add strength carbon fiber over was chosen over the aluminum. A comparison between the two materials can be seen in table A2. Since the carbon fiber is so much stronger than the aluminum a thickness of .375” instead of the .5” was selected. This way the weight of the bot could be brought even more. By changing the material and the thickness weight was cut from each bulkhead by more than half. The left one went from 7.007 lb to 3.288 lb. The right bulkhead went from 9.750 lb to 3.587 lbs. This was reduction of 9.882 pounds for the both of them.

3.0 CONCLUSION

In the drum bearing blocks there will be a combined weight of 3.358 pounds that will be lost by going with alteration 1 for the bracket design. It may have the biggest displacement out of all the choices, but it is still such a miniscule amount that it is worth having the extra weight gone. In the bulkheads the combined loss is 9.882 pounds and a gain in strength by having a much stronger material. In total 13.24 pounds will be shaved off the bot to keep it within the 220 lb maximum limit and be able to have all weapon systems onboard.

Table A1 **–** *Weight and maximum displacement of drum brackets.*

Bracket Design	Weight (lb)	Max Displacement (in)
Original	4.676	.00227
1 (@.375 deep)	2.997	.00487
2 (@.300 deep)	3.333	.00379
3	3.025	.00429
4	3.666	.00288

Table A2 – Aluminum v. Carbon Fiber

	Density lb/in^3	Modulus of Elasticity 10^6 psi	Tensile Strength ksi
Aluminum Alloy 6061	0.0975	10	33
High Modulus Carbon Fiber	0.061	32	110

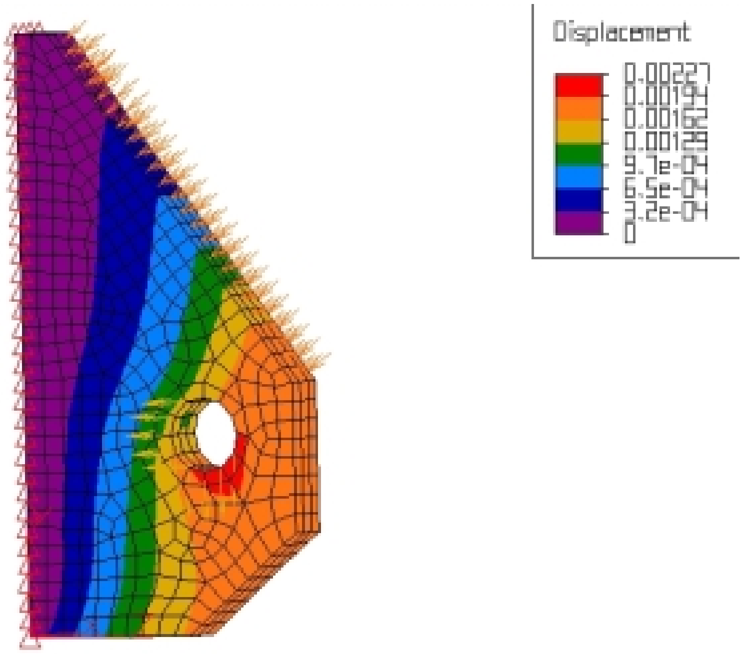


Figure 1- Original Drum Bearing Block

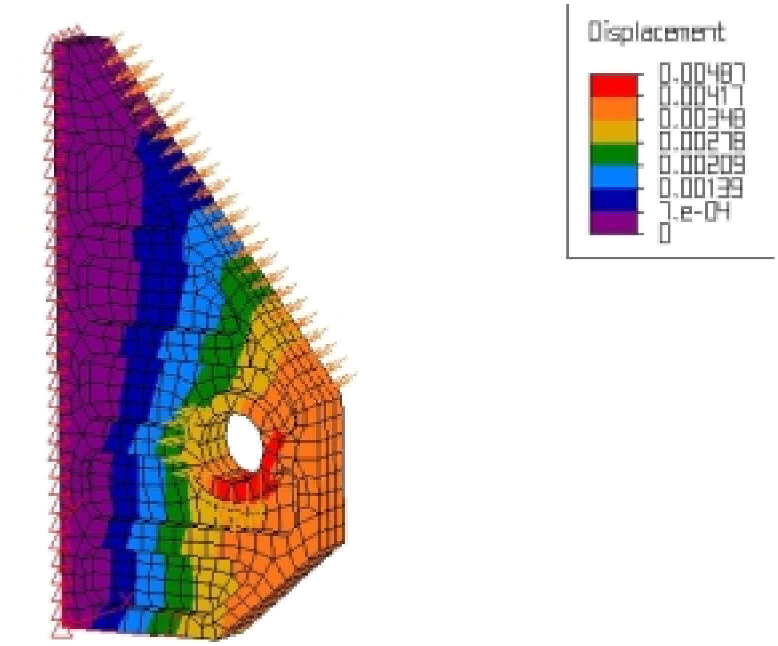


Figure 2- Drum Bearing Block alteration 1 (.375 deep)

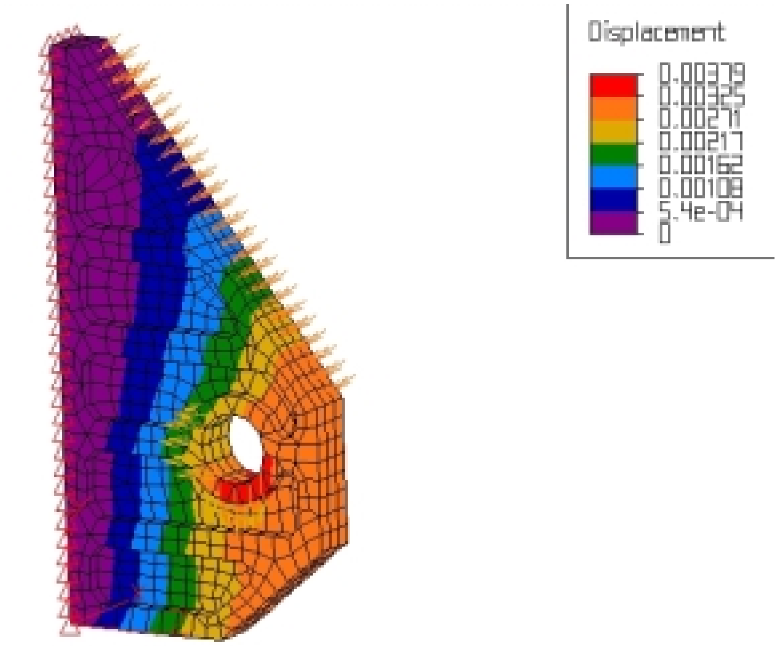


Figure 3- Drum Bearing Block alteration 2 (.300 deep)

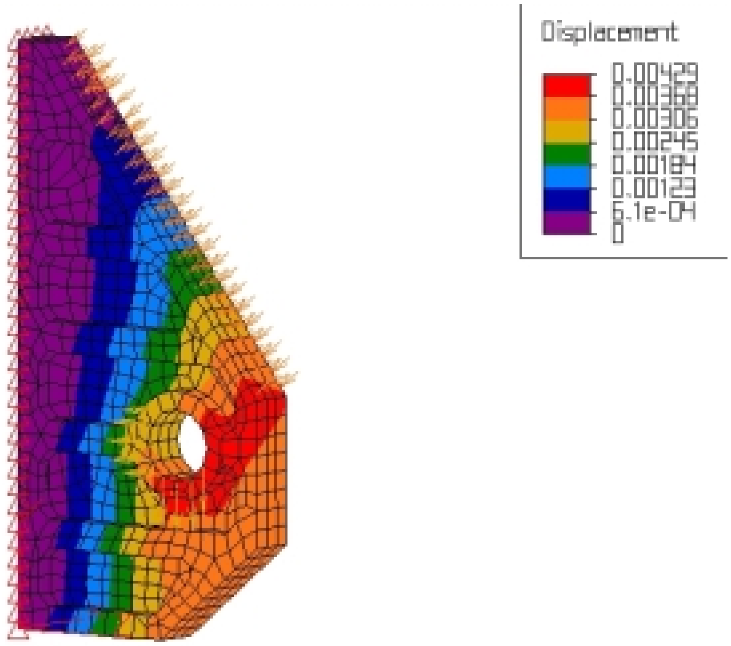


Figure 4- Drum Bearing Block alteration 3

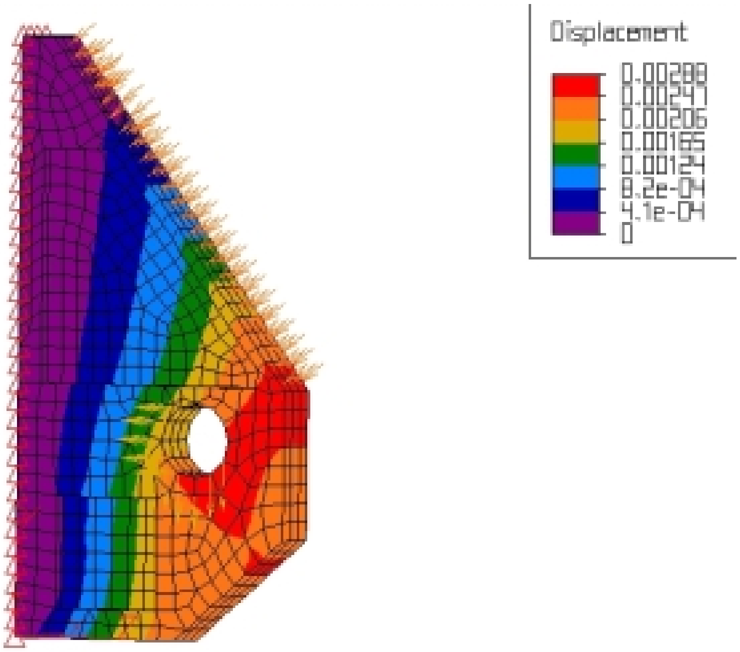


Figure 5- Drum Bearing Block alteration 4

REFERENCES

1. Callister, William D.; Material Science And Engineering An Introduction; John Wiley & Sons, Inc, NY; 2000.

APPENDIX F – MANUFACTURERS PARTS SPECS

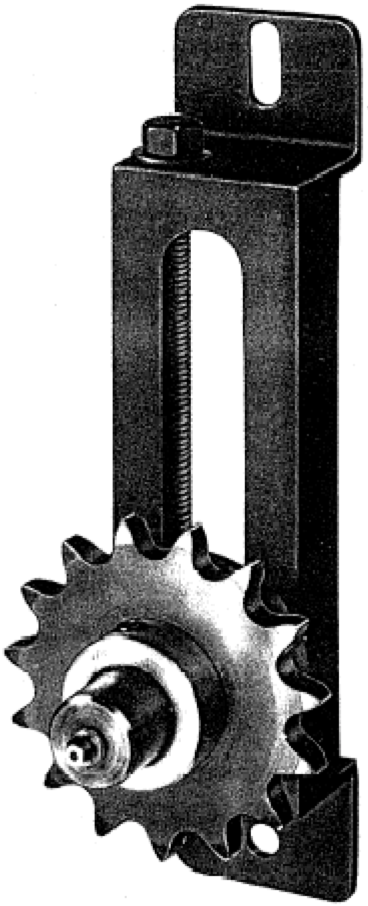
6265K SERIES

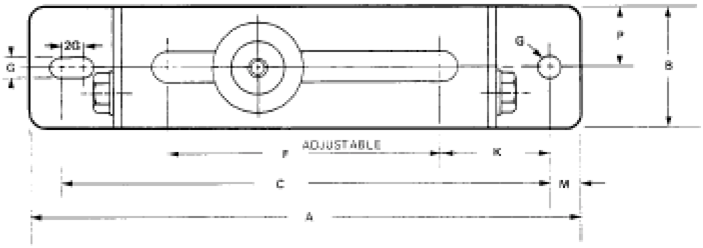
AJUSTO-SCREW TENSIONERS

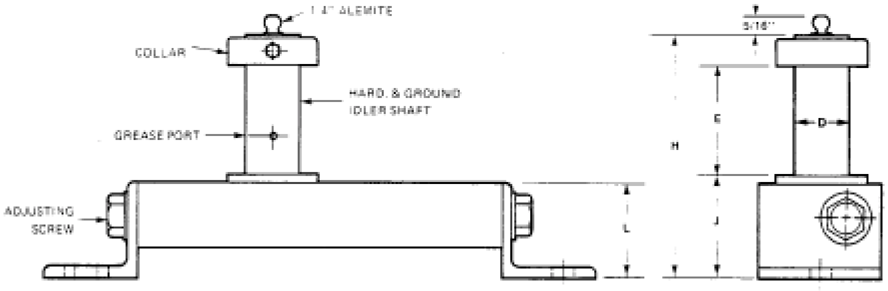
The Adjusto-Screw, which is "slack-side" mounted, uses a screw to provide precise, easily-adjustable tension. The screw adjustment enables the user to set the precise tension necessary to provide maximum life for the sprocket and chain or belt. This is especially advantageous with heavy chains where slack is normally taken up by hand while making the adjustment. With the Ajusto-Screw, chain take-up and tension setting are both controlled with the screw. Ajusto-screw tensioners are useful on vertical drives, preventing lower sprocket disengagement. Constructed of structural steel (many competitive brands use cast iron), this patented tensioner is available in a wide range of capacities capable of handling up to RC 240 roller chain.

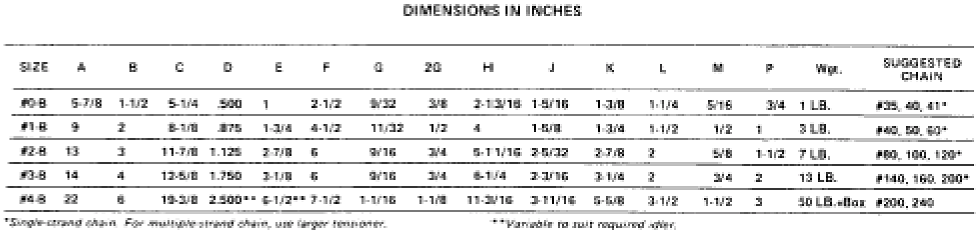
Many drive systems are enclosed, for safety reasons. With conventional tensioners, the enclosure must be removed for drive adjustment. With Ajusto-Screw, tension adjustments can often be made through a hole in the enclosure adjacent the head of the screw, substantially reducing costly maintenance and drive down-time. The screw is adjustable from either end of the tensioner.

All tensioners improve drive performance by eliminating whipping and slipping of loose drive chains and belts. They reduce vibration, noise and maintenance and provide additional life to drive components.





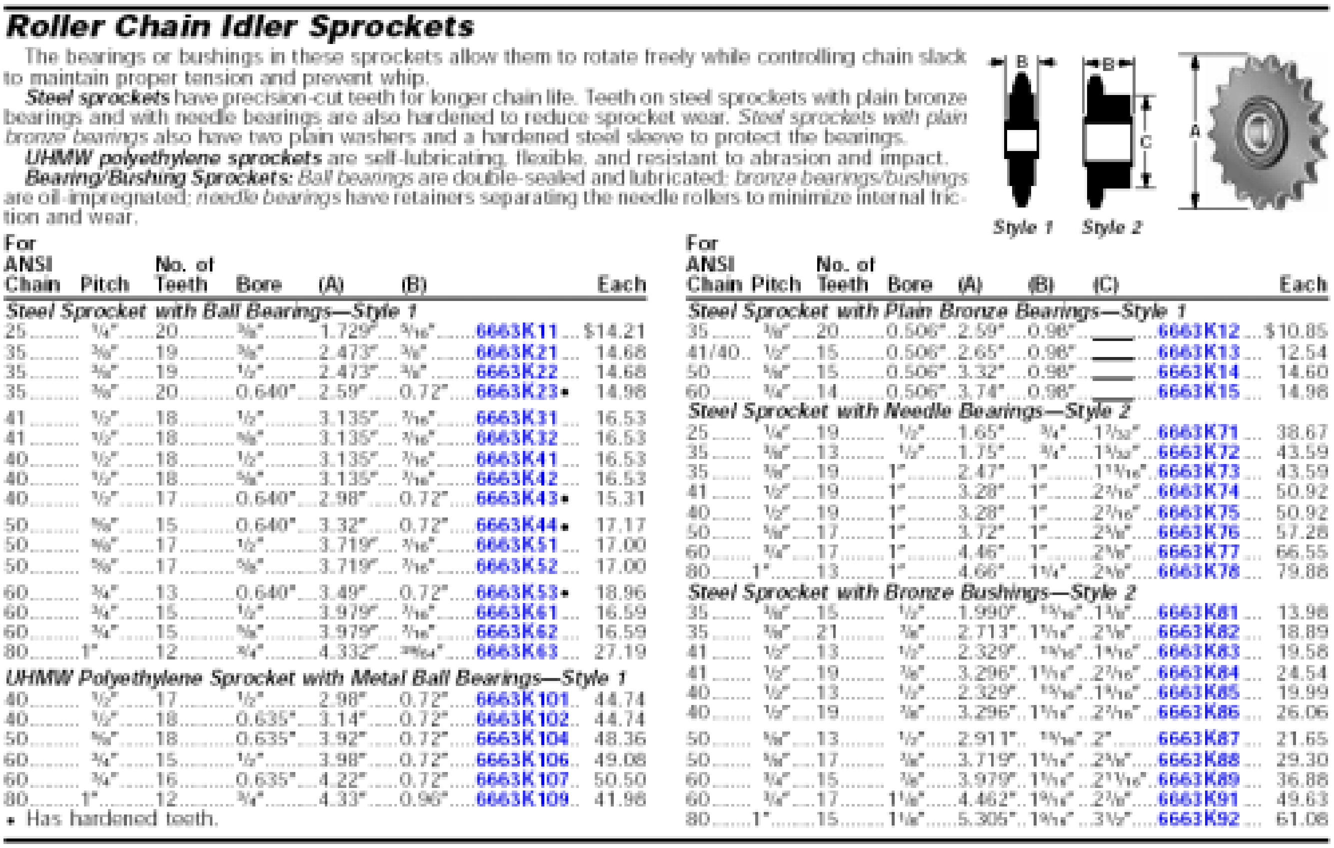




DIMENSIONS IN INCHES

SIZE	A	B	C	D	E	F	G	2G	H	J	K	L	M	P	Wgt.	SUGGESTED CHAIN
#0-B	5-7/8	1-1/2	5-1/4	.500	1	2-1/2	9/32	3/8	2-13/16	1-5/16	1-3/8	1-1/4	5/16	3/4	1 LB.	#35, 40, 41*
#1-B	9	2	8-1/8	.875	1-3/4	4-1/2	11/32	1/2	4	1-5/8	1-3/4	1-1/2	1/2	1	3 LB.	#40, 50, 60*
#2-B	13	3	11-7/8	1.125	2-7/8	6	9/16	3/4	5-11/16	2-5/32	2-7/8	2	5/8	1-1/2	7 LB.	#80, 100, 120*
#3-B	14	4	12-5/8	1.750	3-1/8	6	9/16	3/4	6-1/4	2-3/16	3-1/4	2	3/4	2	13 LB.	#140, 160, 200*
#4-B	22	6	19-3/8	2.500**	6-1/2**	7-1/2	1-1/16	1-1/8	11-3/16	3-11/16	5-5/8	3-1/2	1-1/2	3	50 LB.+Box	#200, 240

*Single-strand chain. For multiple-strand chain, use larger tensioner. **Variable to suit required idler.



