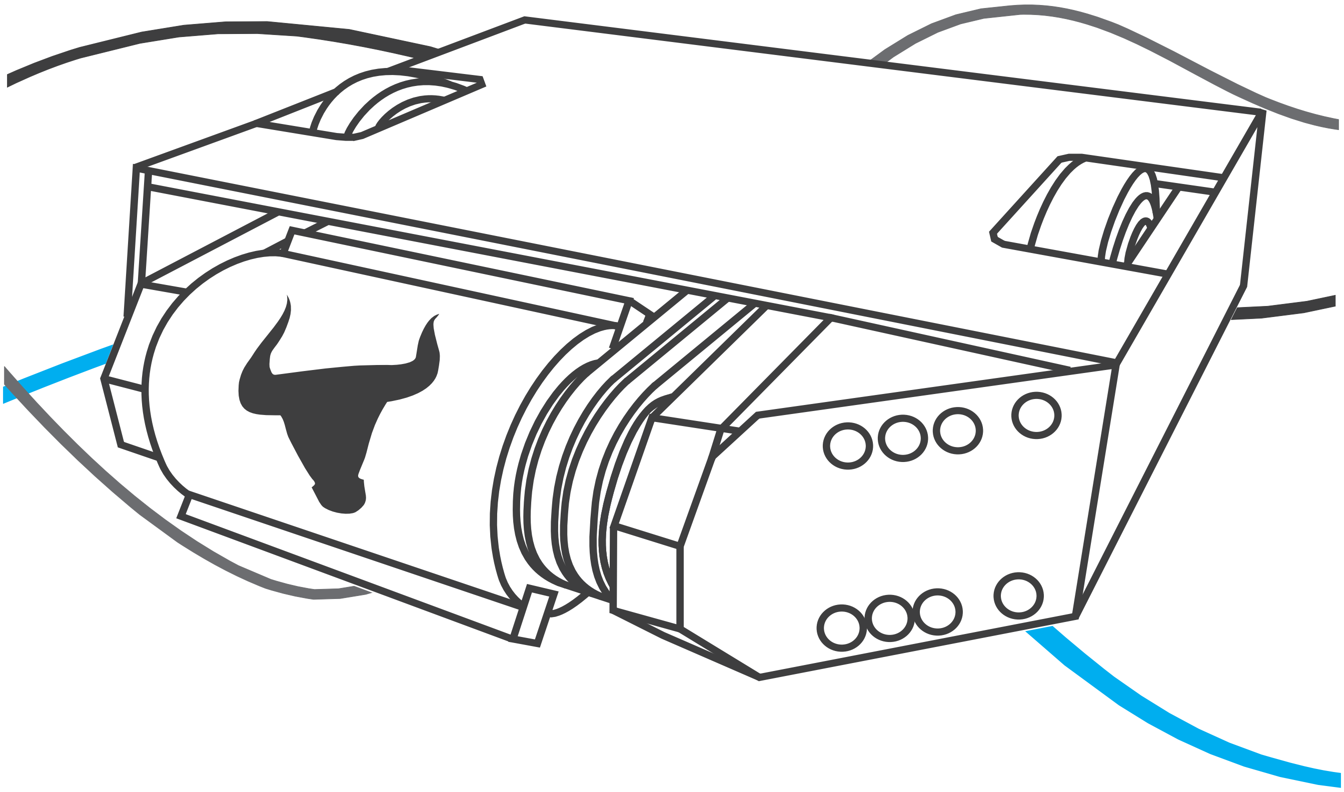
RioBotz

COMBOT TUTORIAL

Version 2.0 March 2009



www.riobotz.com.br

RioBotz Combot Tutorial

version 2.0 – March 2009

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with 895 figures

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1

Introduction

The motivation to write this tutorial came from the great experience we've had during RoboGames 2006, in San Francisco. We were able to see how friendly competitors are, exchanging information, showing their robots in detail even for their next opponents. Several teams publish in their websites detailed build reports, with step by step information on how they've built their robots. There are also great books and tutorials showing how to build combots, however there was nothing written in Portuguese. This is why I started writing this tutorial, right after RoboGames 2006.

The tutorial was first released in August 2006, in Portuguese, as a free download both at the RioBotz website www.riobotz.com.br and at the website of the Brazilian combat robot league RoboCore, www.robocore.net. The idea was to stimulate the creation of new Brazilian combot teams, as well as to help the existing ones. It was very well received, with 1,500 downloads within the first week, 10,000 in the first 6 months, and more than 20,000 so far. A few people say that it might have helped with the increasing number of Brazilian teams that we see today.

A few builders asked me to generate an English version of this tutorial, so here it is. The tutorial was originally aimed for beginners, but its contents grew so much since the 2006 version that even veterans might find it useful. It basically includes everything that we've learned since January 2003, when RioBotz was created. We're still young compared to several great international teams, however we still hope we can contribute in some way with this text.

My biggest challenge was to try to include the maximum possible amount of information, from basic to advanced topics, in a compact way that would be easy to understand. We want to stimulate new teams to start building robots, showing that you don't need to be a rocket scientist to create a competitive combot. It is possible to do it even with little engineering background.

Feel free to distribute or print out this tutorial, I would just ask to keep it in its original form. I believe that this tutorial will help not only combat robot builders, but also anyone who wants to build robust and resistant mobile robots, to participate in any type of competition.

Excuse me if I make any mistakes in the following pages, some pieces of information include personal opinions, and therefore they can be biased. In spite of that, almost all the presented ideas have been tested in practice, in the arena, either by us or by other builders. I would love to receive your feedback in anything related with this tutorial, including comments, suggestions, corrections, anything that might improve future versions of the text, posted to the “RioBotz Combot Tutorial” topic on the RFL Forum. Thanks.

1.1. A Brief History of Robot Combat

Robot competitions have existed for a long time. They have been attracting competitors and spectators from all over the world. A very good review, along with great photos, can be found in the book “Gearheads – The Turbulent Rise of Robotic Sports” by Brad Stone [9].

I'll try to introduce the subject based on my personal experience. One of the first competitions involving robot confrontation was the Design 2.007 course (http://pergatory.mit.edu/2.007), a 2 night event that happens every year since 1970 at the Massachusetts Institute of Technology (MIT). The robots are built during one semester by undergraduate students taking the 2.007 course, Introduction to Design and Manufacturing, from the Department of Mechanical Engineering. The objective is to build a radio-controlled robot that fulfills certain tasks, such as collecting balls or transporting parts, in an arena with obstacles. Every year the task is modified to stimulate creativity.

I had the opportunity to witness as a graduate student the 1996 MIT 2.007 competition (pictured to the right). I was fascinated with the enthusiasm and mainly with the students’ creativity. The best thing about these competitions is that the tasks were disputed with two robots facing each other at the same time in the arena. One wins by scoring more points collecting balls, transporting parts, it varies. At some point, you are allowed to block your opponent. It was noticeable that this was the part that most drivers waited for and when the audience really cheered: blocking the opponent. Seeing robots confronting each other, pushing and blocking in an ingenious way the opponent was more exciting than just completing the tasks. I wish I knew back then that robot combat had already been created, 4 years earlier.

The success of Design 2.007 helped inspire the creation in 1992 of a robot competition among high school students, organized by FIRST (For Inspiration and Recognition of Science and Technology, www.usfirst.org), which is held annually. Unfortunately, it doesn't include combat robots.

In that same year, the US designer Marc Thorpe connected a vacuum cleaner to a remote control tank to help perform domestic tasks. The invention didn't work very well as a vacuum cleaner, but it caused damage, a fundamental requirement for a combat robot. At that time, he worked for Lucas Films and, inspired by the Star Wars movie, he created in 1994 the first official competition, Robot Wars. The first event was disputed in Fort Mason Center, San Francisco.

In 1997, Robot Wars was televised in the United Kingdom by BBC, starting the robot combat fever in that country. Legal disputes aside, it was such a success that Robot Wars moved to the UK. For more information on current UK combot events, check out the Fighting Robot Association (FRA) website at www.fightingrobots.co.uk.

Robotica and BotBash competitions were later created in the United States, filling the void left by Robot Wars.

In 1999, Trey Roski and Greg Munson founded in San Francisco the BattleBots league (www.battlebots.com), creating the competition with most media exposure until today. The first event was held in Long Beach, California, in August 1999, with 70 enrolled robots. The second event was one of the most famous, held in Las Vegas in November 1999, televised by pay-per-view. In 2000, BattleBots started to be televised by Comedy Central, quickly becoming popular, being transmitted during 5 seasons.

In 2001, the first Brazilian combat robot competition was held, based on BattleBots rules, in an arena built at the Unicamp University. In 2002, the second competition was held again at Unicamp, this time during the ENECA event (National Meeting of Control and Automation Students). Since then, Brazilian competitions have been held yearly during the ENECA, organized by the Brazilian league RoboCore (www.robocore.net), attracting an ever increasing public.

In 2002, the Robot Fighting League (www.botleague.com) was created in the US. It is the combat robot league with largest activity in the world, organizing from local events to the RFL Nationals, as well as RoboGames, which counts with several countries.

In December 2003, the RoboWars competition (www.robowars.org) had its debut in Australia.

In 2005, another Brazilian competition was created, the Winter Challenge, which is held annually in July (southern hemisphere, winter, July - you'll figure it out). The 2005 competition was held, for the first time ever, on an ice arena. At the end of 2006, the Brazilian league RoboCore became a proud member of the RFL.

1.2. Structure of the Tutorial

The tutorial is divided into 10 chapters. This chapter includes the introduction, robot combat history, and acknowledgments. Chapter 2 talks about the fundamentals of the design of several types of combots. Chapter 3 introduces the main materials used in those robots, and how to select them. Chapter 4 presents the main joining elements, such as screws and welds. Chapter 5 deals with motors used in the robot's drive and weapon systems, as well as power transmission elements, such as gears and belts. Chapter 6 deals with weapon design, and how to improve your robot's weapon system. Both chapters 5 and 6 include several equations, based on basic physics and dynamics calculations, however they are not essential to understand the text and its conclusions. Chapter 7 discusses the several electronic and electric components necessary to power the robot, while chapter 8 talks about batteries. Chapter 9 gives important tips on how to get ready to an event and how to behave before, during and after it. Chapter 10 shows build reports of all the combots from RioBotz, including the entire Touro family, exemplifying several concepts presented in the preceding chapters. I've also included, after the conclusions, a section of frequently asked questions (FAQ), a bibliography containing a few of the best books about combots, and a few appendices with useful information in a summarized form.

1.3. Acknowledgments

I would like to thank the entire RioBotz team, without whom the ideas here presented would not have left the drawing board, and for the careful revision of this tutorial. More specifically, I thank Eduardo “Dudu” Ristow for his effort as our team captain, for using the mill and lathe at the same time all night long without losing the smile; Bruno Favoreto for being able to master Solidworks even blindfolded; Felipe Maimon and Alexandre Ormiga for their effort in creating powerful and robust electronic systems; Daniel “Esguerda” Freitas and Rodrigo “Delay” Almeida for their great driving skill; Guilherme Porto for his excellent Spektrum programming lessons; Julio Guedes for his fidelity to the team since its creation; Ilana Nigri for helping us turn civilized our most frenzied pitstops; Marcio “Senador” Barros for our webpage; Gustavo “Emo” Parada for his grinding skill; and to Guilherme Franco, Thiago “Tico” Pimenta, Marcos “Pet” Marzano, Camila Borsotto, Carlos “Gotinha” Witte, Carlos “Minhoca” Nascimento, Daniel “Toioio” Lucas, Debora Almeida, Michel “Tocha” Feinstein, and Rodrigo “Cowboy” Nogueira, for all their help building combots. Thanks again to Eduardo Ristow, Felipe Maimon and Bruno Favoreto, for their contributions to this tutorial, especially in chapter 7. Thanks also to our past members, such as Felipe Scofano, Filipe “Saci” Sacchi, Claudio Duvivier, Rafael “Pardal” Moreira, Gustavo “Calouro” Lima, and several other students and alumni from the PUC-Rio University.