Roller Chain Idler Sprockets

The bearings or bushings in these sprockets allow them to rotate freely while controlling chain slack to maintain proper tension and prevent whip.

Steel sprockets have precision-cut teeth for longer chain life. Teeth on steel sprockets with plain bronze bearings and with needle bearings are also hardened to reduce sprocket wear. *Steel sprockets with plain bronze bearings* also have two plain washers and a hardened steel sleeve to protect the bearings.

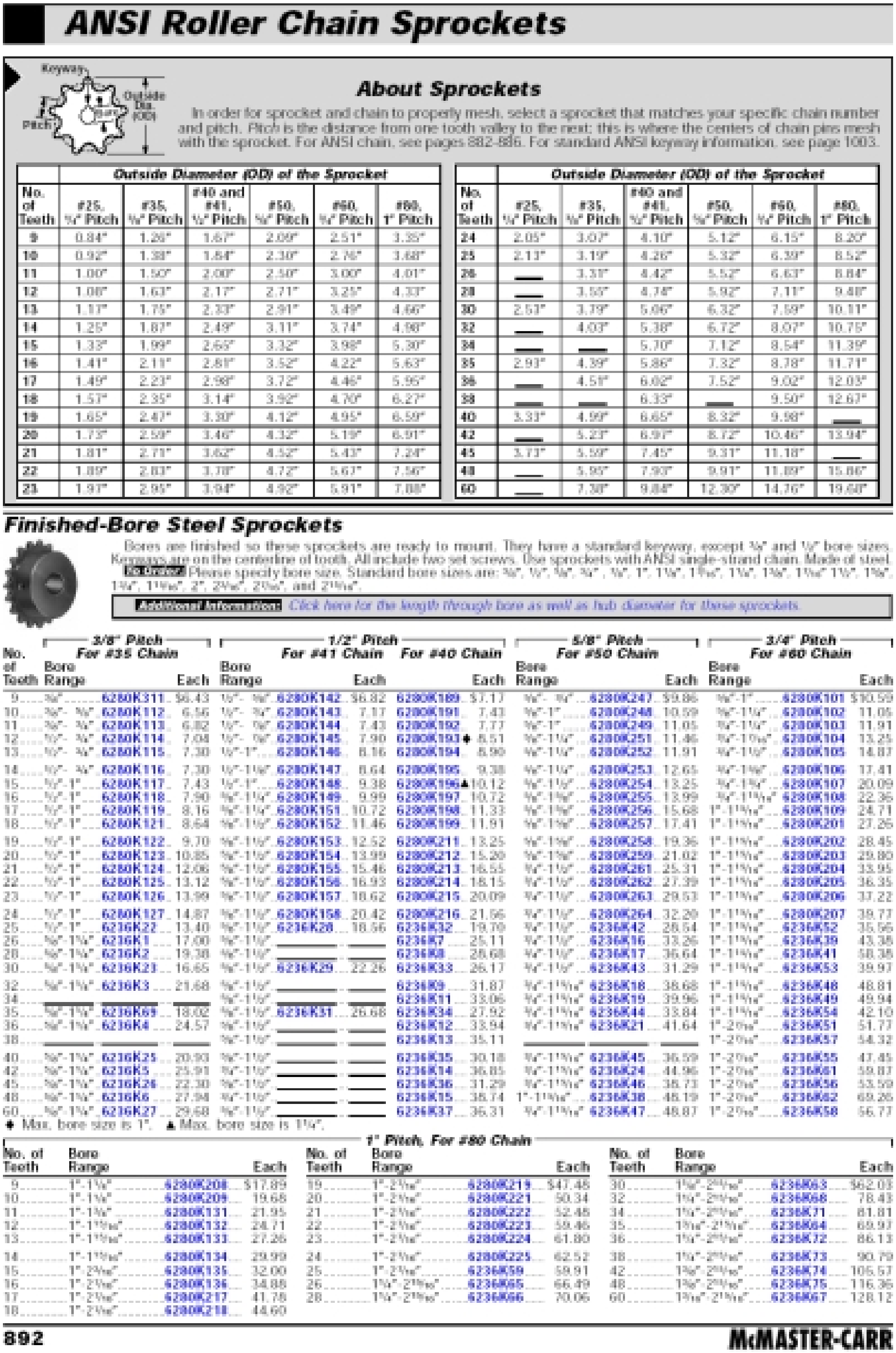
UHMW polyethylene sprockets are self-lubricating, flexible, and resistant to abrasion and impact.

Bearing/Bushing Sprockets: *Ball bearings* are double-sealed and lubricated; *bronze bearings/bushings* are oil-impregnated; *needle bearings* have retainers separating the needle rollers to minimize internal friction and wear.

For ANSI Chain	Pitch	No. of Teeth	Bore	(A)	(B)		Each
Steel Sprocket with Ball Bearings—Style 1							
25	1/4"	20	3/8"	1.729"	5/16"	6663K11	$14.21
35	3/8"	19	3/8"	2.473"	3/8"	6663K21	14.68
35	3/8"	19	1/2"	2.473"	3/8"	6663K22	14.68
35	3/8"	20	0.640"	2.59"	0.72"	6663K23•	14.98
41	1/2"	18	1/2"	3.135"	7/16"	6663K31	16.53
41	1/2"	18	5/8"	3.135"	7/16"	6663K32	16.53
40	1/2"	18	1/2"	3.135"	7/16"	6663K41	16.53
40	1/2"	18	5/8"	3.135"	7/16"	6663K42	16.53
40	1/2"	17	0.640"	2.98"	0.72"	6663K43•	15.31
50	5/8"	15	0.640"	3.32"	0.72"	6663K44•	17.17
50	5/8"	17	1/2"	3.719"	7/16"	6663K51	17.00
50	5/8"	17	5/8"	3.719"	7/16"	6663K52	17.00
60	3/4"	13	0.640"	3.49"	0.72"	6663K53•	18.96
60	3/4"	15	1/2"	3.979"	7/16"	6663K61	16.59
60	3/4"	15	5/8"	3.979"	7/16"	6663K62	16.59
80	1"	12	3/4"	4.332"	39/64"	6663K63	27.19
UHMW Polyethylene Sprocket with Metal Ball Bearings—Style 1							
40	1/2"	17	1/2"	2.98"	0.72"	6663K101	44.74
40	1/2"	18	0.635"	3.14"	0.72"	6663K102	44.74
50	5/8"	18	0.635"	3.92"	0.72"	6663K104	48.36
60	3/4"	15	1/2"	3.98"	0.72"	6663K106	49.08
60	3/4"	16	0.635"	4.22"	0.72"	6663K107	50.50
80	1"	12	3/4"	4.33"	0.96"	6663K109	41.98

• Has hardened teeth.

For ANSI Chain	Pitch	No. of Teeth	Bore	(A)	(B)	(C)		Each
Steel Sprocket with Plain Bronze Bearings—Style 1								
35	3/8"	20	0.506"	2.59"	0.98"	—	6663K12	$10.85
41/40	1/2"	15	0.506"	2.65"	0.98"	—	6663K13	12.54
50	5/8"	15	0.506"	3.32"	0.98"	—	6663K14	14.60
60	3/4"	14	0.506"	3.74"	0.98"	—	6663K15	14.98
Steel Sprocket with Needle Bearings—Style 2								
25	1/4"	19	1/2"	1.65"	3/4"	1 7/32"	6663K71	38.67
35	3/8"	13	1/2"	1.75"	3/4"	1 9/32"	6663K72	43.59
35	3/8"	19	1"	2.47"	1"	1 13/16"	6663K73	43.59
41	1/2"	19	1"	3.28"	1"	2 7/16"	6663K74	50.92
40	1/2"	19	1"	3.28"	1"	2 7/16"	6663K75	50.92
50	5/8"	17	1"	3.72"	1"	2 5/8"	6663K76	57.28
60	3/4"	17	1"	4.46"	1"	2 5/8"	6663K77	66.55
80	1"	13	1"	4.66"	1 1/4"	2 5/8"	6663K78	79.88
Steel Sprocket with Bronze Bushings—Style 2								
35	3/8"	15	1/2"	1.990"	15/16"	1 5/8"	6663K81	13.98
35	3/8"	21	5/8"	2.713"	1 1/16"	2 1/8"	6663K82	18.89
41	1/2"	13	1/2"	2.329"	15/16"	1 9/16"	6663K83	19.58
41	1/2"	19	5/8"	3.296"	1 1/16"	2 7/16"	6663K84	24.54
40	1/2"	13	1/2"	2.329"	15/16"	1 9/16"	6663K85	19.99
40	1/2"	19	5/8"	3.296"	1 1/16"	2 7/16"	6663K86	26.06
50	5/8"	13	1/2"	2.911"	15/16"	2"	6663K87	21.65
50	5/8"	17	5/8"	3.719"	1 1/16"	2 5/8"	6663K88	29.30
60	3/4"	15	5/8"	3.979"	1 1/16"	2 11/16"	6663K89	36.88
60	3/4"	17	1 1/8"	4.462"	1 5/16"	2 7/8"	6663K91	49.63
80	1"	15	1 1/8"	5.305"	1 5/16"	3 1/2"	6663K92	61.08



ANSI Roller Chain Sprockets

About Sprockets

In order for sprocket and chain to properly mesh, select a sprocket that matches your specific chain number and pitch. *Pitch* is the distance from one tooth valley to the next; this is where the centers of chain pins mesh with the sprocket. For ANSI chain, see pages 882-886. For standard ANSI keyway information, see page 1003.

	Outside Diameter (OD) of the Sprocket					
No. of Teeth	#25, 1/4" Pitch	#35, 3/8" Pitch	#40 and #41, 1/2" Pitch	#50, 5/8" Pitch	#60, 3/4" Pitch	#80, 1" Pitch
9	0.84"	1.26"	1.67"	2.09"	2.51"	3.35"
10	0.92"	1.38"	1.84"	2.30"	2.76"	3.68"
11	1.00"	1.50"	2.00"	2.50"	3.00"	4.01"
12	1.08"	1.63"	2.17"	2.71"	3.25"	4.33"
13	1.17"	1.75"	2.33"	2.91"	3.49"	4.66"
14	1.25"	1.87"	2.49"	3.11"	3.74"	4.98"
15	1.33"	1.99"	2.65"	3.32"	3.98"	5.30"
16	1.41"	2.11"	2.81"	3.52"	4.22"	5.63"
17	1.49"	2.23"	2.98"	3.72"	4.46"	5.95"
18	1.57"	2.35"	3.14"	3.92"	4.70"	6.27"
19	1.65"	2.47"	3.30"	4.12"	4.95"	6.59"
20	1.73"	2.59"	3.46"	4.32"	5.19"	6.91"
21	1.81"	2.71"	3.62"	4.52"	5.43"	7.24"
22	1.89"	2.83"	3.78"	4.72"	5.67"	7.56"
23	1.97"	2.95"	3.94"	4.92"	5.91"	7.88"

	Outside Diameter (OD) of the Sprocket					
No. of Teeth	#25, 1/4" Pitch	#35, 3/8" Pitch	#40 and #41, 1/2" Pitch	#50, 5/8" Pitch	#60, 3/4" Pitch	#80, 1" Pitch
24	2.05"	3.07"	4.10"	5.12"	6.15"	8.20"
25	2.13"	3.19"	4.26"	5.32"	6.39"	8.52"
26	—	3.31"	4.42"	5.52"	6.63"	8.84"
28	—	3.55"	4.74"	5.92"	7.11"	9.48"
30	2.53"	3.79"	5.06"	6.32"	7.59"	10.11"
32	—	4.03"	5.38"	6.72"	8.07"	10.75"
34	—	—	5.70"	7.12"	8.54"	11.39"
35	2.93"	4.39"	5.86"	7.32"	8.78"	11.71"
36	—	4.51"	6.02"	7.52"	9.02"	12.03"
38	—	—	6.33"	—	9.50"	12.67"
40	3.33"	4.99"	6.65"	8.32"	9.98"	—
42	—	5.23"	6.97"	8.72"	10.46"	13.94"
45	3.73"	5.59"	7.45"	9.31"	11.18"	—
48	—	5.95"	7.93"	9.91"	11.89"	15.86"
60	—	7.38"	9.84"	12.30"	14.76"	19.68"

Finished-Bore Steel Sprockets

Bores are finished so these sprockets are ready to mount. They have a standard keyway, except 3/8" and 1/2" bore sizes. Keyways are on the centerline of tooth. All include two set screws. Use sprockets with ANSI single-strand chain. Made of steel.

To Order: Please specify bore size. Standard bore sizes are: 3/8", 1/2", 5/8", 3/4", 7/8", 1", 1 1/8", 1 3/16", 1 1/4", 1 3/8", 1 7/16" 1 1/2", 1 5/8", 1 3/4", 1 15/16", 2", 2 3/16", 2 7/16", and 2 15/16".

Additional Information: *Click here for the length through bore as well as hub diameter for these sprockets.*

	3/8" Pitch For #35 Chain			1/2" Pitch For #41 Chain			1/2" Pitch For #40 Chain		5/8" Pitch For #50 Chain			3/4" Pitch For #60 Chain		
No. of Teeth	Bore Range		Each	Bore Range		Each		Each	Bore Range		Each	Bore Range		Each
9	3/8"	6280K311	$6.43	1/2"-5/8"	6280K142	$6.82	6280K189	$7.17	5/8"-3/4"	6280K247	$9.86	5/8"-1"	6280K101	$10.59
10	3/8"-5/8"	6280K112	6.56	1/2"-3/4"	6280K143	7.17	6280K191	7.43	5/8"-1"	6280K248	10.59	5/8"-1 1/4"	6280K102	11.05
11	3/8"-3/4"	6280K113	6.82	1/2"-7/8"	6280K144	7.43	6280K192	7.77	5/8"-1"	6280K249	11.05	3/4"-1 1/4"	6280K103	11.91
12	1/2"-3/4"	6280K114	7.04	1/2"-7/8"	6280K145	7.90	6280K193◆	8.51	5/8"-1 1/4"	6280K251	11.46	3/4"-1 3/16"	6280K104	13.25
13	1/2"-3/4"	6280K115	7.30	1/2"-1"	6280K146	8.16	6280K194	8.90	5/8"-1 1/4"	6280K252	11.91	3/4"-1 1/2"	6280K105	14.87
14	1/2"-3/4"	6280K116	7.30	1/2"-1 1/8"	6280K147	8.64	6280K195	9.38	5/8"-1 1/4"	6280K253	12.65	3/4"-1 5/8"	6280K106	17.41
15	1/2"-1"	6280K117	7.43	1/2"-1"	6280K148	9.38	6280K196▲	10.12	5/8"-1 1/2"	6280K254	13.25	3/4"-1 3/4"	6280K107	20.09
16	1/2"-1"	6280K118	7.90	5/8"-1 1/4"	6280K149	9.99	6280K197	10.72	5/8"-1 5/8"	6280K255	13.99	3/4"-1 15/16"	6280K108	22.36
17	1/2"-1"	6280K119	8.16	5/8"-1 1/4"	6280K151	10.72	6280K198	11.33	5/8"-1 5/8"	6280K256	15.68	1"-1 15/16"	6280K109	24.71
18	1/2"-1"	6280K121	8.64	5/8"-1 1/2"	6280K152	11.46	6280K199	11.91	5/8"-1 5/8"	6280K257	17.41	1"-1 15/16"	6280K201	27.26
19	1/2"-1"	6280K122	9.70	5/8"-1 1/2"	6280K153	12.52	6280K211	13.25	5/8"-1 5/8"	6280K258	19.36	1"-1 15/16"	6280K202	28.45
20	1/2"-1"	6280K123	10.85	5/8"-1 1/2"	6280K154	13.99	6280K212	15.20	5/8"-1 5/8"	6280K259	21.02	1"-1 15/16"	6280K203	29.80
21	1/2"-1"	6280K124	12.06	5/8"-1 1/2"	6280K155	15.46	6280K213	16.55	3/4"-1 1/2"	6280K261	25.31	1"-1 15/16"	6280K204	33.95
22	1/2"-1"	6280K125	13.12	5/8"-1 1/2"	6280K156	16.93	6280K214	18.15	3/4"-1 1/2"	6280K262	27.39	1"-1 15/16"	6280K205	36.35
23	1/2"-1"	6280K126	13.99	5/8"-1 1/2"	6280K157	18.62	6280K215	20.09	3/4"-1 1/2"	6280K263	29.53	1"-1 15/16"	6280K206	37.22
24	1/2"-1"	6280K127	14.87	5/8"-1 1/2"	6280K158	20.42	6280K216	21.56	3/4"-1 1/2"	6280K264	32.20	1"-1 15/16"	6280K207	39.77
25	1/2"-1"	6236K22	13.40	5/8"-1 1/2"	6236K28	18.56	6236K32	19.70	3/4"-1 1/2"	6236K42	28.54	1"-1 15/16"	6236K52	35.56
26	5/8"-1 1/4"	6236K1	17.00	5/8"-1 1/2"	—	—	6236K7	25.11	3/4"-1 1/2"	6236K16	33.26	1"-1 15/16"	6236K39	43.38
28	5/8"-1 1/4"	6236K2	19.38	5/8"-1 1/2"	—	—	6236K8	28.68	3/4"-1 1/2"	6236K17	36.64	1"-1 15/16"	6236K41	58.38
30	5/8"-1 1/4"	6236K23	16.65	5/8"-1 1/2"	6236K29	22.26	6236K33	26.17	3/4"-1 1/2"	6236K43	31.29	1"-1 15/16"	6236K53	39.97
32	5/8"-1 1/4"	6236K3	21.68	5/8"-1 1/2"	—	—	6236K9	31.87	3/4"-1 15/16"	6236K18	38.68	1"-1 15/16"	6236K48	48.81
34	—	—	—	5/8"-1 1/2"	—	—	6236K11	33.06	3/4"-1 15/16"	6236K19	39.96	1"-1 15/16"	6236K49	49.94
35	5/8"-1 1/4"	6236K69	18.02	5/8"-1 1/2"	6236K31	26.68	6236K34	27.92	3/4"-1 15/16"	6236K44	33.84	1"-1 15/16"	6236K54	42.10
36	5/8"-1 1/4"	6236K4	24.57	5/8"-1 1/2"	—	—	6236K12	33.94	3/4"-1 15/16"	6236K21	41.64	1"-2 3/16"	6236K51	51.77
38	—	—	—	5/8"-1 1/2"	—	—	6236K13	35.11	—	—	—	1"-2 3/16"	6236K57	54.32
40	5/8"-1 1/4"	6236K25	20.93	5/8"-1 1/2"	—	—	6236K35	30.18	3/4"-1 15/16"	6236K45	36.59	1"-2 3/16"	6236K55	47.45
42	5/8"-1 1/4"	6236K5	25.91	3/4"-1 1/2"	—	—	6236K14	36.85	3/4"-1 15/16"	6236K24	44.96	1"-2 3/16"	6236K61	59.87
45	5/8"-1 1/4"	6236K26	22.30	5/8"-1 1/2"	—	—	6236K36	31.29	3/4"-1 15/16"	6236K46	38.73	1"-2 3/16"	6236K56	53.59
48	5/8"-1 1/4"	6236K6	27.98	3/4"-1 1/2"	—	—	6236K15	38.74	1"-1 15/16"	6236K38	48.19	1"-2 3/16"	6236K62	69.26
60	5/8"-1 1/4"	6236K27	29.68	5/8"-1 1/2"	—	—	6236K37	36.31	3/4"-1 15/16"	6236K47	48.87	1"-2 3/16"	6236K58	56.77

◆ Max. bore size is 1". ▲ Max. bore size is 1 1/4".