I cannot thank enough Profs. Mauro Schwanke, for everything he has taught us, and Mauro Speranza, for the fundamental administrative support, as well as the entire support of PUC-Rio.

Thanks to Mark Demers for his great contributions to the pneumatics section. To Mike Phillips, Matt & Wendy Maxham, Kevin Barker, Ray Billings and Carlo Bertocchini for their helpful pictures and information. Thanks to Robert “Trebor the Mad Overlord” Woodhead for the great action shots, and to the several other builders who have helped us along our way, either during a competition or through their websites or forum posts. To Dave Calkins and Simone for their warm welcome at every RoboGames, and for all their effort to promote robotic competitions. And, finally, to Paulo Lenz and Thacia Frank, whose dedication in organizing all Brazilian combot events inspired me to dedicate time to write this tutorial. Thanks to everyone!

Chapter

2

Design Fundamentals

The starting point of any combat robot design is the choice of the weight class, discussed next.

2.1. Weight Classes

The lightest combat robots ever built have less than 35 grams (35g), but they are so rare that there is no name yet for this weight class. Fleaweights (a.k.a. nanoweights or UK fairyweights), in general with a weight limit of 75g (or 50g depending on the event organizers), are also very rare. Fairyweights (up to 150g, known as antweights in the UK) are becoming popular, however there are still few events including them. Antweights (1lb) and beetleweights (3lb) are the most competitive among the “insect” classes (ants, beetles, fleas...). There are also autonomous ant and beetle classes.

The kilobots (1kg) events only exist in Canada, and the 15lb class is only for students between 12 and 18 years old, who participate in the competition BattleBots IQ. The Mantis (6lb) weight class has not really caught yet, there are very few robots in it. Featherweights (30lb) are becoming increasingly popular, especially in Brazil.

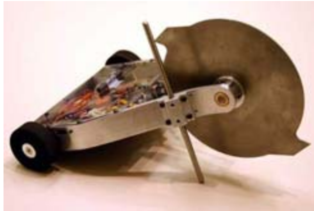
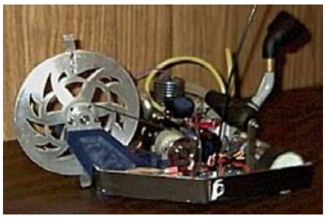
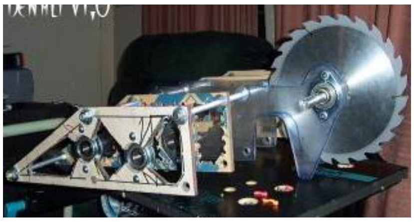
The 12lb and 30lb Sportsman’s classes are special categories where all robots must have an active weapon, wedges of any form are forbidden, and spinners are severely restricted.

Possibly the most competitive classes are the hobbyweight (12lb), lightweight (60lb) and middleweight (120lb). Heavyweight (220lb) is the most famous class, in spite of having nowadays much fewer competitors than when BattleBots was televised.

Unfortunately, super-heavyweights (up to 340lb, or 320lb in UK events) are in decline, their apogee was also during the BattleBots era. The heaviest class is the Mechwars megaweight (390lb), exclusive to the Twin Cities Mechwars competition, however few robots exist.

There are still heavier robots, such as the MonsterBots, however events involving them are very rare due to logistic problems and high costs involved.

Back in 2006, when the first version of this tutorial was released, most Brazilian combat robots were middleweights (but not anymore, since the hobbyweight and featherweight classes started in Brazil). Because of that, several examples in this tutorial make reference to middleweights. However, the contents of this tutorial can be applied to any robot size, as it will be discussed in the next section, which deals with scale factor.

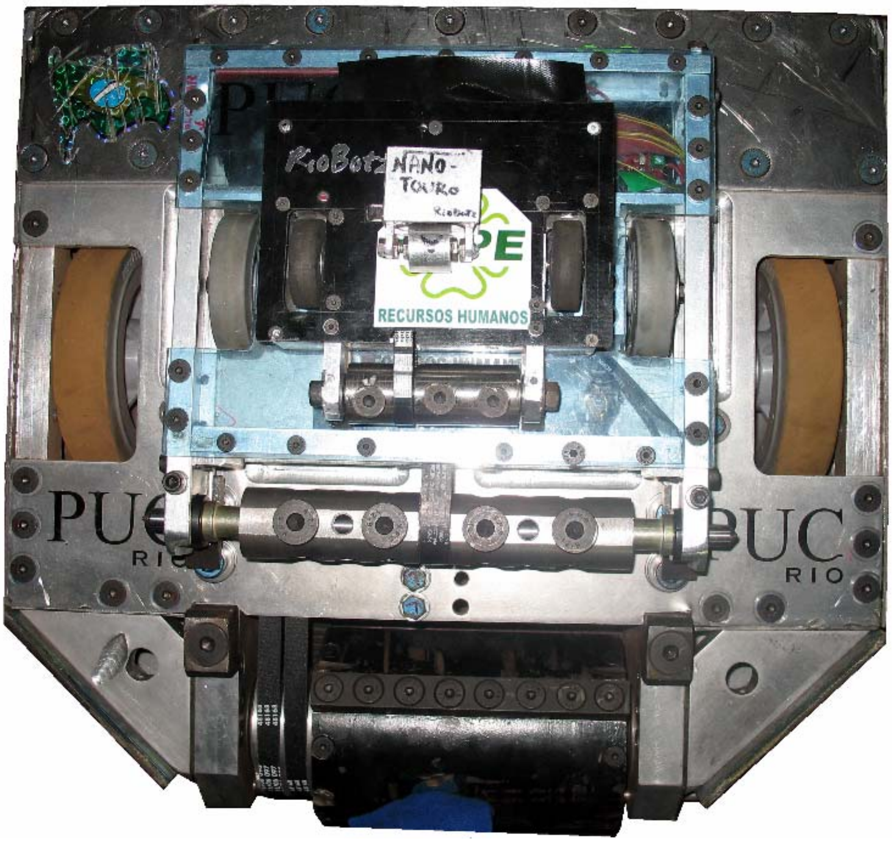
 *class still without a name - 35g*	 *Fleaweight - 75g*	 *Fairyweight - 150g*
 *Antweight - 1lb (454g)*	 *Kilobot (Canada) - 1kg*	 *Beetleweight - 3lb (1.36kg)*
 *Mantis - 6lb (2.72kg)*	 *Hobbyweight - 12lb (5.44kg)*	 *BBIQ - 15lb (6.80kg)*
 *Featherweight - 30lb (13.6kg)*	 *Lightweight - 60lb (27.2kg)*	 *Middleweight - 120lb (54.4kg)*
 *Heavyweight - 220lb (99.8kg)*	 *Super-Heavyweight - 340lb (154.2kg)*	 *Mechwars Megaweight - 390lb (176.9kg)*

2.2. Scale Factor

One important thing to keep in mind during the design phase of a combot is the scale factor. If you grew up in all your body dimensions, you would be twice as tall, and with eight times your weight (because your volume would be multiplied by $2^3 = 8$). However, the area of the cross section of your bones and muscles would only have been multiplied by $2^2 = 4$. Since the cross section area (of a column of a building, for instance) dictates the resistance and load capacity, you would be 8 times heavier but only 4 times stronger. Conclusion: the larger the scale, the worse the force/weight ratio.

To compensate for that, your bones would have to be proportionally wider and shorter so that they wouldn't fracture or buckle. This is why rhinos and elephants have such wide and short legs. On the other hand, when reducing the scale, the inverse effect happens. An ant is about 100 times smaller than a human being, and because of that its weight is about 100^3 times smaller, however its force is only 100^2 smaller. As a result, ants can carry objects $100^3/100^2 = 100$ times heavier (relatively) than a human being would be able to. That estimate is confirmed in practice: a typical human can carry an object with half of his/her weight, while it was already proven that ants can lift loads 50 times their own weight, a factor of 100 more!

You should be wondering: what does this have to do with combots? Everything. If for instance you have designed a hobbyweight that is resistant and works well, you could take advantage of a lot of its design to build a middleweight, as long as you keep in mind the scale effect. To do that, you would need to multiply the weight by 10, which happens when you multiply all the robot dimensions by the cube root of 10, which results in a scale factor of 2.15.



The picture to the right shows a few drumbots, the middleweight *Touro*, the hobbyweight *Tourinho*, the beetleweight *Mini-Touro*, and the mock-up of a fleaweight *Pocket-Touro*. The scale factor between the 12lb *Tourinho* and the 120lb *Touro* is a little lower than 2 (which is close to the theoretical 2.15, but this suggests that *Tourinho* could still have been optimized to arrive in that 2.15 value, since both robots have similar shapes and weapons). This rule works very well in all scales, as long as the robots are similar: *Touro* is 40 times heavier than *Mini-Touro*, and the scale factor measured among them is about 3.25, very close to 3.42, the cube root of 40!

The question is: following the reasoning of the ant and the human, is it true that a middleweight such as *Touro* is, relatively, about $2.15^3/2.15^2 = 2.15$ times less strong, agile, powerful and resistant than the hobbyweight *Tourinho*? Yes and no. *Touro* will probably be relatively less strong and agile. If for instance *Tourinho* used a pneumatic cylinder, which has a force that depends on the piston area, a cylinder scaled to 2.15 in *Touro* would be only 2.15^2 times stronger, while the robot would be 2.15^3 times heavier. The drive system accelerations, which depend on the ratio between the robot's traction force and mass, would be compromised as well. This is why, comparatively to their sizes, the insect robots seem to be much more agile.

However, *Touro* won't be relatively 2.15 times less powerful and resistant. In the case of a pneumatic cylinder, its energy comes from its internal volume (multiplied by the operating pressure). Therefore, a cylinder scaled to *Touro* would have 2.15^3 times more volume and energy, which is compatible with a weight increase of 2.15^3 times. The same is observed, for instance, in electrical direct current (DC) motors. In practice, the power/weight ratio of the best DC motors does not depend much on the scale factor. Otherwise, it would be worthwhile to replace a large motor with hundreds of small ones in parallel. Since power generates energy, and energy generates damage, *Touro* and *Tourinho* would have the same relative power and therefore the same relative damaging capabilities.

This conclusion is not very intuitive, especially when you consider that both *Touro* and *Tourinho* are able to fling opponents from their same weight classes up to the same 3 feet in the air. One can think that *Tourinho* would generate more destruction, because the relative throw height would be larger if compared to the robot size. But that same height is not surprising, it is verified by the expression of the potential energy $E = m \cdot g \cdot h$, where m is the robot mass, g is the acceleration of gravity, and h is the height reached in the throw. As the E/m ratios of *Touro* and *Tourinho* are approximately the same (as discussed before) and g is a constant, the height h should be the same. Although small robots are flung to a greater height with respect to their size, both energy and resistance depend on the cube of the scale factor. Therefore the destruction power (damaging capability) is relatively the same.

But why are *Touro* and *Tourinho* equally resistant, considering that the resistance of a column depends on the square of its scale and not on the cube? In fact, if *Touro* used in some way slender columns, subject to compression and buckling, it would be relatively 2.15 less resistant than *Tourinho*, following the "ant reasoning" and the dependence on the square of the scale. But the best combots are compact and robust, without slender parts. The most important loads that act in their compact structure are due to bending and torsion. But the resistances to bending and torsion depend on the cube of the scale factor (a shaft with diameter d, for instance, has bending and torsion resistances proportional to d^3), not on the square such as in buckling. Therefore, the bending and torsion resistance-to-weight ratios are still similar for both *Touro* and *Tourinho*.