1" Pitch, For #80 Chain

No. of Teeth	Bore Range		Each	No. of Teeth	Bore Range		Each	No. of Teeth	Bore Range		Each
9	1"-1 1/4"	6280K208	$17.89	19	1"-2 3/16"	6280K219	$47.48	30	1 3/8"-2 15/16"	6236K63	$62.03
10	1"-1 1/4"	6280K209	19.68	20	1"-2 3/16"	6280K221	50.34	32	1 1/4"-2 15/16"	6236K68	78.43
11	1"-1 1/4"	6280K131	21.95	21	1"-2 3/16"	6280K222	52.48	34	1 1/4"-2 15/16"	6236K71	81.81
12	1"-1 15/16"	6280K132	24.71	22	1"-2 3/16"	6280K223	59.46	35	1 15/16"-2 15/16"	6236K64	69.97
13	1"-1 15/16"	6280K133	27.26	23	1"-2 3/16"	6280K224	61.80	36	1 1/4"-2 15/16"	6236K72	86.13
14	1"-1 15/16"	6280K134	29.99	24	1"-2 3/16"	6280K225	62.52	38	1 1/4"-2 15/16"	6236K73	90.79
15	1"-2 3/16"	6280K135	32.00	25	1"-2 3/16"	6236K59	59.91	42	1 3/8"-2 15/16"	6236K74	105.57
16	1"-2 3/16"	6280K136	34.88	26	1 1/4"-2 15/16"	6236K65	66.49	48	1 3/8"-2 15/16"	6236K75	116.36
17	1"-2 3/16"	6280K217	41.78	28	1 1/4"-2 15/16"	6236K66	70.06	60	1 15/16"-2 15/16"	6236K67	128.12
18	1"-2 3/16"	6280K218	44.60								

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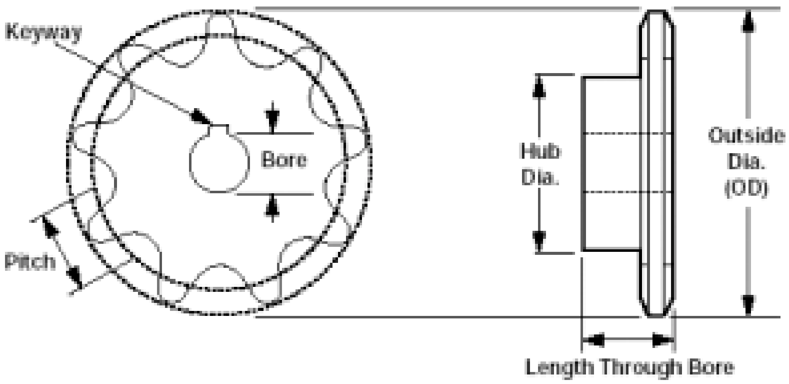
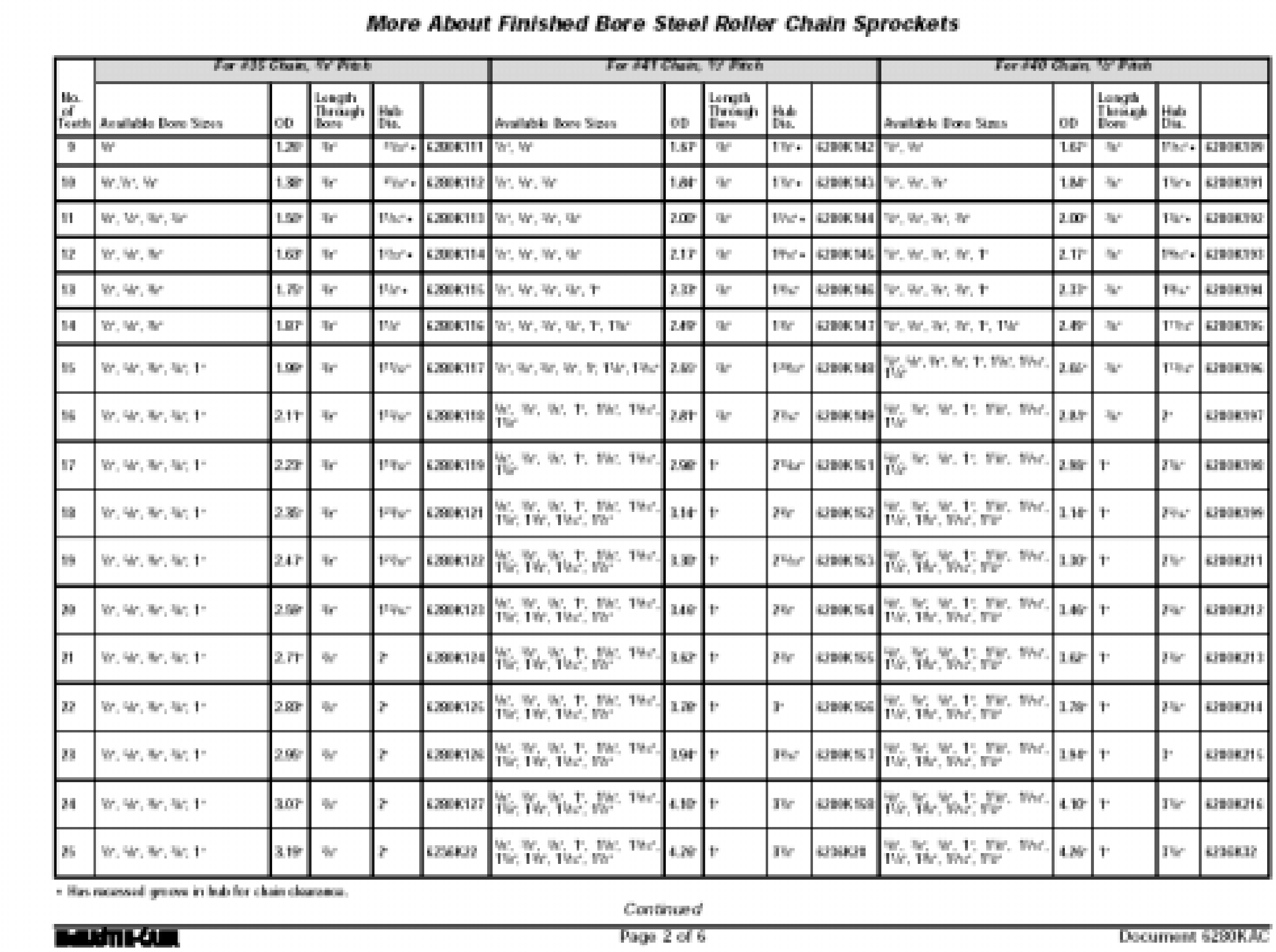
More About Finished Bore Steel Roller Chain Sprockets





More About Finished Bore Steel Roller Chain Sprockets

• Has recessed groove in hub for chain clearance.

Continued

Page 2 of 6

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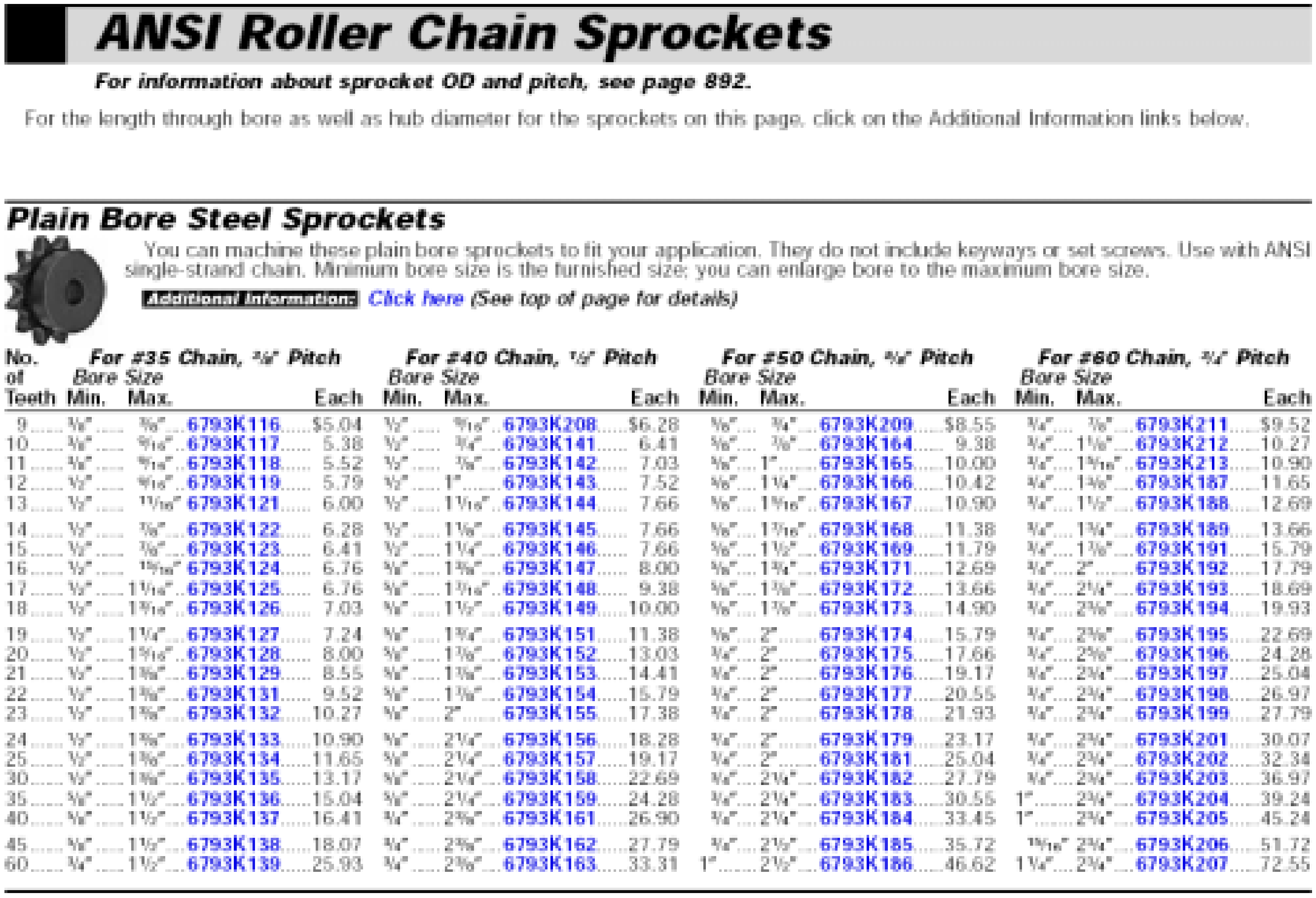


ANSI Roller Chain Sprockets

For information about sprocket OD and pitch, see page 892.

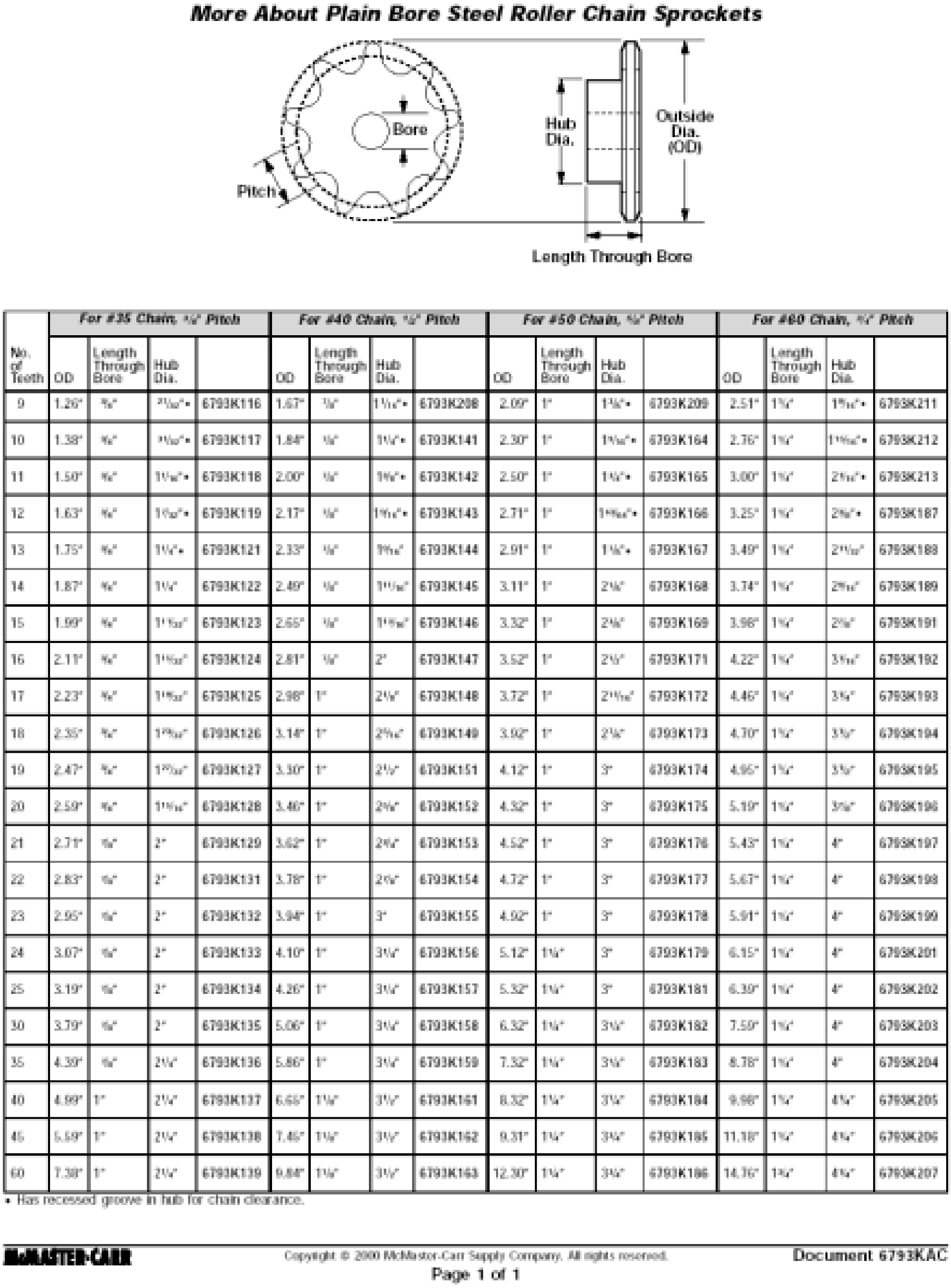
For the length through bore as well as hub diameter for the sprockets on this page, click on the Additional Information links below.

Plain Bore Steel Sprockets

You can machine these plain bore sprockets to fit your application. They do not include keyways or set screws. Use with ANSI single-strand chain. Minimum bore size is the furnished size; you can enlarge bore to the maximum bore size.

Additional Information: *Click here (See top of page for details)*

No.	*For #35 Chain, ⅜" Pitch*				*For #40 Chain, ½" Pitch*				*For #50 Chain, ⅝" Pitch*				*For #60 Chain, ¾" Pitch*			
of	*Bore Size*				*Bore Size*				*Bore Size*				*Bore Size*			
Teeth	Min.	Max.		Each	Min.	Max.		Each	Min.	Max.		Each	Min.	Max.		Each
9	⅜"	⅜"	6793K116	$5.04	½"	⁹⁄₁₆"	6793K208	$6.28	⅝"	¾"	6793K209	$8.55	¾"	⅞"	6793K211	$9.52
10	⅜"	⁹⁄₁₆"	6793K117	5.38	½"	¾"	6793K141	6.41	⅝"	⅞"	6793K164	9.38	¾"	1⅛"	6793K212	10.27
11	⅜"	⁹⁄₁₆"	6793K118	5.52	½"	⅞"	6793K142	7.03	⅝"	1"	6793K165	10.00	¾"	1⁵⁄₁₆"	6793K213	10.90
12	½"	⁹⁄₁₆"	6793K119	5.79	½"	1"	6793K143	7.52	⅝"	1¼"	6793K166	10.42	¾"	1⅜"	6793K187	11.65
13	½"	¹¹⁄₁₆"	6793K121	6.00	½"	1¹⁄₁₆"	6793K144	7.66	⅝"	1⁵⁄₁₆"	6793K167	10.90	¾"	1½"	6793K188	12.69
14	½"	⅞"	6793K122	6.28	½"	1⅛"	6793K145	7.66	⅝"	1⁷⁄₁₆"	6793K168	11.38	¾"	1¾"	6793K189	13.66
15	½"	⅞"	6793K123	6.41	½"	1¼"	6793K146	7.66	⅝"	1½"	6793K169	11.79	¾"	1⅞"	6793K191	15.79
16	½"	¹⁵⁄₁₆"	6793K124	6.76	⅝"	1⅜"	6793K147	8.00	⅝"	1¾"	6793K171	12.69	¾"	2"	6793K192	17.79
17	½"	1¹⁄₁₆"	6793K125	6.76	⅝"	1⁷⁄₁₆"	6793K148	9.38	⅝"	1⅝"	6793K172	13.66	¾"	2¼"	6793K193	18.69
18	½"	1³⁄₁₆"	6793K126	7.03	⅝"	1½"	6793K149	10.00	⅝"	1⅞"	6793K173	14.90	¾"	2⅜"	6793K194	19.93
19	½"	1¼"	6793K127	7.24	⅝"	1¾"	6793K151	11.38	⅝"	2"	6793K174	15.79	¾"	2⅜"	6793K195	22.69
20	½"	1⁵⁄₁₆"	6793K128	8.00	⅝"	1⅞"	6793K152	13.03	¾"	2"	6793K175	17.66	¾"	2⅜"	6793K196	24.28
21	½"	1⅜"	6793K129	8.55	⅝"	1⅞"	6793K153	14.41	¾"	2"	6793K176	19.17	¾"	2¾"	6793K197	25.04
22	½"	1⅜"	6793K131	9.52	⅝"	1⅞"	6793K154	15.79	¾"	2"	6793K177	20.55	¾"	2¾"	6793K198	26.97
23	½"	1⅜"	6793K132	10.27	⅝"	2"	6793K155	17.38	¾"	2"	6793K178	21.93	¾"	2¾"	6793K199	27.79
24	½"	1⅜"	6793K133	10.90	⅝"	2¼"	6793K156	18.28	¾"	2"	6793K179	23.17	¾"	2¾"	6793K201	30.07
25	½"	1⅜"	6793K134	11.65	⅝"	2¼"	6793K157	19.17	¾"	2"	6793K181	25.04	¾"	2¾"	6793K202	32.34
30	½"	1⅜"	6793K135	13.17	⅝"	2¼"	6793K158	22.69	¾"	2¼"	6793K182	27.79	¾"	2¾"	6793K203	36.97
35	⅝"	1½"	6793K136	15.04	⅝"	2¼"	6793K159	24.28	¾"	2¼"	6793K183	30.55	1"	2¾"	6793K204	39.24
40	⅝"	1½"	6793K137	16.41	¾"	2⅜"	6793K161	26.90	¾"	2¼"	6793K184	33.45	1"	2¾"	6793K205	45.24
45	⅝"	1½"	6793K138	18.07	¾"	2⅜"	6793K162	27.79	¾"	2½"	6793K185	35.72	1³⁄₁₆"	2¾"	6793K206	51.72
60	¾"	1½"	6793K139	25.93	¾"	2⅜"	6793K163	33.31	1"	2½"	6793K186	46.62	1¼"	2¾"	6793K207	72.55