The conclusion is that the scale factor can be used directly in the entire robot, without any significant loss of the power-to-weight or resistance-to-weight ratios. For instance, if you multiply by 2 the robot size, its weight is multiplied by 8. The analogy with ants would say that the diameter of a shaft in this robot would need to be multiplied by the square root of 8, about 2.83, to maintain the same resistance-to-weight ratio. That would be necessary if you were designing the column of a building, subject to buckling, but this is not the case for combots. In that case, it would be enough to multiply by 2 the shaft diameter to keep the same resistance-to-weight ratio. This is useful for two reasons: first, this means that you can apply the same scale factor (2, in this case) to all the individual components of the robot; and second, you save weight, because the shaft with diameter multiplied by 2.83 would have twice the weight of the one multiplied by 2.

But there is another factor to consider: shafts in combat robots are usually relatively short, which are subject to high shear stresses. In addition, great impacts can generate tensile stresses or significant compression. The resistance to those traction, compression and shear stresses in a shaft with diameter d is proportional to d^2, not to d^3, taking us back to the ant analogy. As during combat we cannot predict which stresses will be more or less significant, and as the shafts are very critical components that cannot break or get bent, it is desirable to be conservative and adopt the higher factor $2^{1.5} = 2.83$ for the shaft from the previous example.

In summary, you should use the scale factor to multiply (or divide) the dimensions of all the robot components, except for the most critical ones such as shafts, where the scale factor should be raised to the power of 1.5. Don't use such larger factor in the entire robot, otherwise the robot might gain too much weight (when upsizing it) or lose strength (when downsizing it). Use the higher factor only for multiplying shaft diameters or for the dimensions of a few other critical components.

All those considerations are not just philosophical, they are verified in practice. Steel shafts used to drive the wheels of several combat robots typically have, in average, a diameter of about:

- 13mm (about 0.5”) for lightweights (60lb);
- 18mm (a little less than 0.75”) for middleweights (120lb);
- 25mm (about 1”) for heavyweights (220lb); and
- 31mm (a little less than 1.25”) for super-heavyweights (340lb).

Comparing lightweights and middleweights with similar aspect, the theoretical scale factor would be $(120lb/60lb)^{1/3} = 2^{1/3} = 1.26$, and the ratio between the shaft diameters is 18mm/13mm = 1.38, a value incredibly close to $1.26^{1.5} = 1.41$.

Between middleweights and heavyweights, the theoretical scale factor is $(220lb/120lb)^{1/3} = 1.22$, and the diameter ratio is 25mm/18mm = 1.39, very close to $1.22^{1.5} = 1.35$.

And between heavyweights and super-heavyweights, the theoretical factor is $(340lb/220lb)^{1/3} = 1.16$, and the diameter ratio is 31mm/25mm = 1.24, which also agrees extremely well with $1.16^{1.5} = 1.25$.

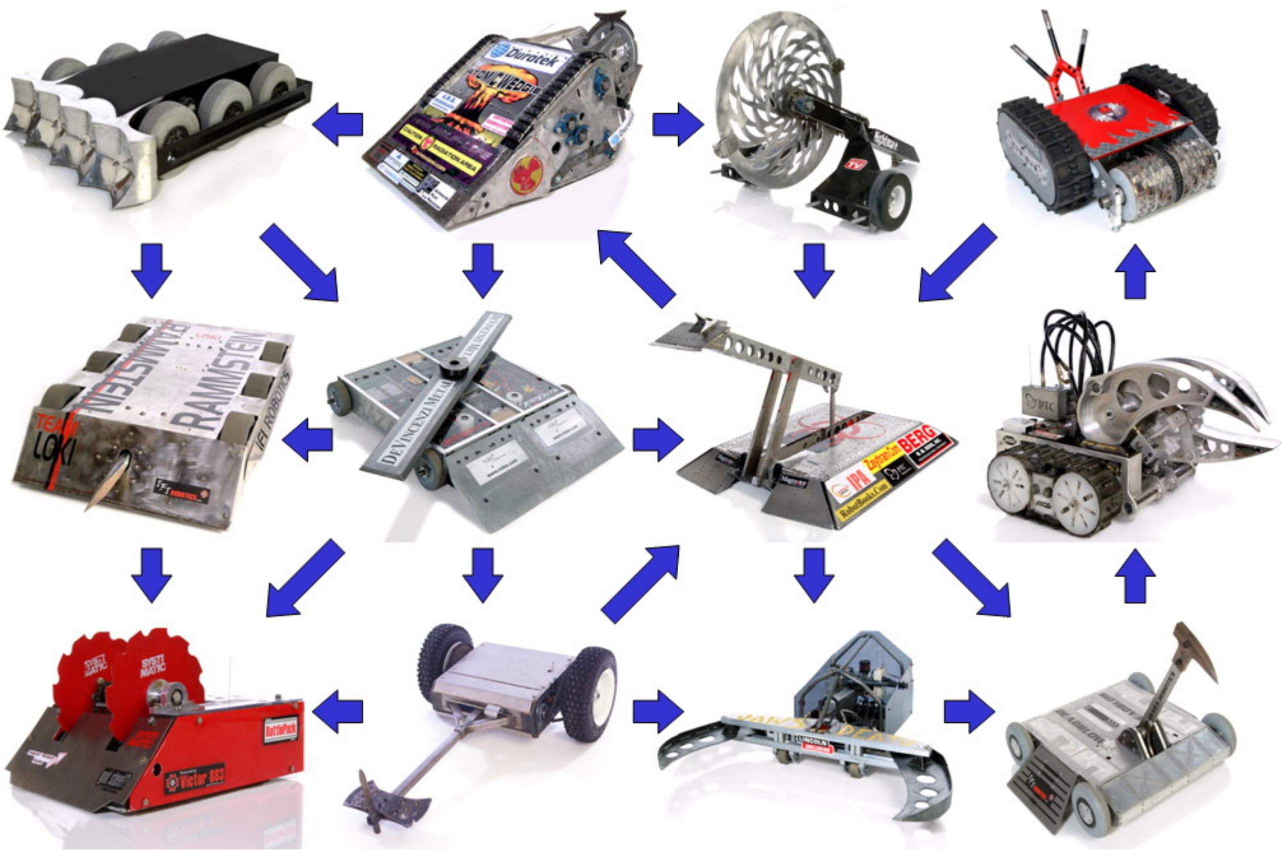
The bottom line is that theory, combined with common sense, is a very powerful design tool in practice. Imagine how many shafts have been broken in combats worldwide before arriving at these optimized diameters, while with a few simple calculations we’ve arrived at the same result.

Note however that these are average diameters, the actual values may vary depending on the steel alloy used in the shaft, number of wheels and combat robot type. The combat robot types are discussed next.

2.3. Combat Robot Types

After choosing the weight class of your robot, the next step is the choice of the robot type. There are several types of combat robots. None of them is the best. It is a rock-paper-scissors game. Or, as combot builders say, a wedge-spinner-hammer game. The wedges tend to flip over the spinners, which in turn tend to cut off hammers, which tend to puncture or damage the wedges. But they only tend to.

The truth is that a well designed robot can win against a robot of any type, independently of the trends. In the figure below there is a diagram showing such trends for several types of robots. In the figure, each robot has a tendency to win against the one it is pointing to. But a good design and a good driver can completely change this.



There are basically 16 types of combots: rammers, wedges, lifters, launchers, thwackbots, overhead thwackbots, spearbots, horizontal spinners, sawbots, vertical spinners, drumbots, hammerbots, clampers, crushers, flamethrowers and multibots, which will be described next.

Other types of robots exist, but they can almost always be categorized into one of the 16 types above, or in a combination of them. Consider for instance the robot known as the “Swiss army knife,” one with two or more weapons. The Swiss army knives in general are not very efficient, it is better to concentrate the weight on a single powerful and efficient weapon than on two or more smaller weapons. It may be a good idea when the weapons act together, at the same time against an opponent. For instance, the 2006 version of our middleweight spinner Titan (pictured to the right) used a wedge (the weapon of the wedge robots) together with its blade to lift lower opponents and hit them.

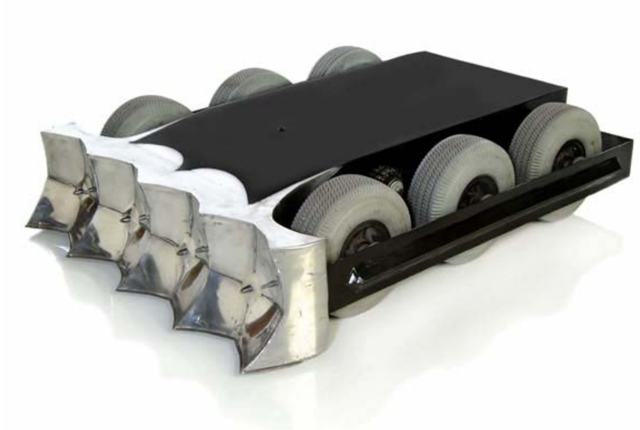
Most secondary weapons that are efficient in practice are wedges, used for instance to slow down the spinning bar of an opponent before it is safe to attack it with the main weapon.

There is also the “chameleon” robot, with weapons that can be switched during each pitstop depending on the opponent from the next fight. These robots can change their type very quickly, taking advantage of the best each type has to offer. The super-heavyweight Shovelhead (pictured to the right) has 15 different weapons that can be installed on its articulated front, one for each type of opponent.

A few accessories can make a big difference. For instance, it is not a bad idea to install some sort of bumper if you’ll face a spinner. There are even specific accessories against specific robots, such as using a long stick to hold the shell spinner Megabyte by its vertical tube, as pictured to the right, to repeatedly shove it against the arena walls. However, it is not easy to design efficient weapons that can be quickly dismounted and assembled during a pitstop.

The 16 main types of robots are discussed next. Several photos below were taken from the BattleBots website, www.battlebots.com.

2.3.1. Rammers



Rammers are ramming robots, they damage the opponent throwing themselves against them or pushing them against the borders of the arena. They usually have 4 (or more) wheel drive, wide wheels with high traction, a sturdy drive system, robust armor, high resistance to impacts, and they don’t have weapons except for their passive shields. In general, they are invertible (they can be driven upside down). They need to be capable to push at least 2 times their own weight. They are effective against robots with spinning weapons, such as spinners, drumbots and sawbots.

2.3.2. Wedges

Wedges are robots with a sloped plate shaped as a wedge. They usually have 2 or 4 wheels, with a very resistant drive system. They can be invertible or not. Despite rarely causing damage directly, they are a good tactic against spinners, making them flip over when hitting the wedge. Wedges win against their opponents by entering underneath them and dragging them around the arena, or flipping them at high speeds. Fast wedges usually reach 20 to 25km/h (12.4 to 15.5 mph). The front of the wedge should not be made out of sheet metal, because it can get easily bent and lose functionality. Use thick plates chamfered at the edge to withstand the opponents’ impacts. Wedges are good against rammers and robots with spinning weapons, and they are vulnerable mainly to other lower, faster and more powerful wedges.

2.3.3. Lifters

Lifters are robots capable of lifting the opponent, immobilizing it or turning it upside down. They are efficient against robots that depend on traction such as rammers and wedges, or robots that have protuberating parts that can be reached by the lifting arm. They are inefficient against thwackbots and overhead thwackbots, because they are difficult to catch and they can work inverted. Lifters are vulnerable to spinners. The lifter design involves a slow linear actuator to lift the opponent, which can stop in the middle of its course. In this way, one can lift an opponent and drag it around the arena instead of just flipping it over. A few lifters use pneumatic systems, but most of them use electric motors with linear actuators. Place the batteries as far behind as possible in the robot, to act as a counterweight when lifting an opponent. The front wheels need to have high torque and high traction, because the robot weight will move forward when lifting and dragging the opponent. A few robots, such as the famous Sewer Snake, use active wedges that also work as lifters.