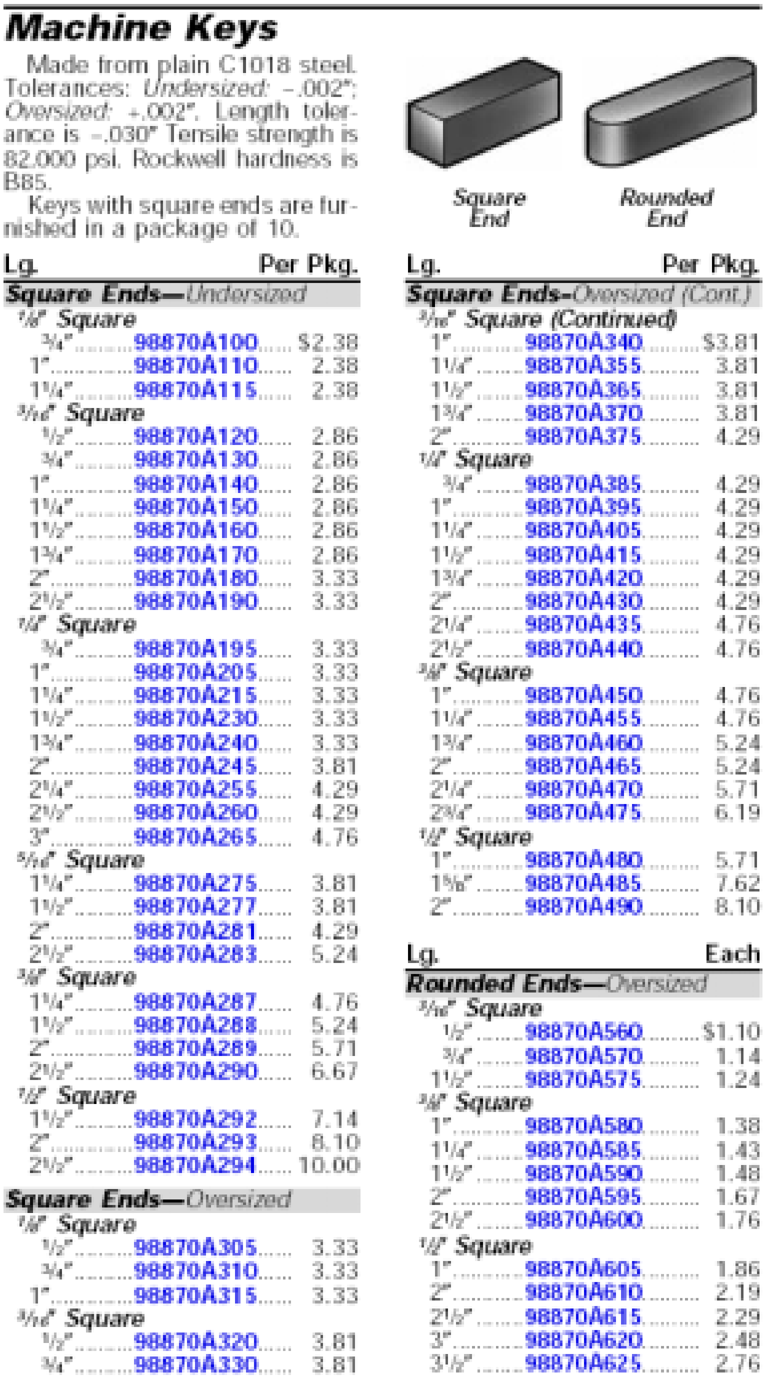
More About Plain Bore Steel Roller Chain Sprockets

No. of Teeth	For #35 Chain, ⅜" Pitch				For #40 Chain, ½" Pitch				For #50 Chain, ⅝" Pitch				For #60 Chain, ¾" Pitch			
	OD	Length Through Bore	Hub Dia.		OD	Length Through Bore	Hub Dia.		OD	Length Through Bore	Hub Dia.		OD	Length Through Bore	Hub Dia.	
9	1.26"	⅞"	²¹⁄₃₂"•	6793K116	1.67"	⅞"	1³⁄₃₂"•	6793K208	2.09"	1"	1⅜"•	6793K209	2.51"	1½"	1⁹⁄₁₆"•	6793K211
10	1.38"	⅞"	²⁵⁄₃₂"•	6793K117	1.84"	⅞"	1¼"•	6793K141	2.30"	1"	1⁹⁄₁₆"•	6793K164	2.76"	1½"	1¹³⁄₁₆"•	6793K212
11	1.50"	⅞"	1¹⁄₃₂"•	6793K118	2.00"	⅞"	1⅜"•	6793K142	2.50"	1"	1¾"•	6793K165	3.00"	1½"	2¹⁄₁₆"•	6793K213
12	1.63"	⅞"	1⁵⁄₃₂"•	6793K119	2.17"	⅞"	1⁹⁄₁₆"•	6793K143	2.71"	1"	1¹⁵⁄₁₆"•	6793K166	3.25"	1½"	2⅜"•	6793K187
13	1.75"	⅞"	1⅛"•	6793K121	2.33"	⅞"	1⁹⁄₁₆"	6793K144	2.91"	1"	1⅞"•	6793K167	3.49"	1½"	2¹¹⁄₁₆"	6793K188
14	1.87"	⅞"	1¼"	6793K122	2.49"	⅞"	1¹¹⁄₁₆"	6793K145	3.11"	1"	2⅛"	6793K168	3.74"	1½"	2²⁹⁄₃₂"	6793K189
15	1.99"	⅞"	1¹¹⁄₃₂"	6793K123	2.65"	⅞"	1¹³⁄₁₆"	6793K146	3.32"	1"	2⅜"	6793K169	3.98"	1½"	2⅞"	6793K191
16	2.11"	⅞"	1¹⁵⁄₃₂"	6793K124	2.81"	⅞"	2"	6793K147	3.52"	1"	2½"	6793K171	4.22"	1½"	3³⁄₁₆"	6793K192
17	2.23"	⅞"	1¹⁹⁄₃₂"	6793K125	2.98"	1"	2⅛"	6793K148	3.72"	1"	2¹¹⁄₁₆"	6793K172	4.46"	1½"	3¼"	6793K193
18	2.35"	⅞"	1²³⁄₃₂"	6793K126	3.14"	1"	2⁵⁄₁₆"	6793K149	3.92"	1"	2⅞"	6793K173	4.70"	1½"	3½"	6793K194
19	2.47"	⅞"	1²⁷⁄₃₂"	6793K127	3.30"	1"	2½"	6793K151	4.12"	1"	3"	6793K174	4.95"	1½"	3½"	6793K195
20	2.59"	⅞"	1¹⁵⁄₁₆"	6793K128	3.46"	1"	2⅝"	6793K152	4.32"	1"	3"	6793K175	5.19"	1½"	3⅝"	6793K196
21	2.71"	⅝"	2"	6793K129	3.62"	1"	2¾"	6793K153	4.52"	1"	3"	6793K176	5.43"	1½"	4"	6793K197
22	2.83"	⅝"	2"	6793K131	3.78"	1"	2⅞"	6793K154	4.72"	1"	3"	6793K177	5.67"	1½"	4"	6793K198
23	2.95"	⅝"	2"	6793K132	3.94"	1"	3"	6793K155	4.92"	1"	3"	6793K178	5.91"	1½"	4"	6793K199
24	3.07"	⅝"	2"	6793K133	4.10"	1"	3¼"	6793K156	5.12"	1¼"	3"	6793K179	6.15"	1½"	4"	6793K201
25	3.19"	⅝"	2"	6793K134	4.26"	1"	3¼"	6793K157	5.32"	1¼"	3"	6793K181	6.39"	1½"	4"	6793K202
30	3.79"	⅝"	2"	6793K135	5.06"	1"	3¼"	6793K158	6.32"	1¼"	3¼"	6793K182	7.59"	1½"	4"	6793K203
35	4.39"	⅝"	2¼"	6793K136	5.86"	1"	3¼"	6793K159	7.32"	1¼"	3¼"	6793K183	8.78"	1½"	4"	6793K204
40	4.99"	1"	2¼"	6793K137	6.65"	1⅛"	3½"	6793K161	8.32"	1¼"	3¼"	6793K184	9.98"	1½"	4¼"	6793K205
45	5.59"	1"	2¼"	6793K138	7.45"	1⅛"	3½"	6793K162	9.31"	1¼"	3¼"	6793K185	11.18"	1½"	4¼"	6793K206
60	7.38"	1"	2¼"	6793K139	9.84"	1⅛"	3½"	6793K163	12.30"	1¼"	3¼"	6793K186	14.76"	1½"	4¼"	6793K207

• Has recessed groove in hub for chain clearance.

McMASTER-CARR

Page 1 of 1 Document 6793KAC



Machine Keys

Made from plain C1018 steel. Tolerances: *Undersized:* –.002"; *Oversized:* +.002". Length tolerance is –.030" Tensile strength is 82,000 psi. Rockwell hardness is B85.

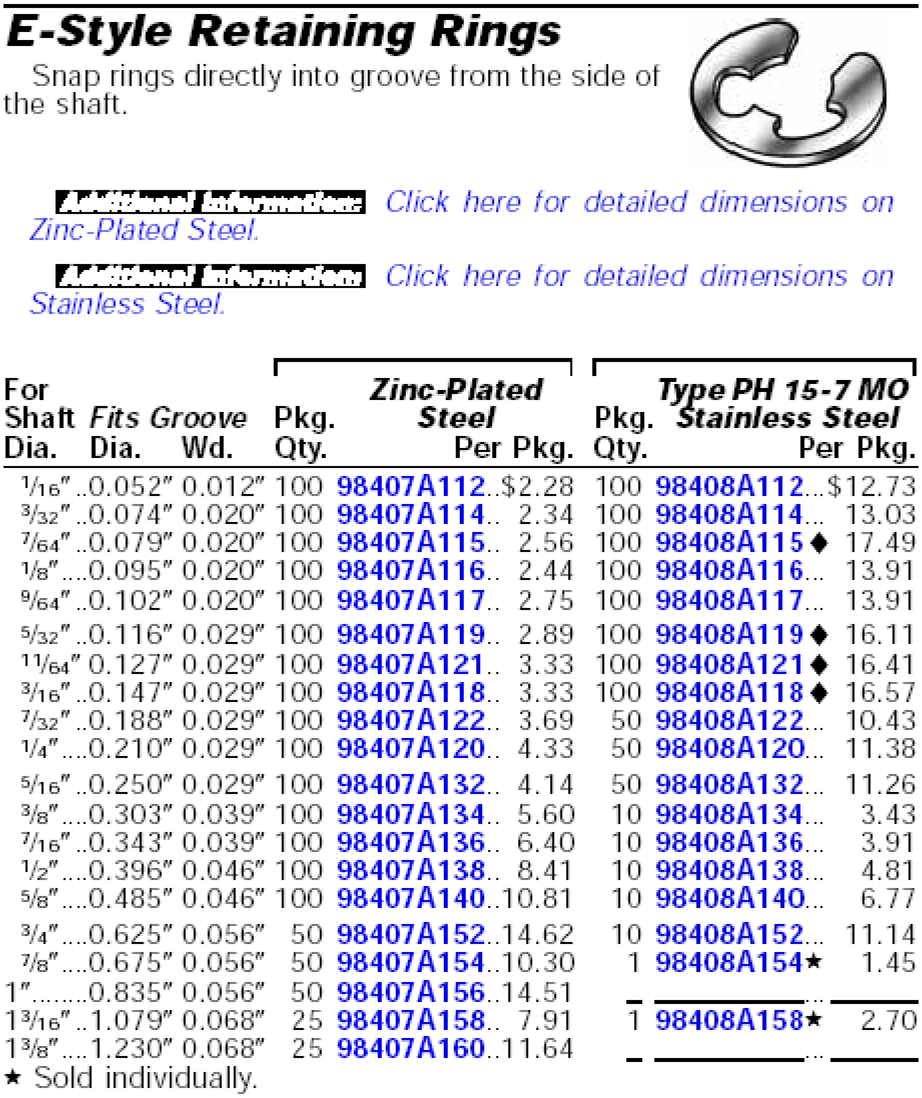
Keys with square ends are furnished in a package of 10.

Square End

Rounded End

Lg.		Per Pkg.
Square Ends—*Undersized*		
1/8" Square		
¾"	98870A100	$2.38
1"	98870A110	2.38
1¼"	98870A115	2.38
3/16" Square		
½"	98870A120	2.86
¾"	98870A130	2.86
1"	98870A140	2.86
1¼"	98870A150	2.86
1½"	98870A160	2.86
1¾"	98870A170	2.86
2"	98870A180	3.33
2½"	98870A190	3.33
1/4" Square		
¾"	98870A195	3.33
1"	98870A205	3.33
1¼"	98870A215	3.33
1½"	98870A230	3.33
1¾"	98870A240	3.33
2"	98870A245	3.81
2¼"	98870A255	4.29
2½"	98870A260	4.29
3"	98870A265	4.76
5/16" Square		
1¼"	98870A275	3.81
1½"	98870A277	3.81
2"	98870A281	4.29
2½"	98870A283	5.24
3/8" Square		
1¼"	98870A287	4.76
1½"	98870A288	5.24
2"	98870A289	5.71
2½"	98870A290	6.67
1/2" Square		
1½"	98870A292	7.14
2"	98870A293	8.10
2½"	98870A294	10.00
Square Ends—*Oversized*		
1/8" Square		
½"	98870A305	3.33
¾"	98870A310	3.33
1"	98870A315	3.33
3/16" Square		
½"	98870A320	3.81
¾"	98870A330	3.81
1"	98870A340	$3.81
1¼"	98870A355	3.81
1½"	98870A365	3.81
1¾"	98870A370	3.81
2"	98870A375	4.29
1/4" Square		
¾"	98870A385	4.29
1"	98870A395	4.29
1¼"	98870A405	4.29
1½"	98870A415	4.29
1¾"	98870A420	4.29
2"	98870A430	4.29
2¼"	98870A435	4.76
2½"	98870A440	4.76
3/8" Square		
1"	98870A450	4.76
1¼"	98870A455	4.76
1¾"	98870A460	5.24
2"	98870A465	5.24
2¼"	98870A470	5.71
2¾"	98870A475	6.19
1/2" Square		
1"	98870A480	5.71
1⅝"	98870A485	7.62
2"	98870A490	8.10

Lg.		Each
Rounded Ends—*Oversized*		
3/16" Square		
½"	98870A560	$1.10
¾"	98870A570	1.14
1½"	98870A575	1.24
3/8" Square		
1"	98870A580	1.38
1¼"	98870A585	1.43
1½"	98870A590	1.48
2"	98870A595	1.67
2½"	98870A600	1.76
1/2" Square		
1"	98870A605	1.86
2"	98870A610	2.19
2½"	98870A615	2.29
3"	98870A620	2.48
3½"	98870A625	2.76



E-Style Retaining Rings

Snap rings directly into groove from the side of the shaft.

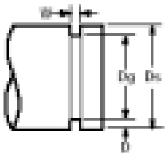
Additional Information: Click here for detailed dimensions on Zinc-Plated Steel.

Additional Information: Click here for detailed dimensions on Stainless Steel.

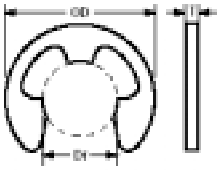
For Shaft Dia.	Fits Groove Dia.	Fits Groove Wd.	Pkg. Qty.	Zinc-Plated Steel	Per Pkg.	Pkg. Qty.	Type PH 15-7 MO Stainless Steel	Per Pkg.
1/16"	0.052"	0.012"	100	98407A112	$2.28	100	98408A112	$12.73
3/32"	0.074"	0.020"	100	98407A114	2.34	100	98408A114	13.03
7/64"	0.079"	0.020"	100	98407A115	2.56	100	98408A115 ◆	17.49
1/8"	0.095"	0.020"	100	98407A116	2.44	100	98408A116	13.91
9/64"	0.102"	0.020"	100	98407A117	2.75	100	98408A117	13.91
5/32"	0.116"	0.029"	100	98407A119	2.89	100	98408A119 ◆	16.11
11/64"	0.127"	0.029"	100	98407A121	3.33	100	98408A121 ◆	16.41
3/16"	0.147"	0.029"	100	98407A118	3.33	100	98408A118 ◆	16.57
7/32"	0.188"	0.029"	100	98407A122	3.69	50	98408A122	10.43
1/4"	0.210"	0.029"	100	98407A120	4.33	50	98408A120	11.38
5/16"	0.250"	0.029"	100	98407A132	4.14	50	98408A132	11.26
3/8"	0.303"	0.039"	100	98407A134	5.60	10	98408A134	3.43
7/16"	0.343"	0.039"	100	98407A136	6.40	10	98408A136	3.91
1/2"	0.396"	0.046"	100	98407A138	8.41	10	98408A138	4.81
5/8"	0.485"	0.046"	100	98407A140	10.81	10	98408A140	6.77
3/4"	0.625"	0.056"	50	98407A152	14.62	10	98408A152	11.14
7/8"	0.675"	0.056"	50	98407A154	10.30	1	98408A154 ★	1.45
1"	0.835"	0.056"	50	98407A156	14.51	—	—	—
1 3/16"	1.079"	0.068"	25	98407A158	7.91	1	98408A158 ★	2.70
1 3/8"	1.230"	0.068"	25	98407A160	11.64	—	—	—

★ Sold individually.