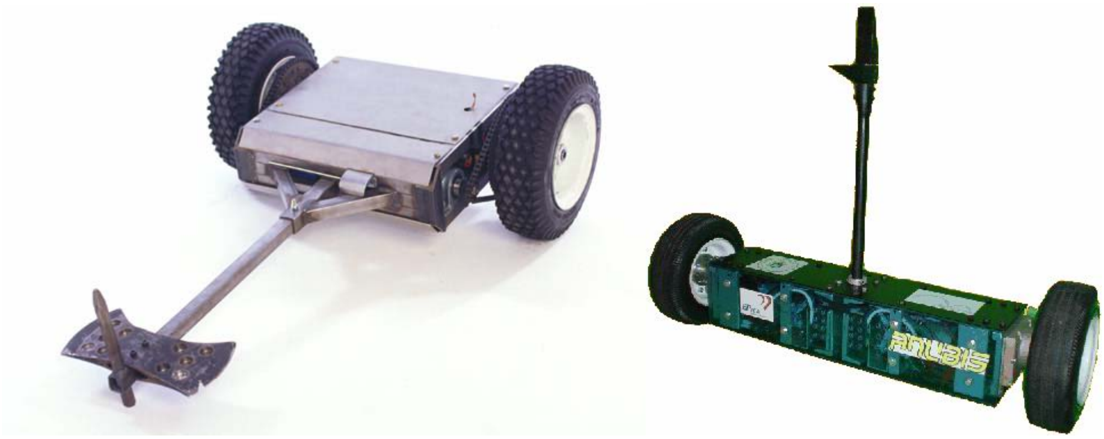
2.3.4. Launchers / Flippers

Launchers (or *flippers*) are lifters on steroids, being capable of flinging the opponent high into the air. The opponent not only can be flipped over, but it can also suffer great damage when hitting the ground. Therefore, launchers are good against opponents with weak chassis, or batteries and electronics without protection against impacts. Launchers need pneumatic components with large diameters actuated by high pressure air or CO_2. Eliminate all needle valves from the system, or use a big accumulator, to guarantee the high gas flow necessary to power the weapon.

2.3.5. Thwackbots

Thwackbots are usually 2-wheeled robots, invertible, which rotate all their structure in the same place at high speeds. They usually have one or more long rods with a hammer, axe, or some piercing weapon. They use the energy of their own drive motors to power the weapon, leaving more weight for their armor. The tires need to be narrow, otherwise they will suffer large friction losses when trying to turn on a dime at high speeds. The wheels, besides being narrow, cannot be too far apart. The closer they are, the faster will be the final angular speed of the robot, however the slower will be the acceleration and the harder will be to drive on a straight line if necessary. The drive motors need to have high RPM. The main problem is that most thwackbots are not capable of moving around to pursue their opponent while they are spinning. Very few thwackbots have developed successful mechanical or electronic systems with that purpose, as studied in chapter 6. Thwackbots are sometimes called full-body spinners, for obvious reasons.

2.3.6. Overhead Thwackbots



Overhead thwackbots use their weapon in an overhead movement, instead of a horizontal one such as with the thwackbots. They have 2 wheels and a long rod, which rotates when the drive motors are reversed, attacking the opponent's top. It is important that the motors have high torque, because the weapon has only a 180 degree course to acquire its maximum speed. Unlike thwackbots, the wheels should be far apart to help it move on a straight line and to increase the precision of the attack. The tires should be wide to maximize traction. The center of mass of the robot needs to be very close to the line passing through the axes of the wheels, to guarantee that it can lift the weapon to attack. They are good against rammers, wedges and lifters.

2.3.7. Spearbots

Spearbots have a long and thin penetrating weapon, usually pneumatically actuated, which tries to penetrate into the walls of the opponent’s armor and damage vital internal components. The weapon needs to be resistant and sharp, reaching the largest possible speed. Some conicity in the spear tip is a must to avoid it getting stuck in the opponents. They usually have 6 wheels, to guarantee high traction, necessary so that the robot doesn’t move too much backwards during the attack. They are not too efficient, except against robots with thin lateral armors or with exposed vital components. A few robots tried to implement attacks with tethered projectiles (projectiles are forbidden unless they are tethered), but they ended up converging to the spearbot design.

2.3.8. Horizontal Spinners

Horizontal spinners are the most destructive robots. They have a bar, disk, shell or ring that spins at high speeds. When the weapon spins very low near the ground, the spinner is called an undercutter. Ring or shell spinners (such as the robot Megabyte) spin their entire ring or shell-shaped armor, being capable of storing a high kinetic energy, becoming almost impossible for the opponents to reach them without being hit by their weapon. The weapon needs to spin as fast as possible, and you should be able to accelerate to a speed that can cause significant damage in less than 4 seconds. Spinners that take longer than 8 seconds to accelerate may never have a chance to damage a resistant and aggressive opponent. Spinners need to be fast to escape from their opponents while they spin up. Their greatest disadvantage is that, in general, they are not invertible, depending on luck to flip back. To compensate for that, a few robots such as The Mortician and Last Rites, called offset spinners, have moved their blade forward, making them invertible. However, by doing so the robot ends up with large dimensions, compromising its robustness, its back is vulnerable to attacks, and its center of gravity is moved too much forward, away from its wheels, decreasing traction.