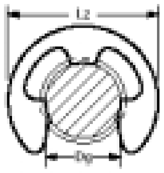
Zinc-Plated Steel E-Style External Retaining Rings



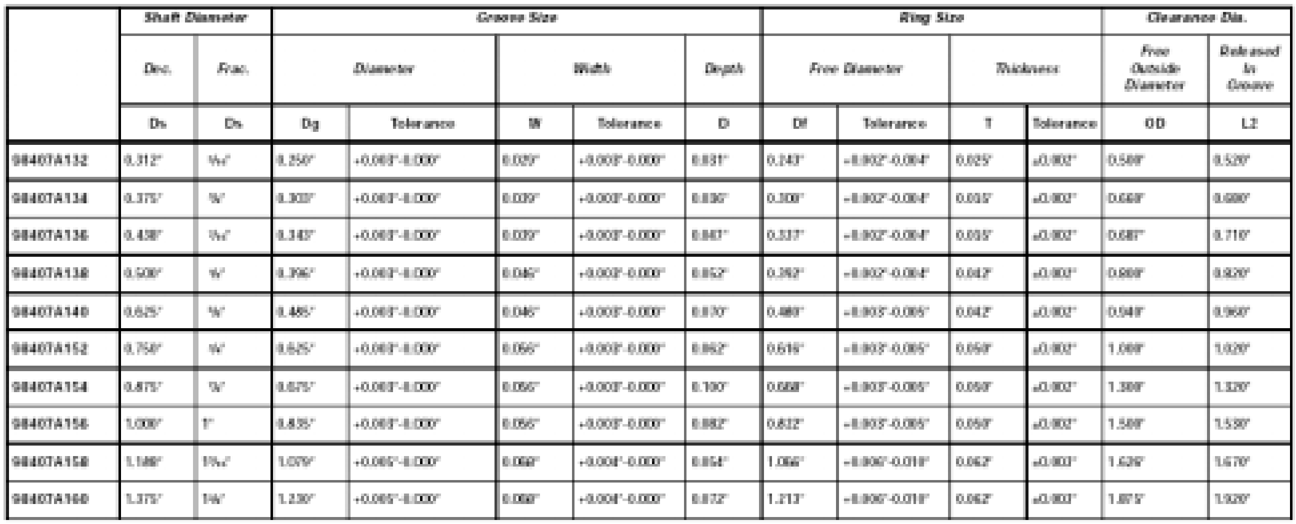
Shaft Diameter and Groove Size



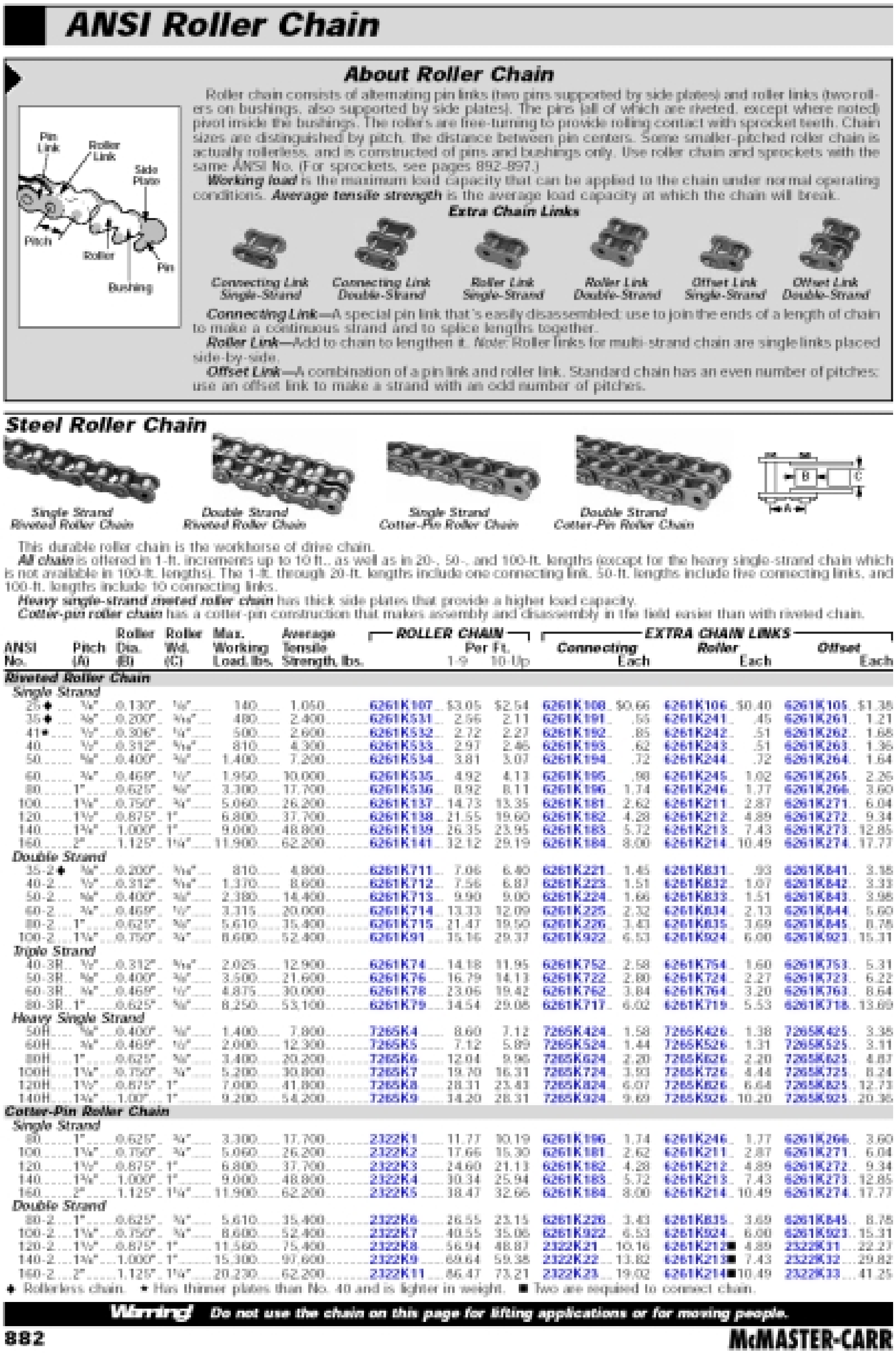
Free Diameter, Thickness, and Free Outside Diameter



Clearance Diameter



	Shaft Diameter		*Groove Size*					*Ring Size*				*Clearance Dia.*	
	Dec.	*Frac.*	*Diameter*		*Width*		*Depth*	*Free Diameter*		*Thickness*		*Free Outside Diameter*	*Released In Groove*
	Ds	Ds	Dg	Tolerance	W	Tolerance	D	Df	Tolerance	T	Tolerance	OD	L2
98407A132	0.312"	5/16"	0.250"	+0.003"-0.000"	0.029"	+0.003"-0.000"	0.031"	0.243"	+0.002"-0.004"	0.025"	±0.002"	0.500"	0.520"
98407A134	0.375"	3/8"	0.300"	+0.003"-0.000"	0.039"	+0.003"-0.000"	0.036"	0.300"	+0.002"-0.004"	0.035"	±0.002"	0.660"	0.690"
98407A136	0.438"	7/16"	0.343"	+0.003"-0.000"	0.039"	+0.003"-0.000"	0.047"	0.337"	+0.002"-0.004"	0.035"	±0.002"	0.687"	0.710"
98407A138	0.500"	1/2"	0.396"	+0.003"-0.000"	0.046"	+0.003"-0.000"	0.052"	0.392"	+0.002"-0.004"	0.042"	±0.002"	0.800"	0.820"
98407A140	0.625"	5/8"	0.485"	+0.003"-0.000"	0.046"	+0.003"-0.000"	0.070"	0.480"	+0.003"-0.005"	0.042"	±0.002"	0.940"	0.960"
98407A152	0.750"	3/4"	0.625"	+0.003"-0.000"	0.056"	+0.003"-0.000"	0.062"	0.616"	+0.003"-0.005"	0.050"	±0.002"	1.000"	1.020"
98407A154	0.875"	7/8"	0.675"	+0.003"-0.000"	0.056"	+0.003"-0.000"	0.100"	0.668"	+0.003"-0.005"	0.050"	±0.002"	1.300"	1.320"
98407A156	1.000"	1"	0.835"	+0.003"-0.000"	0.056"	+0.003"-0.000"	0.082"	0.832"	+0.003"-0.005"	0.050"	±0.002"	1.500"	1.530"
98407A158	1.188"	1 3/16"	1.079"	+0.005"-0.000"	0.068"	+0.004"-0.000"	0.054"	1.066"	+0.006"-0.010"	0.062"	±0.003"	1.626"	1.670"
98407A160	1.375"	1 3/8"	1.230"	+0.005"-0.000"	0.068"	+0.004"-0.000"	0.072"	1.213"	+0.006"-0.010"	0.062"	±0.003"	1.875"	1.920"



ANSI Roller Chain

About Roller Chain

Roller chain consists of alternating pin links (two pins supported by side plates) and roller links (two rollers on bushings, also supported by side plates). The pins (all of which are riveted, except where noted) pivot inside the bushings. The rollers are free-turning to provide rolling contact with sprocket teeth. Chain sizes are distinguished by pitch, the distance between pin centers. Some smaller-pitched roller chain is actually rollerless, and is constructed of pins and bushings only. Use roller chain and sprockets with the same ANSI No. (For sprockets, see pages 892-897.)

Working load is the maximum load capacity that can be applied to the chain under normal operating conditions. ***Average tensile strength*** is the average load capacity at which the chain will break.

Extra Chain Links

Connecting Link Single-Strand *Connecting Link Double-Strand* *Roller Link Single-Strand* *Roller Link Double-Strand* *Offset Link Single-Strand* *Offset Link Double-Strand*

Connecting Link—A special pin link that's easily disassembled; use to join the ends of a length of chain to make a continuous strand and to splice lengths together.

Roller Link—Add to chain to lengthen it. *Note:* Roller links for multi-strand chain are single links placed side-by-side.

Offset Link—A combination of a pin link and roller link. Standard chain has an even number of pitches; use an offset link to make a strand with an odd number of pitches.

Steel Roller Chain

Single Strand Riveted Roller Chain *Double Strand Riveted Roller Chain* *Single Strand Cotter-Pin Roller Chain* *Double Strand Cotter-Pin Roller Chain*

This durable roller chain is the workhorse of drive chain.

All chain is offered in 1-ft. increments up to 10 ft., as well as in 20-, 50-, and 100-ft. lengths (except for the heavy single-strand chain which is not available in 100-ft. lengths). The 1-ft. through 20-ft. lengths include one connecting link. 50-ft. lengths include five connecting links, and 100-ft. lengths include 10 connecting links.

Heavy single-strand riveted roller chain has thick side plates that provide a higher load capacity.

Cotter-pin roller chain has a cotter-pin construction that makes assembly and disassembly in the field easier than with riveted chain.

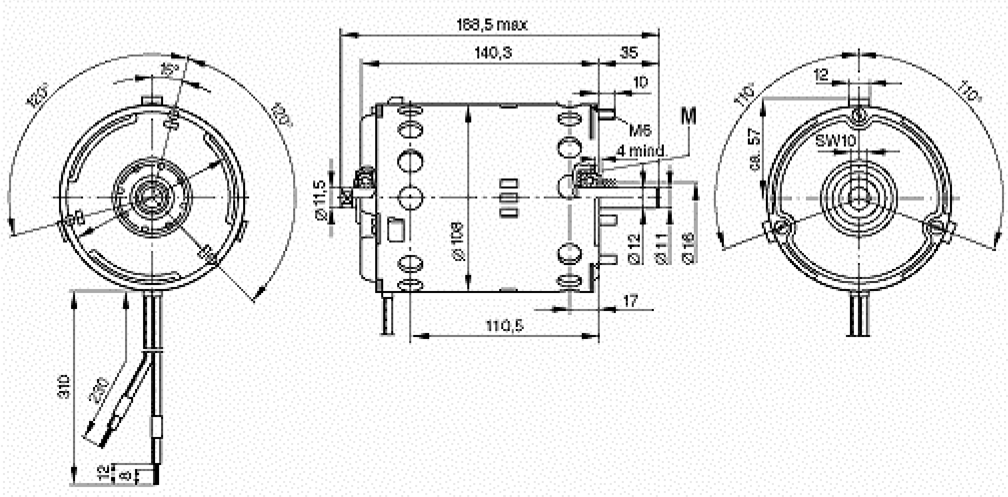
ANSI No.	Pitch (A)	Roller Dia. (B)	Roller Wd. (C)	Max. Working Load, lbs.	Average Tensile Strength, lbs.	ROLLER CHAIN	Per Ft. 1-9	Per Ft. 10-Up	EXTRA CHAIN LINKS Connecting	Each	Roller	Each	Offset	Each
Riveted Roller Chain														
Single Strand														
25◆	¼"	0.130"	⅛"	140	1,050	6261K107	$3.05	$2.54	6261K108	$0.66	6261K106	$0.40	6261K105	$1.38
35◆	⅜"	0.200"	³⁄₁₆"	480	2,400	6261K531	2.56	2.11	6261K191	.55	6261K241	.45	6261K261	1.21
41•	½"	0.306"	¼"	500	2,600	6261K532	2.72	2.27	6261K192	.85	6261K242	.51	6261K262	1.68
40	½"	0.312"	⁵⁄₁₆"	810	4,300	6261K533	2.97	2.46	6261K193	.62	6261K243	.51	6261K263	1.36
50	⅝"	0.400"	⅜"	1,400	7,200	6261K534	3.81	3.07	6261K194	.72	6261K244	.72	6261K264	1.64
60	¾"	0.469"	½"	1,950	10,000	6261K535	4.92	4.13	6261K195	.98	6261K245	1.02	6261K265	2.26
80	1"	0.625"	⅝"	3,300	17,700	6261K536	8.92	8.11	6261K196	1.74	6261K246	1.77	6261K266	3.60
100	1¼"	0.750"	¾"	5,060	26,200	6261K137	14.73	13.35	6261K181	2.62	6261K211	2.87	6261K271	6.04
120	1½"	0.875"	1"	6,800	37,700	6261K138	21.55	19.60	6261K182	4.28	6261K212	4.89	6261K272	9.34
140	1¾"	1.000"	1"	9,000	48,800	6261K139	26.35	23.95	6261K183	5.72	6261K213	7.43	6261K273	12.85
160	2"	1.125"	1¼"	11,900	62,200	6261K141	32.12	29.19	6261K184	8.00	6261K214	10.49	6261K274	17.77
Double Strand														
35-2◆	⅜"	0.200"	³⁄₁₆"	810	4,800	6261K711	7.06	6.40	6261K221	1.45	6261K831	.93	6261K841	3.18
40-2	½"	0.312"	⁵⁄₁₆"	1,370	8,600	6261K712	7.56	6.87	6261K223	1.51	6261K832	1.07	6261K842	3.33
50-2	⅝"	0.400"	⅜"	2,380	14,400	6261K713	9.90	9.00	6261K224	1.66	6261K833	1.51	6261K843	3.98
60-2	¾"	0.469"	½"	3,315	20,000	6261K714	13.33	12.09	6261K225	2.32	6261K834	2.13	6261K844	5.60
80-2	1"	0.625"	⅝"	5,610	35,400	6261K715	21.47	19.50	6261K226	3.43	6261K835	3.69	6261K845	8.78
100-2	1¼"	0.750"	¾"	8,600	52,400	6261K91	35.16	29.37	6261K922	6.53	6261K924	6.00	6261K923	15.31
Triple Strand														
40-3R	½"	0.312"	⁵⁄₁₆"	2,025	12,900	6261K74	14.18	11.95	6261K752	2.58	6261K754	1.60	6261K753	5.31
50-3R	⅝"	0.400"	⅜"	3,500	21,600	6261K76	16.79	14.13	6261K722	2.80	6261K724	2.27	6261K723	6.22
60-3R	¾"	0.469"	½"	4,875	30,000	6261K78	23.06	19.42	6261K762	3.84	6261K764	3.20	6261K763	8.64
80-3R	1"	0.625"	⅝"	8,250	53,100	6261K79	34.54	29.08	6261K717	6.02	6261K719	5.53	6261K718	13.69
Heavy Single Strand														
50H	⅝"	0.400"	⅜"	1,400	7,800	7265K4	8.60	7.12	7265K424	1.58	7265K426	1.38	7265K425	3.38
60H	¾"	0.469"	½"	2,000	12,300	7265K5	7.12	5.89	7265K524	1.44	7265K526	1.31	7265K525	3.11
80H	1"	0.625"	⅝"	3,400	20,200	7265K6	12.04	9.96	7265K624	2.20	7265K626	2.20	7265K625	4.87
100H	1¼"	0.750"	¾"	5,200	30,800	7265K7	19.70	16.31	7265K724	3.93	7265K726	4.44	7265K725	8.24
120H	1½"	0.875"	1"	7,000	41,800	7265K8	28.31	23.43	7265K824	6.07	7265K826	6.64	7265K825	12.73
140H	1¾"	1.00"	1"	9,200	54,200	7265K9	34.20	28.31	7265K924	9.69	7265K926	10.20	7265K925	20.36
Cotter-Pin Roller Chain														
Single Strand														
80	1"	0.625"	⅝"	3,300	17,700	2322K1	11.77	10.19	6261K196	1.74	6261K246	1.77	6261K266	3.60
100	1¼"	0.750"	¾"	5,060	26,200	2322K2	17.66	15.30	6261K181	2.62	6261K211	2.87	6261K271	6.04
120	1½"	0.875"	1"	6,800	37,700	2322K3	24.60	21.13	6261K182	4.28	6261K212	4.89	6261K272	9.34
140	1¾"	1.000"	1"	9,000	48,800	2322K4	30.34	25.94	6261K183	5.72	6261K213	7.43	6261K273	12.85
160	2"	1.125"	1¼"	11,900	62,200	2322K5	38.47	32.66	6261K184	8.00	6261K214	10.49	6261K274	17.77
Double Strand														
80-2	1"	0.625"	⅝"	5,610	35,400	2322K6	26.55	23.15	6261K226	3.43	6261K835	3.69	6261K845	8.78
100-2	1¼"	0.750"	¾"	8,600	52,400	2322K7	40.55	35.06	6261K922	6.53	6261K924	6.00	6261K923	15.31
120-2	1½"	0.875"	1"	11,560	75,400	2322K8	56.94	48.87	2322K21	10.16	6261K212■	4.89	2322K31	22.27
140-2	1¾"	1.000"	1"	15,300	97,600	2322K9	69.64	59.38	2322K22	13.82	6261K213■	7.43	2322K32	29.82
160-2	2"	1.125"	1¼"	20,230	62,200	2322K11	86.47	73.21	2322K23	19.02	6261K214■	10.49	2322K33	41.25

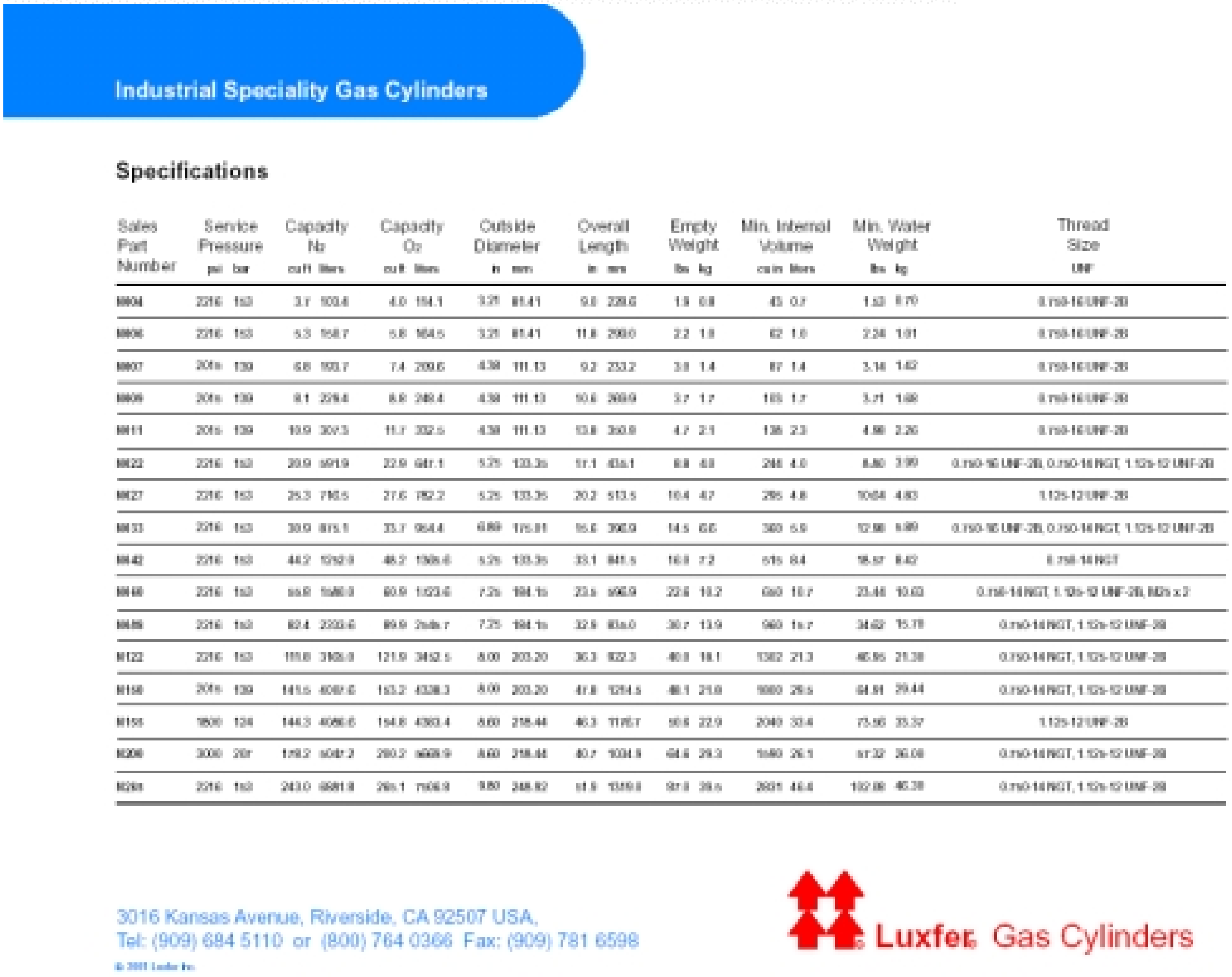
◆ Rollerless chain. • Has thinner plates than No. 40 and is lighter in weight. ■ Two are required to connect chain.

Warning! *Do not use the chain on this page for lifting applications or for moving people.*

882 McMASTER-CARR

Motor Schematic





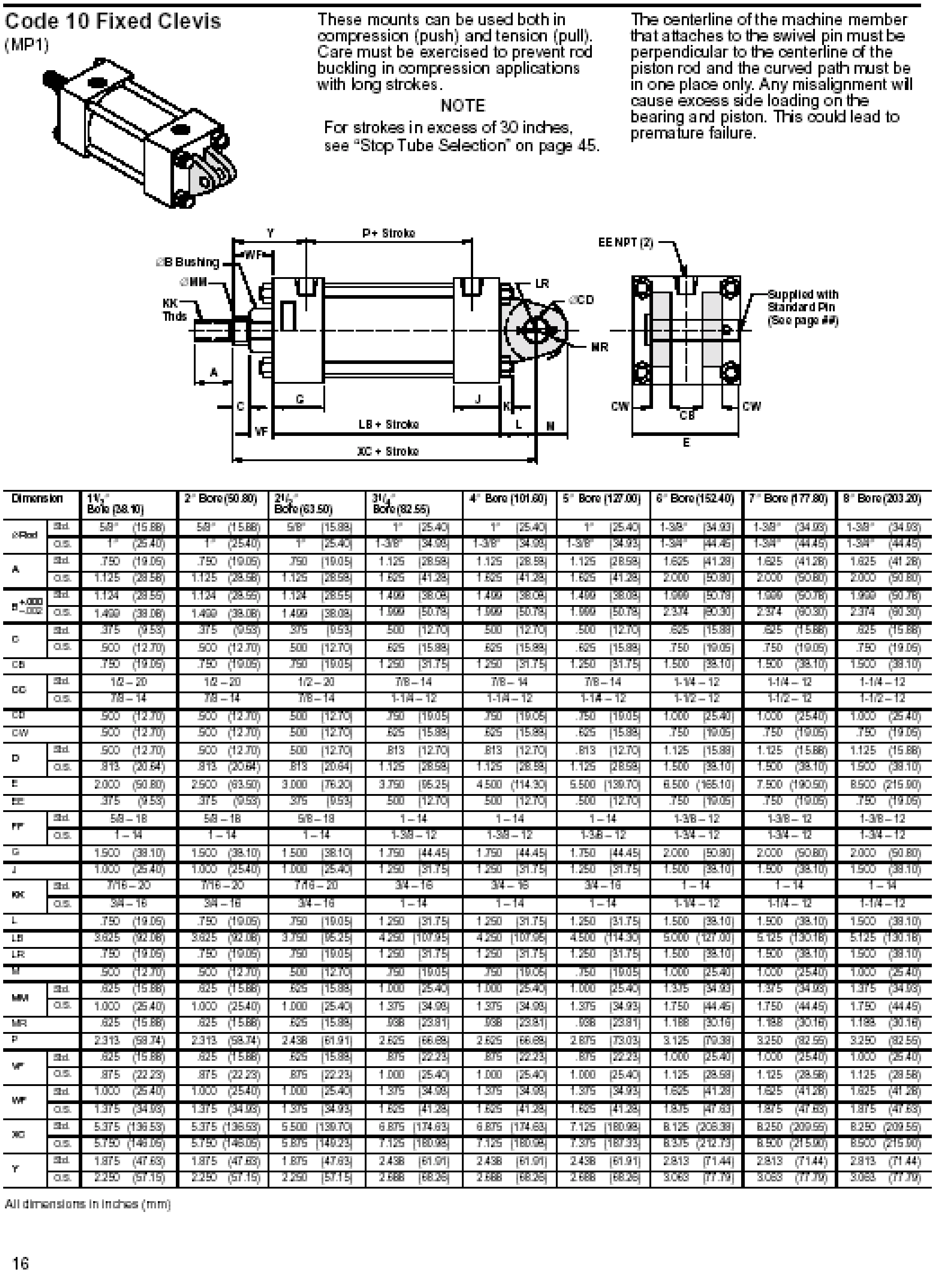
Industrial Speciality Gas Cylinders

Specifications

Sales Part Number	Service Pressure psi	Service Pressure bar	Capacity N₂ cu ft	Capacity N₂ liters	Capacity O₂ cu ft	Capacity O₂ liters	Outside Diameter in	Outside Diameter mm	Overall Length in	Overall Length mm	Empty Weight lbs	Empty Weight kg	Min. Internal Volume cu in	Min. Internal Volume liters	Min. Water Weight lbs	Min. Water Weight kg	Thread Size UNF
M004	2216	153	3.7	103.4	4.0	114.1	3.21	81.41	9.0	228.6	1.8	0.8	43	0.7	1.53	0.70	0.750-16 UNF-2B
M006	2216	153	5.3	150.7	5.8	164.5	3.21	81.41	11.8	299.0	2.2	1.0	62	1.0	2.24	1.01	0.750-16 UNF-2B
M007	2015	139	6.8	193.7	7.4	209.6	4.38	111.13	9.2	233.2	3.0	1.4	87	1.4	3.14	1.42	0.750-16 UNF-2B
M009	2015	139	8.1	229.4	8.8	249.4	4.38	111.13	10.6	269.9	3.7	1.7	105	1.7	3.71	1.68	0.750-16 UNF-2B
M011	2015	139	10.9	307.3	11.7	332.5	4.38	111.13	13.8	350.8	4.7	2.1	138	2.3	4.98	2.26	0.750-16 UNF-2B
M022	2216	153	20.9	591.9	22.9	647.1	5.25	133.35	17.1	435.1	8.8	4.0	244	4.0	8.80	3.99	0.750-16 UNF-2B, 0.750-14 NGT, 1.125-12 UNF-2B
M027	2216	153	25.3	716.5	27.6	782.2	5.25	133.35	20.2	513.5	10.4	4.7	295	4.8	10.64	4.83	1.125-12 UNF-2B
M033	2216	153	30.9	875.1	33.7	954.4	6.89	175.01	15.6	396.9	14.5	6.6	360	5.9	12.98	5.89	0.750-16 UNF-2B, 0.750-14 NGT, 1.125-12 UNF-2B
M042	2216	153	44.2	1252.0	48.2	1365.6	5.25	133.35	33.1	841.5	16.0	7.2	515	8.4	18.57	8.42	0.750-14 NGT
M048	2216	153	55.8	1580.0	60.9	1723.6	7.25	184.15	23.5	596.9	22.6	10.2	650	10.7	23.48	10.63	0.750-14 NGT, 1.125-12 UNF-2B, M25 x 2
M088	2216	153	82.4	2333.6	89.9	2545.7	7.25	184.15	32.5	825.0	30.7	13.9	960	15.7	34.62	15.70	0.750-14 NGT, 1.125-12 UNF-2B
M122	2216	153	111.8	3165.0	121.9	3452.5	8.00	203.20	36.3	922.3	40.0	18.1	1302	21.3	46.95	21.30	0.750-14 NGT, 1.125-12 UNF-2B
M150	2015	139	141.5	4007.6	153.2	4338.3	8.00	203.20	47.8	1214.5	48.1	21.8	1800	29.5	64.91	29.44	0.750-14 NGT, 1.125-12 UNF-2B
M155	1800	124	144.3	4086.6	154.8	4383.4	8.60	218.44	46.3	1176.7	50.6	22.9	2040	33.4	73.56	33.37	1.125-12 UNF-2B
M200	3000	207	175.2	4961.2	200.2	5669.9	8.60	218.44	40.7	1034.5	64.6	29.3	1590	26.1	57.32	26.00	0.750-14 NGT, 1.125-12 UNF-2B
M265	2216	153	243.0	6881.8	265.1	7506.9	9.80	248.92	51.5	1310.0	97.0	39.5	2831	46.4	102.08	46.30	0.750-14 NGT, 1.125-12 UNF-2B

3016 Kansas Avenue, Riverside, CA 92507 USA,
Tel: (909) 684 5110 or (800) 764 0366 Fax: (909) 781 6598

Luxfer Gas Cylinders



Code 10 Fixed Clevis

(MP1)

These mounts can be used both in compression (push) and tension (pull). Care must be exercised to prevent rod buckling in compression applications with long strokes.

NOTE

For strokes in excess of 30 inches, see "Stop Tube Selection" on page 45.

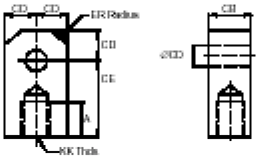
The centerline of the machine member that attaches to the swivel pin must be perpendicular to the centerline of the piston rod and the curved path must be in one place only. Any misalignment will cause excess side loading on the bearing and piston. This could lead to premature failure.

Dimension		1½" Bore (38.10)	2" Bore (50.80)	2½" Bore (63.50)	3¼" Bore (82.55)	4" Bore (101.60)	5" Bore (127.00)	6" Bore (152.40)	7" Bore (177.80)	8" Bore (203.20)
ØRod	Std.	5/8" (15.88)	5/8" (15.88)	5/8" (15.88)	1" (25.40)	1" (25.40)	1" (25.40)	1-3/8" (34.93)	1-3/8" (34.93)	1-3/8" (34.93)
	O.S.	1" (25.40)	1" (25.40)	1" (25.40)	1-3/8" (34.93)	1-3/8" (34.93)	1-3/8" (34.93)	1-3/4" (44.45)	1-3/4" (44.45)	1-3/4" (44.45)
A	Std.	.750 (19.05)	.750 (19.05)	.750 (19.05)	1.125 (28.58)	1.125 (28.58)	1.125 (28.58)	1.625 (41.28)	1.625 (41.28)	1.625 (41.28)
	O.S.	1.125 (28.58)	1.125 (28.58)	1.125 (28.58)	1.625 (41.28)	1.625 (41.28)	1.625 (41.28)	2.000 (50.80)	2.000 (50.80)	2.000 (50.80)
B $^{+.000}_{-.002}$	Std.	1.124 (28.55)	1.124 (28.55)	1.124 (28.55)	1.499 (38.08)	1.499 (38.08)	1.499 (38.08)	1.999 (50.78)	1.999 (50.78)	1.999 (50.78)
	O.S.	1.499 (38.08)	1.499 (38.08)	1.499 (38.08)	1.999 (50.78)	1.999 (50.78)	1.999 (50.78)	2.374 (60.30)	2.374 (60.30)	2.374 (60.30)
C	Std.	.375 (9.53)	.375 (9.53)	.375 (9.53)	.500 (12.70)	.500 (12.70)	.500 (12.70)	.625 (15.88)	.625 (15.88)	.625 (15.88)
	O.S.	.500 (12.70)	.500 (12.70)	.500 (12.70)	.625 (15.88)	.625 (15.88)	.625 (15.88)	.750 (19.05)	.750 (19.05)	.750 (19.05)
CB		.750 (19.05)	.750 (19.05)	.750 (19.05)	1.250 (31.75)	1.250 (31.75)	1.250 (31.75)	1.500 (38.10)	1.500 (38.10)	1.500 (38.10)
CC	Std.	1/2 – 20	1/2 – 20	1/2 – 20	7/8 – 14	7/8 – 14	7/8 – 14	1-1/4 – 12	1-1/4 – 12	1-1/4 – 12
	O.S.	7/8 – 14	7/8 – 14	7/8 – 14	1-1/4 – 12	1-1/4 – 12	1-1/4 – 12	1-1/2 – 12	1-1/2 – 12	1-1/2 – 12
CD		.500 (12.70)	.500 (12.70)	.500 (12.70)	.750 (19.05)	.750 (19.05)	.750 (19.05)	1.000 (25.40)	1.000 (25.40)	1.000 (25.40)
CW		.500 (12.70)	.500 (12.70)	.500 (12.70)	.625 (15.88)	.625 (15.88)	.625 (15.88)	.750 (19.05)	.750 (19.05)	.750 (19.05)
D	Std.	.500 (12.70)	.500 (12.70)	.500 (12.70)	.813 (12.70)	.813 (12.70)	.813 (12.70)	1.125 (15.88)	1.125 (15.88)	1.125 (15.88)
	O.S.	.813 (20.64)	.813 (20.64)	.813 (20.64)	1.125 (28.58)	1.125 (28.58)	1.125 (28.58)	1.500 (38.10)	1.500 (38.10)	1.500 (38.10)
E		2.000 (50.80)	2.500 (63.50)	3.000 (76.20)	3.750 (95.25)	4.500 (114.30)	5.500 (139.70)	6.500 (165.10)	7.500 (190.50)	8.500 (215.90)
EE		.375 (9.53)	.375 (9.53)	.375 (9.53)	.500 (12.70)	.500 (12.70)	.500 (12.70)	.750 (19.05)	.750 (19.05)	.750 (19.05)
FF	Std.	5/8 – 18	5/8 – 18	5/8 – 18	1 – 14	1 – 14	1 – 14	1-3/8 – 12	1-3/8 – 12	1-3/8 – 12
	O.S.	1 – 14	1 – 14	1 – 14	1-3/8 – 12	1-3/8 – 12	1-3/8 – 12	1-3/4 – 12	1-3/4 – 12	1-3/4 – 12
G		1.500 (38.10)	1.500 (38.10)	1.500 (38.10)	1.750 (44.45)	1.750 (44.45)	1.750 (44.45)	2.000 (50.80)	2.000 (50.80)	2.000 (50.80)
J		1.000 (25.40)	1.000 (25.40)	1.000 (25.40)	1.250 (31.75)	1.250 (31.75)	1.250 (31.75)	1.500 (38.10)	1.500 (38.10)	1.500 (38.10)
KK	Std.	7/16 – 20	7/16 – 20	7/16 – 20	3/4 – 16	3/4 – 16	3/4 – 16	1 – 14	1 – 14	1 – 14
	O.S.	3/4 – 16	3/4 – 16	3/4 – 16	1 – 14	1 – 14	1 – 14	1-1/4 – 12	1-1/4 – 12	1-1/4 – 12
L		.750 (19.05)	.750 (19.05)	.750 (19.05)	1.250 (31.75)	1.250 (31.75)	1.250 (31.75)	1.500 (38.10)	1.500 (38.10)	1.500 (38.10)
LB		3.625 (92.08)	3.625 (92.08)	3.750 (95.25)	4.250 (107.95)	4.250 (107.95)	4.500 (114.30)	5.000 (127.00)	5.125 (130.18)	5.125 (130.18)
LR		.750 (19.05)	.750 (19.05)	.750 (19.05)	1.250 (31.75)	1.250 (31.75)	1.250 (31.75)	1.500 (38.10)	1.500 (38.10)	1.500 (38.10)
M		.500 (12.70)	.500 (12.70)	.500 (12.70)	.750 (19.05)	.750 (19.05)	.750 (19.05)	1.000 (25.40)	1.000 (25.40)	1.000 (25.40)
MM	Std.	.625 (15.88)	.625 (15.88)	.625 (15.88)	1.000 (25.40)	1.000 (25.40)	1.000 (25.40)	1.375 (34.93)	1.375 (34.93)	1.375 (34.93)
	O.S.	1.000 (25.40)	1.000 (25.40)	1.000 (25.40)	1.375 (34.93)	1.375 (34.93)	1.375 (34.93)	1.750 (44.45)	1.750 (44.45)	1.750 (44.45)
MR		.625 (15.88)	.625 (15.88)	.625 (15.88)	.938 (23.81)	.938 (23.81)	.938 (23.81)	1.188 (30.16)	1.188 (30.16)	1.188 (30.16)
P		2.313 (58.74)	2.313 (58.74)	2.438 (61.91)	2.625 (66.68)	2.625 (66.68)	2.875 (73.03)	3.125 (79.38)	3.250 (82.55)	3.250 (82.55)
VF	Std.	.625 (15.88)	.625 (15.88)	.625 (15.88)	.875 (22.23)	.875 (22.23)	.875 (22.23)	1.000 (25.40)	1.000 (25.40)	1.000 (25.40)
	O.S.	.875 (22.23)	.875 (22.23)	.875 (22.23)	1.000 (25.40)	1.000 (25.40)	1.000 (25.40)	1.125 (28.58)	1.125 (28.58)	1.125 (28.58)
WF	Std.	1.000 (25.40)	1.000 (25.40)	1.000 (25.40)	1.375 (34.93)	1.375 (34.93)	1.375 (34.93)	1.625 (41.28)	1.625 (41.28)	1.625 (41.28)
	O.S.	1.375 (34.93)	1.375 (34.93)	1.375 (34.93)	1.625 (41.28)	1.625 (41.28)	1.625 (41.28)	1.875 (47.63)	1.875 (47.63)	1.875 (47.63)
XC	Std.	5.375 (136.53)	5.375 (136.53)	5.500 (139.70)	6.875 (174.63)	6.875 (174.63)	7.125 (180.98)	8.125 (206.38)	8.250 (209.55)	8.250 (209.55)
	O.S.	5.750 (146.05)	5.750 (146.05)	5.875 (149.23)	7.125 (180.98)	7.125 (180.98)	7.375 (187.33)	8.375 (212.73)	8.500 (215.90)	8.500 (215.90)
Y	Std.	1.875 (47.63)	1.875 (47.63)	1.875 (47.63)	2.438 (61.91)	2.438 (61.91)	2.438 (61.91)	2.813 (71.44)	2.813 (71.44)	2.813 (71.44)
	O.S.	2.250 (57.15)	2.250 (57.15)	2.250 (57.15)	2.688 (68.26)	2.688 (68.26)	2.688 (68.26)	3.063 (77.79)	3.063 (77.79)	3.063 (77.79)

All dimensions in inches (mm)

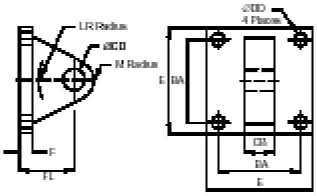
16

NFPA Rod Eye



	VP60008A	VP60008C	VP6000CA	VP60010A	VP60016A
CB	.750 (19.05]	.750 (19.05]	1.250 (31.75)	1.500 [38.10)	2.000 [50.80]
CD	.500 [12.70]	.500 (12.70]	.750 (19.05)	1.000 [25.40)	1.375 [60.33]
CE	1.500 (38.10]	1.500 (38.10)	2.375 (60.33)	3.125 [79.38)	4.125 [104.78]
ER	.5]	.500 (12.70]	.750 (19.05)	1.000 [25.40)	1.375 [60.33]
L	.750 [19.05]	.750 (19.05]	1.250 (31.75)	1.500 [38.10)	2.125 [53.98]

NFPA Eye Bracket



	VP62008A	VP62008B	VP6200CA	VP62010A
BA	1.625 [41.28]	2.562 [65.07]	3.250 (82.55]	3.812 (96.82]
CB	.750 [19.05)	1.250 [31.75]	1.500 (38.10]	2.000 (50.80)
CD	.500 [12.70)	.750 [19.05]	1.000 (25.40]	1.375 (60.33]
DD	.406 [10.31)	.531 [13.49)	.656 [16.66]	.656 [16.66]
E	2.500 [63.50)	3.500 [88.90]	4.500 [114.30)	5.000 (127.00)
F	.375 [9.53)	.625 [15.88)	.750 [19.05]	.875 (22.23]
FL	1.125 [28.58)	1.875 [47.63]	2.250 (57.15]	3.000 (76.20]
LR	.750 [19.05)	1.250 [31.75]	1.500 (38.10]	2.125 (53.98]

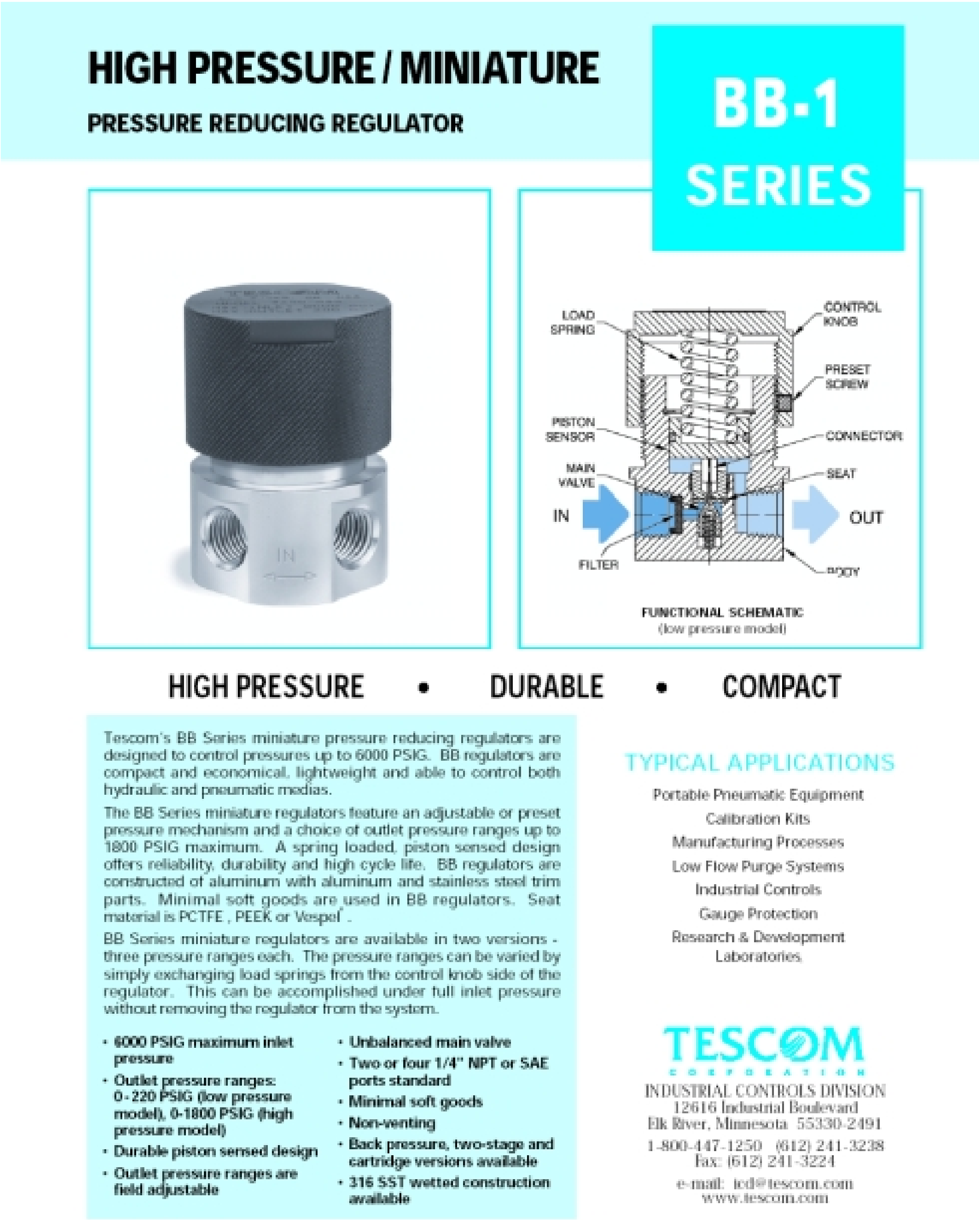
Cylinder Force and Volume Charts

Extend Forces in pounds (newtons)

Bore	Piston Area in^2 (cm^2)	psi (bar)						Vol. Cu. Ft. (cm^3) **Displacement** Per Stroke Inch
		40 (3)	60 (4)	80 (6)	100 (7)	150 (10)	200 (14)	
$1^{1}/_{2}$"	1.77 (11.40)	71 [315]	106 [472]	142 [629]	177 (786)	266 (1179)	353 (1570)	.00102 [29)
2"	3.14 [20.27)	126 [559]	189 [839]	251 (1119)	314 [1398)	471 [2097)	628 (2793)	.00182 [52)
$2^{1}/_{2}$"	4.91 [31.67)	196 [874]	295 [1311)	393 (1748)	491 [2185)	737 [3277)	982 (4368)	.00284 [80)
$3^{1}/_{4}$"	8.30 [53.32)	332 (1477]	498 (2215]	664 (2953]	830 [3692)	1245 [5538)	1659 (7379]	.00480 (136)
4"	12.57 [81.07)	503 (2237]	754 (3355]	1005 (4473]	1257 [5592)	1886 [8388)	2513 [11178]	.00727 (206)
5"	19.64(126.71)	785 (3491]	1178 (5240]	1571 (6988]	1964 [8736)	2946 [13104)	3928[17472]	.01137 (322)
6"	28.27(182.39)	1130 (5026]	1696 (7544]	2262 [10061]	2827 [12574)	4240 [18860)	5654[25149]	.01837 (520)
8"	50.26(324.26)	2010 (8940]	3015 [13411]	4020 [17881]	5026 [22356)	7539 [33533)	10052(44711]	.02227 (631)

Deduct these Forces for Retract Strokes

Bore	Piston Area in^2 (cm^2)	psi (bar)						Vol. Cu. Ft. (cm^3) **Displacement** Per Stroke Inch
		40 (3)	60 (4)	80 (6)	100 (7)	150 (10)	200 (14)	
$^{5}/_{8}$"	.307 (1.98)	12 [53]	18 [80]	25 (111)	31 (138)	46 [205]	61 [271)	.00018 [5]
1"	.785 [5.06)	31 (138]	47 [209]	63 [280]	70 (351]	118 (525)	157 (698)	.00045 [13]
$1^{3}/_{8}$"	1.485 [9.58)	59 [262]	89 [396)	119 [529)	118 [525)	222 [997)	297 (1321)	.00086 (24)
$1^{3}/_{4}$"	2.404 (15.51]	95 [423]	144 (641)	192 [854]	240 (1068]	380 [1601)	480 (2135)	.00139 (39)



HIGH PRESSURE / MINIATURE

PRESSURE REDUCING REGULATOR

BB-1 SERIES

FUNCTIONAL SCHEMATIC
(low pressure model)

HIGH PRESSURE • DURABLE • COMPACT

Tescom's BB Series miniature pressure reducing regulators are designed to control pressures up to 6000 PSIG. BB regulators are compact and economical, lightweight and able to control both hydraulic and pneumatic medias.

The BB Series miniature regulators feature an adjustable or preset pressure mechanism and a choice of outlet pressure ranges up to 1800 PSIG maximum. A spring loaded, piston sensed design offers reliability, durability and high cycle life. BB regulators are constructed of aluminum with aluminum and stainless steel trim parts. Minimal soft goods are used in BB regulators. Seat material is PCTFE , PEEK or Vespel® .

BB Series miniature regulators are available in two versions - three pressure ranges each. The pressure ranges can be varied by simply exchanging load springs from the control knob side of the regulator. This can be accomplished under full inlet pressure without removing the regulator from the system.

- **6000 PSIG maximum inlet pressure**
- **Outlet pressure ranges: 0-220 PSIG (low pressure model), 0-1800 PSIG (high pressure model)**
- **Durable piston sensed design**
- **Outlet pressure ranges are field adjustable**
- **Unbalanced main valve**
- **Two or four 1/4" NPT or SAE ports standard**
- **Minimal soft goods**
- **Non-venting**
- **Back pressure, two-stage and cartridge versions available**
- **316 SST wetted construction available**

TYPICAL APPLICATIONS

Portable Pneumatic Equipment
Calibration Kits
Manufacturing Processes
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Gauge Protection
Research & Development Laboratories

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INDUSTRIAL CONTROLS DIVISION
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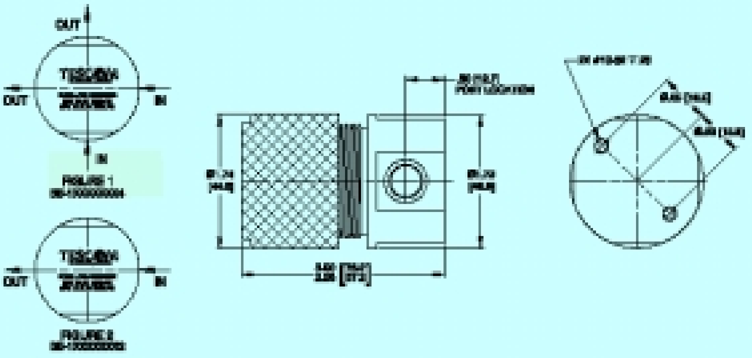
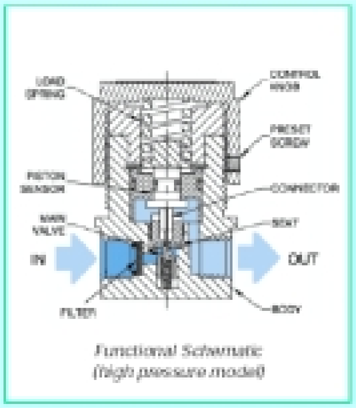
INSTALLATION DIMENSIONS METRIC EQUIVALENTS ARE IN PARENTHESES

BB-1 SERIES





Functional Schematic
(high pressure model)

ALL DIMENSIONS ARE REFERENCE AND NOMINAL

SPECIFICATIONS

FLUID MEDIA - All gases and liquids compatible with materials of construction. For other media, consult factory.**

PRESSURE RATING - Per criteria of ANSI / ASME B31.3.

Rated inlet pressure (maximum)	6000 PSIG (408 bar)
Outlet pressure range	See Ordering Information
Design outlet proof pressure	150% of maximum rated pressure
Materials in contact with media:	
Body	Aluminum 6061 (Nickel Plated)[1]
Seat	PCTFE, PEEK or Vespel®
O-rings	Ethylene Propylene, Buna-N or Viton®
Remaining parts	300 SST or aluminum
Flow capacity	C_V = .06
Porting	1/8" or 1/4" NPT
Internal leakage	Bubble tight
Operating temperature[2]	-15°F to +165°F (-25°C to +75°C)
Weight (approximate)	.5 lbs. (.23 kg)
Porting	See Ordering Information

[1] *316 Stainless Steel wetted construction available, consult factory.*
[2] *Extended temperatures from -65°F to +400°F available, consult factory.*

** **NOTE:** Tescom may make suggestions for a material to use with a specific media. These suggestions will be based on technical compatibility resources both through associations and manufacturers. Tescom does not guarantee the material to be compatible with the specific media - this is the responsibility of the user. Users must test under their own operating conditions to determine the suitability of any material in a particular application.

ORDERING INFORMATION

EXAMPLE: BB-1 3 A L3 K E A4

BASIC SERIES

FUNCTION
- **1** - Pressure Reducing

BODY MATERIAL
- **3** - Aluminum 6061

LOAD TYPE
- **A** - Adjustable
- **P** - Preset

PORTING

	NO. OF PORTS
A4 - 1/4" NPT	4 (Fig. 1)
B4 - 1/4" SAE	4 (Fig. 1)
A2 - 1/4" NPT	2 (Fig. 2)
B2 - 1/4" SAE	2 (Fig. 2)

O-RING SEAL
- **E** - Ethylene Propylene
- **N** - Buna-N
- **V** - Viton

SEAT MATERIAL
- **K** - PCTFE
- **V** - Vespel®
- **P** - PEEK

OUTLET PRESSURE RANGE

Adjustable	Preset
L1 - 0-80 PSIG (0-5.4 bar)	0-80 PSIG (0-5.4 bar)
L2 - 0-140 PSIG (0-9.5 bar)	80-140 PSIG (5.4-9.5 bar)
L3 - 0-220 PSIG (0-15 bar)1	140-220 PSIG (9.5-15 bar)
H1 - 0-700 PSIG (0-47.6 bar)	220-700 PSIG (15-47.6 bar)
H2 - 0-1200 PSIG (47.6-81.6 bar)	700-1200 PSIG (47.6-81.6 bar)
H3 - 0-1800 PSIG (0-122.4 bar)	1200-1800 PSIG (81.6-122.4 bar)

Form No. 17B1 8-96 30M TESCOM/GU Printed in U.S.A.

ACCESSORIES

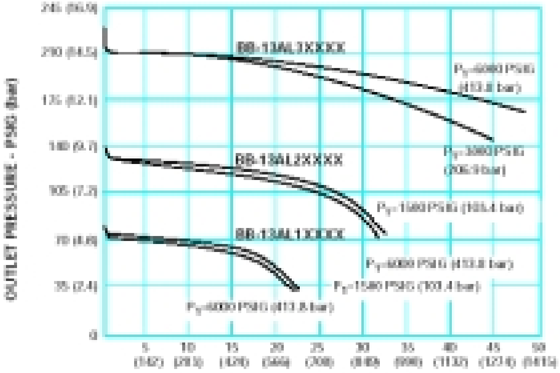
STANDARD REPAIR KIT . . . . Consult factory.

GAUGES: Consult 'Special Products, Valves, Gauges' section of catalog.

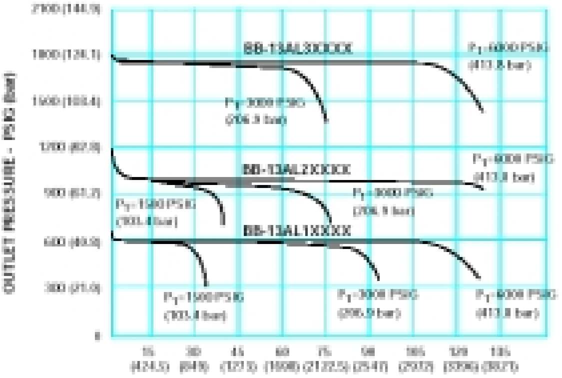
FLOW CHARTS (Metric units are in parentheses)

REGULATOR DISCHARGE CHARACTERISTICS CURVES

BB-1 SERIES - LOW PRESSURE MODEL



BB-1 SERIES - HIGH PRESSURE MODEL



Viton® and Vespel® are registered trademarks of DuPont.

APPENDIX G – POWER CALCULATIONS

Battery Specification

Time required is at least five minutes

2 batteries both in series together
-each battery is rated at 12 Volts / 12 Amp Hr and has 1052.5 Watts

P=V*I
I = P / V = (2 * 1052.5 Watts) / (2 * 12 Volts)
I= 87.7 Amps which is the maximum current draw

87.7 Amps * 5 min = 438.5 AminRequired amperage per minute of operation

43805 Amin * (1 hr / 60 min) = 7.308 Ahr Required amperage per hour of operation

<u>Battery Life Used</u>

2 * 12 Volt / 12 Ahr in series for a total of 24 Volts

Maximum current for five minutes

12 Ahr * (60 min / 1 hr) = 720 Amin

720 Amin / 5 min = 144 Amps

Maximum operation time at maximum current

720 Amin / 87.7 A = 8.21 min

Time required is five minutes which is considerably below the above value so it is safe to conclude that the batteries will provide the desired power for the required time of five minutes!

Pneumatic Switch Specs

Power required by pneumatics

10 Watts Which were given by the Valve specs

Current handling requirement for drum switch

P = 10 Watts , V= 24Volts

I= P/V = 10 Watts / 24 Volts

I = .417Amps

Drum Switch Specs

Power required by drum motor

Efficiency = 80 %

Drum Motor 3 1/3 Hp = 250 Watts

M3 = 250 Watts

Switch used

24 Volt 20 Amp Swith

Max Power = V * I = 24Volts * 20Amps = 480 Watts

Relay Contacts

SPDT 20 Amps at 28 VDC

Max Power = 560 Watts

Power Requirement

Power required by drive motors

M1 = 750 Watts Drive Motor 1 1Hp = 750 Watts
M2 = 750 Watts Drive Motor 2 1Hp = 750 Watts

Efficiency of each motor is 80 %

Power required by drum motor

M3 = 250 Watts Drum Motor 3 1/3 = 250 Watts

Efficiency of the drum motor is 80%

Power required by pneumatics

10 Watts Given by Valve Specs

Total power required

P= m1 + m2 + m3 + 10W = 1760 Watts

Actual power capacity of both batteries is 2105 Watts

1760 Watts / 2105 Watts * 100% = 83.6 %

So the total power of the motors and pneumatics will only be using 83.6% of the power capacity of both batteries together.

Speed Controller Specs

Our minimum requirements are set by the motors and pneumatics used.

Power required by drive motors

M1 = 750 Watts	Drive Motor 1 1Hp = 750 Watts
M2 = 750 Watts	Drive Motor 2 1Hp = 750 Watts

Motors have an efficiency of 80%

Voltage = 24 V

Power = 2 * 750 Watts = 1500 Watts

P/V = I = 1500 Watts / 24 V

I = 62.5 Amps	Continuous current draw

Speed controller used

Model RDFR38E Vantec

9-32V	Voltage range
80A	Continuous current
220A	Starting current

APPENDIX H – FUTABA REMOTE CONTROL INSTRUCTIONS

AIRCRAFT SETUP INSTRUCTIONS (GENERAL 120 CLASS STUNT PLANE)

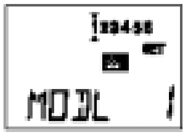
The aircraft setup procedure presented below uses a F3A-class model as an example and assumes that there are two aileron servos, one in each wing. You may use a similar procedure to set up your own model, but your setting's numbers and percentages will probably be different.

1. Be sure that all of your servos are plugged into the proper receiver channels:

CH1 — Aileron (Right aileron*)
CH2 — Elevator
CH3 — Throttle
CH4 — Rudder
CH5 — Gear
CH6 — Flap (Left aileron*)
* = if FLPR activated

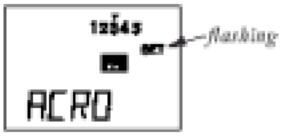
We recommend that you begin your programming exercise with the servos installed in the model and connected to the respective control surfaces. This will enable you to immediately see the effect of each programming action we're about to take.

2. Turn on your transmitter and receiver, and select the desired model memory. To do this, enter the programming mode by pressing the two MODE keys, then press the down MODE key until "MODL" appears. Press the CURSOR key and choose a vacant model memory with the plus (+) and minus (–) DATA INPUT keys. Select it by pressing the CURSOR key until "SET" is flashing, then press both the DATA INPUT keys at once. The figure shows memory #1 being utilized.



There are a number of ways to keep track of which model is in each memory. You may attach a small piece of white tape to the transmitter front and write the model's name along with the model setup number, or you may use a notebook, or label the model with its memory number prominently near its on-off switch inside the fuselage.

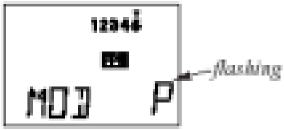
3. Enter the Parameter (PARA, p. 38) menu by pressing the down MODE key three times. Press the key three times to select the ACRO model type (four presses gets the HELI function). Select ACRO by pressing both DATA INPUT keys. When the flashing "SET" appears, again press both DATA INPUT keys to lock it in.



The reason for the separate functions within the PARA setup is that these are seldom used, and the parameter menu provides a convenient way of bypassing them for most programming operations.

WARNING: selecting a different model type will erase the settings in the model memory. BE SURE you're in the correct model memory before selecting a new model type.

4. If your receiver happens to be different than the transmission mode (as shown it's PPM), continue to the modulation (MOD, p. 40) menu to select the proper mode of transmission (F is for FM/PPM transmission, and C is for PCM). This should be set to match your receiver. If you make a change, it won't take effect until you cycle the power off and on again. So if you have changed modulation, cycle power now.



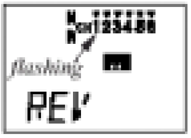
5. If your model has flaperons, turn on the Flaperon function (FLPR, p. 28) in the menu.

To do this, press one of the MODE buttons until "FLPR" appears in the display. Press the CURSOR key to get the "INH" flashing, then activate by pressing the plus (+) DATA INPUT key ("ON" should appear flashing in the display).

Connect the right aileron servo to receiver CH1 and the left aileron servo to receiver CH6.

Note that you can get differential by adjusting the up and down motion of the two servos in the FLPR menu. Now we'll set the servo throw directions.

6. Now we'll check that each servo moves the proper direction, and we'll use the Reversing function (REV, p. 27) if they don't.



We'll start by setting the right aileron servo direction. This is channel 1, and the '1' should be flashing for this command. When you move the right-hand stick to the right, the aileron on the right wing should move upwards, and the aileron on the left should move downward. Check that the right aileron moves the correct way!

If it does not, activate the opposite direction for the aileron servo by pressing the DATA INPUT keys: the PLUS (+) key switches from Reversed to Normal, and the MINUS (–) key switches from Normal to Reversed. In the display, 'N' for Normal is chosen when the little triangle is *above* the channel number, and 'R' for Reversed is chosen when the little triangle is below the channel number. Move the right-hand stick again and verify the right aileron moves the right directions. The display shows Channel 1 reversed.

7. Next we'll set the direction of the elevator servo, channel 2. When you move the right-hand stick towards the BOTTOM of the transmitter, the elevator should move up. Check to make sure it moves the proper direction! (More planes are crashed due to reversed controls than for any other reason.)

If the elevator control moves the wrong direction, move over to Channel 2 by pressing the CURSOR key. Now the '2' should be flashing in the display. Activate the opposite direction for the elevator servo by pressing the Minus (–) DATA INPUT key. Move the right-hand stick up-and-down again and verify the elevator moves the right direction.

Now we'll set the direction of the throttle servo. When you move the left-hand stick towards the BOTTOM of the transmitter, the throttle should close, meaning that the hole in the carburetor should close. Check to make sure that the throttle lever on the engine moves the proper direction!

If the throttle servo moves the wrong direction, activate the opposite direction for the throttle servo by pressing the CURSOR key. Now the '3' should be flashing in the display. Activate the opposite direction for the throttle servo by pressing the Minus (–) DATA INPUT key. Verify the throttle stick makes the servo move the carburetor opening in the correct direction.

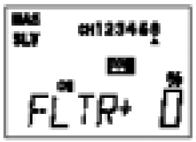
8. Now we'll set the direction of the rudder servo. When you move the left-hand stick towards the CENTER of the transmitter (to the right), the trailing edge or rear rudder should move to the right. Check to make sure!

If the rudder moves the wrong direction, activate the opposite direction by pressing the Minus (–) DATA INPUT key. Move the left-hand stick left-and-right again and verify the rudder moves the right direction.

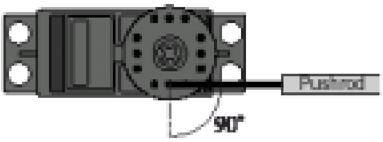
9. If your model has retracts, set the correct response direction when commanded by the retract switch, using the same approach.

10. If you're using a second aileron servo, you'll now set the left aileron servo direction (otherwise skip this and the next step). This is channel 6, and the '6' should be flashing for this command. When you move the right-hand stick to the right, the aileron on the left wing should move downwards. Check that the left aileron moves the correct way! If it does not, activate the opposite direction for the aileron servo by pressing the DATA INPUT keys. Move the right-hand stick again and verify the left aileron moves the proper directions.

11. Go to the Flap Trim function (FLTR), and input a percentage of zero (0). Then press the CURSOR key and activate the function. This temporarily disables the flap knob so that you can set aileron neutrals without regard to the flap knob position. Later we'll turn it back on.

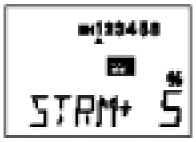


12. Now we will set the servo neutrals. Center all the trims – you can tell when each is centered because you'll feel a small indentation at the center. Once you have centered all the trims, unscrew the screws holding the servo arms onto the elevator, aileron, and rudder (we'll set the throttle travel later). You will want to place the servo arms on the output shaft so they are near neutral — that is, about 90° to the servo case sides or, if the servo is mounted sideways, 90° to the pushrod (sideways mounting is not recommended). This way you won't run out of subtrim authority. Remove all the arms that are in the way or interfere with your pushrods.



Adjust the clevises on each servo pushrod to get the position of each control to be as close as you can to neutral (lined up with the adjacent portion of wing or tail).

13. Now we'll set all the subtrims to electronically set the desired neutral locations. To do so, get to the STRM menu by pressing either MODE SELECT button repeatedly until it appears.

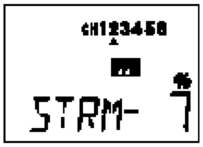


Set the right aileron subtrim first. If the little arrow is not pointing at channel 1, press the one of the CURSOR buttons until it is (see figure). Then, adjust the subtrim amount by adding or subtracting with the DATA INPUT keys. When you have reached a place where both ailerons match up with the fixed portion of the wing, you are done. If you can't get both to match up, then set the subtrim back to zero and mechanically adjust the clevis to get as close as you can, then readjust the subtrim if necessary.

Note 1: you should NOT use subtrims instead of mechanically adjusting the pushrods to be close. This is because you can reduce the travel of the radio, especially if you have to set the subtrim near 100%. As we stated before, get the pushrods close mechanically first, then use the subtrim adjustment to get it just right.

Note 2: if you mess up the number you've entered or find the percentage the wrong direction, you can get back to zero quickly by pressing BOTH the DATA INPUT keys simultaneously.

14. Repeat the subtrim adjustment with the elevator servo (Ch 2). First set the pushrod length mechanically to get as close to neutral as possible, then set the subtrim to get the elevator lined up to be parallel with the stabilizer portion. For full-flying surfaces, use an incidence meter or another method to get the incidence angle recommended by the kit manufacturer or model designer.



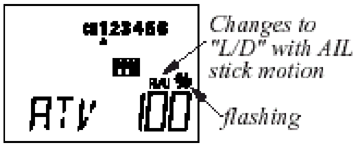
15. For the throttle, we recommend not setting a subtrim at this time. You will use the trim tab on the transmitter for idle and shutting off the motor, after the throw adjustments are done. You can then set the throttle subtrim with the STRM command.

The T6XAs/T6XHs automatically provides a special function called Adjustable Travel Limit. This function makes the trim work at low throttle levels, but disables it at high throttle. Most people set up their engines to idle with the throttle trim near center, and have the engine quit when they move the trim to the bottom position. You'll set this up later in the Travel volume settings.

16. Repeat the subtrim adjustment with the rudder, gear, and 2nd aileron channels. As before, first set them mechanically, then adjust the electronic settings. Be sure you have selected CH4, CH5, or CH6 respectively.

17. Now we'll go through and set the servo travels for each channel. This is both helpful and important, because you can set the throw of each servo, in each direction, so that there is no *binding*. Binding is important because it causes very high current drain, and can lead to a battery dying prematurely.

To set travels, get to the ATV menu by pressing the MODE SELECT button repeatedly until it appears. In sequence, we'll set Right aileron right travel, right aileron left travel, up and down elevator travels, right and left rudder travels, open and closed throttle positions, and left aileron travels.



When you reach the ATV menu, you'll see the screen as shown. The channel indicator is below numeral 1 for right aileron, the percent symbol will be flashing, and you'll notice that you can change the L/D indicator to R/U (or vice versa) by moving the aileron (right) stick. You are about to see that this is how you set the travel directions independently for each stick motion.

18. To set the RIGHT aileron motion, move the aileron stick all the way to the right and hold it. The letters "R/U" should appear next to the flashing percent sign, meaning you are setting either Right or Up travel (with ailerons it's right or left only, but the display is set up to use the same indicators for elevator and throttle, thus the dual meanings for the letters). Now if your servo is stalled or binding, you'll hear a buzzing sound. Hit the minus DATA INPUT key until the buzzing stops. If the servo is not buzzing, leave the setting at 100%. Choose a location on the

APPENDIX I – BILL OF MATERIALS

Number	Description	Vendor	Part #	Qty.	Price	Extended
1.1	10 tooth sprocket, #35 ANSI, 5/8 bore	McMaster	6280K112	2	6.56	13.12
1.2	21 tooth sprocket, #35 ANSI, 5/8 bore	McMaster	6280K124	6	12.06	72.36
1.3	25 tooth sprocket, #35 ANSI, 5/8 bore	McMaster	6236K22	2	13.40	26.80
1.4	10 tooth sprocket, #35, 3/8 unfinished bore	McMaster	6793K117	2	5.38	10.76
1.5	19 tooth idler sprocket, #35, 1/2 bore	McMaster	6663K22	2	14.68	29.36
1.6	Manually Adjustable Tensioner, 1/2 bore	McMaster	6265K5	2	43.60	87.20
1.7	Keys (pkg of 10) 3/16 square, 3/4 long	McMaster	98870A130	2 pk	2.86	5.72
1.8	E style retaining rings, 5/8 shaft (pkg 100)	McMaster	98407A140	1 pk	10.81	10.81
1.9	#35 ANSI Roller Chain (2 8-foot pieces)	McMaster	6261K531	16 ft	2.11	33.76
1.10	#35 ANSI Roller Chain Connecting Link	McMaster	6261K191	10	0.55	5.50
1.11	Chain Break for #25-60 Chain	McMaster	6051K15	1	17.63	17.63
					Total	313.02
	Pneumatics					
2.1	BB-1 Regulator, Adj 0-700 psi, .25 NPT	Flow Tech	BB-13AH1KEA4	1	177.00	177.00
2.2	Luxfer 4 cu. Ft. Medical grade Tank (Buffer)	Luxfer	M004	2	35.00	70.00
2.3	2-way, 24V Soleniod Valve, 3/8 NPT, brass	Skinner Valve	73212BN3SN00N0C111C2	4	124.99	499.96
2.4	Piston, 3.5" bore, 8 in stroke	Hydraulic Sup.	VP10EACA1FN08000	1	160.00	160.00
2.5	Braided hose	Capital Rubber	Donation	0	0.00	0.00
					Total	906.96
	Assembly Parts					
3.1	Hose clamp, 3.625 - 6.5" dia, 10 pk.	McMaster	5415K37	1 pk	9.83	9.83
3.2	Flat head Socket Cap Screw 10-32, 3/8" 100 pk.	McMaster	91253A001	1 pk	9.25	9.25
3.3	SHCS 1/4-20, 1.25" 100 pk	McMaster	91251A544	1 pk	13.99	13.99
3.4	SHCS 1/4-20, .75" 100 pk	McMaster	91251A540	1 pk	11.94	11.94
3.5	SHCS 1/4-20, 1.75" 25 pk.	McMaster	91251A548	2 pk	5.00	10.00
3.6	SHCS 3/8-16, 1.25:, 25 pk.	McMaster	91251A626	1 pk	5.87	5.87
3.7	Flat Round Washer, Blk Oxide, 1/4", 100 pk.	McMaster	96765A140	2 pk	4.21	8.42
3.8	Flat Round Washer, Blk Oxide, 3/8", 100 pk.	McMaster	96765A150	1 pk	5.91	5.91
3.9	Neoprene washer, #6, 100 pk.	McMaster	90133A005	1 pk	5.91	5.91
3.10	Hex nut, 1/4-20, 100 pk.	McMaster	90490A029	1 pk	1.19	1.19
3.11	Lock nut, 1/4-20, 25 pk.	McMaster	97135A210	4 pk	6.80	27.20
3.12	Lock nut, 3/8-16, 20 pk.	McMaster	97135A230	1 pk	7.88	7.88
3.13	Lock nut, M5 (metric), 100 pk.	McMaster	93625A200	1 pk	5.23	5.23
3.14	3/32" Cotter pin, 1" long, 100 pk.	McMaster	98338A140	1 pk	1.08	1.08
3.15	ABEC 1 Steel, double seal, R10 bearing	McMaster	60355K91	10	6.55	65.50
3.16	SHCS 1/4-20, .5"	Donation		8	0.00	0.00
3.17	SHCS 1/4-20, 2"	Donation		2	0.00	0.00
3.18	SHCS #6-32, .75"	Donation		4	0.00	0.00
3.19	SHCS #10-32, .625"	Donation		2	0.00	0.00
3.20	SHCS 1/4-20, .5"	Donation		8	0.00	0.00
					Total	189.20

	Material						
4.1	Polycarbonate .220 X 48 X 96	Laird Plast.	181393	2		250.00	500.00
4.2	Carbon Fiber, 3/8" and 1/4" sheet	MC Gill		2		55.00	110.00
4.3	HR Flat Bar 1.5 X .75	Metal Super.	HF0000075150	2	in	0.24	0.48
4.4	HR Flat Bar 1.5 X .375	Metal Super.	HF0000037150	6	in	0.09	0.52
4.5	Al 6061 Square Stock .75	Metal Super.	AQAM00007500	20	in	0.18	3.63
4.6	Al Hex Stock 1.0	Metal Super.	AHAB00010000	3	in	0.19	0.58
4.7	HR Angle 2 X 2 X .25	Metal Super.	HA0000252020	14	in		0.00
4.8	HR Angle 1 X 1 X .125	Metal Super.	HA0000121010	5	in		0.00
4.9	CR Flat Bar 1018 2 X .5	Metal Super.	CFCA00500200	8	in		0.00
4.10	CR Flat Bar 1018 2 X .75	Metal Super.	CFCA00750200	14	in		0.00
4.11	CR Round 1018 .5	Metal Super.	CRCA00005000	18	in		0.00
4.12	HR C-channel C2	Metal Super.	HC0000025702	31	in		0.00
4.13	HR Plate 8 X .375	Metal Super.	HF0000037800	7	in		0.00
4.14	Al Angle 6061 1.5 X 1.5 X .25	Metal Super.	AAAMAR251515	24	in		0.00
4.15	Al Angle 6061 .75 X .75 X .125	Metal Super.	AAAMAR120707	12	in		0.00
4.16	Al Plate 6061 8 x .25	Metal Super.	AFAM00250800	15	in		0.00
4.17	Al Round 6061 .625	Metal Super.	ARAM00006250	14	in		0.00
4.18	Al Flat Bar 6061 4 X .5	Metal Super.	AFAM00500400	48	in		0.00
4.19	Al Flat Bar 6061 6 X .5	Metal Super.	AFAM00500600	24	in		0.00
4.20	Al Flat Bar 6061 4 X .375	Metal Super.	AFAM00375400	30	in		0.00
4.21	CR Round 1018 .625	Metal Super.	CRCA00006250	84	in		0.00
				Total 4.7-4.21			134.79
4.22	Al 5/32 plate	Donation		3		0.00	0.00
4.23	Al 6061 .25 plate	Donation		2		0.00	0.00
						Total	749.99
						Total	2159.17

APPENDIX J – DRAWING PACKAGE