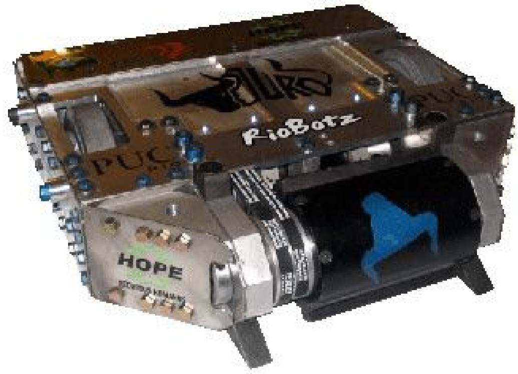
2.3.9. Sawbots

Sawbots have abrasive or toothed disks powered at high speeds by a powerful motor. They are in general combined with other designs, such as wedge-saws. The saws have little efficiency to cut through the opponent, especially if it is trying to escape. They can easily cut sheet metal and Lexan, but they can hardly cut any metal plates during a fight. Their greatest advantage is the cosmetic damage they cause, generating a shower of sparks, scratches and shallow cuts, which can impress judges and guarantee victory in a close match. Saws that rotate in such a way to lift the other robots have high risk of getting stuck on the opponent, breaking or bending. Saws that rotate downwards reduce this problem, however they increase the chance of self-flipping over.

2.3.10. Vertical Spinners

Vertical spinners are sawbots on steroids. Unlike sawbots, in general they use large diameter disks with very few teeth, or bars, spinning on a vertical plane. Damage is caused by both impacts: when the opponent is hit by the weapon and thrown into the air, and when it hits the ground. Vertical spinners need to have a wide base so that they don't tumble when turning due to the gyroscopic effect of the weapon (discussed in chapter 6). The impact force is transmitted to the ground, and not sideways such as with spinners, allowing them not to be flung to the sides due to their own impact. Their disadvantages are having their lateral and back exposed, and having a hard time making quick turns due to the gyroscopic effect. They have problems against very low wedges and tough rammers. The fights against horizontal spinners are extremely violent and fast, and they can go either way, although vertical disks with large diameter usually lose to powerful horizontal bars.

2.3.11. Drumbots

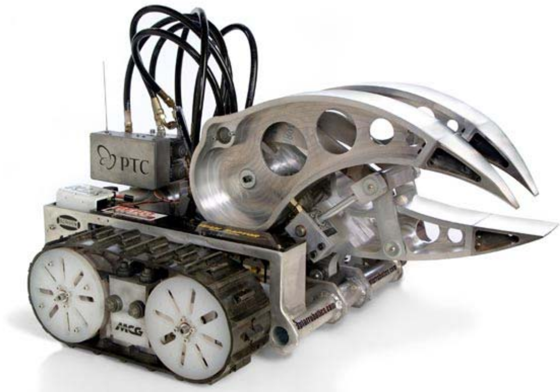


Drumbots have a spinning drum or eggbeater with teeth, in general powered by belts or chains, horizontally mounted in front of the robot. They usually rotate in such a way to launch the opponent, turning it over or causing damage from the impact with the weapon or with the ground. Drumbots are more compact versions of vertical spinners, with less moment of inertia in the weapon. This allows a shorter acceleration time for the drum, however causing less damage to the opponent. They are very stable due to their low center of gravity, they can be invertible, and they make turns more easily than vertical spinners due to the smaller gyroscopic effect (discussed in chapter 6). Wider drums allow drumbots to reach their opponent without needing a perfect alignment. The acceleration time of the drum should be at most 4 seconds. Their worst enemies are very resistant, well armored invertible robots.

2.3.12. Hammerbots

Hammerbots are robots with hammers or axes that hit their opponents' top. Usually with 4 wheels, their attack is similar to the one from overhead thwackbots, however the weapon actuation is independent of the drive system. The weapon can be fired repeatedly and quickly. It is usually pneumatically powered to deliver enough speed in its course, which has only 180 degrees. The weapon system can work as a mechanism to flip back the robot itself. They are very efficient against robots with weak top armors. Powerful hammerbots are good against rammers, wedges, thwackbots and sawbots. Their worst enemies are the spinners.

2.3.13. Clampers



Clampers are robots capable of holding and lifting an opponent, usually carrying them to the dead zone on the borders of the arena. They’re usually pneumatically actuated (faster), or they use an electric system with high gear reduction (slower). Their design strategies are similar to the lifters’, where the robot weight should be shifted back to avoid tipping forward when lifting the opponent. Clampers need to be fast enough to reach their opponents before they can escape from their claws. They are good against rammers, wedges and thwackbots. Hammerbots should be caught from their sides, so the clamper can avoid being repeatedly hit by the hammer while clamping them. Instead of a lifting platform, a few clampers use a *dustpan*, which is basically a wide box open at the front and top where an opponent is maneuvered into. A few dustpan designs do not include a restraining claw.

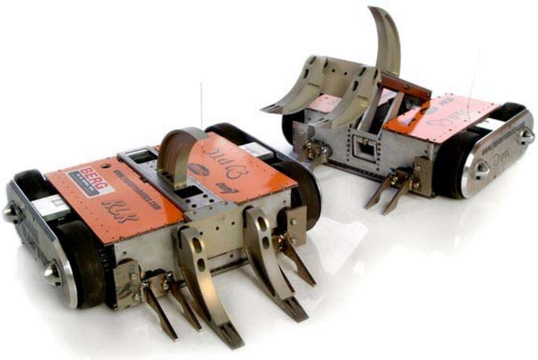
2.3.14. Crushers

Crushers are robots with hydraulic claws capable of slowly puncturing or crushing the opponents. The claws need to have long tips to penetrate efficiently, and they need to have a long course to be able to work against an opponent with large dimensions. Their main advantage is that it is almost impossible for the opponent to escape after being caught, ending the match. Crushers need to be hydraulically powered to generate enough forces to crush, which makes them very complex and heavy, leaving little weight left for the drive system. They are usually heavyweights or super-heavyweights. More sophisticated robots use a two-stage hydraulic system: the first stage is fast enough to hold the opponent before it can escape, and the second stage is slow but with enough force to puncture and crush.

2.3.15. Flamethrowers

A few competitions allow the use of flamethrowers. The *flamethrowers* are usually used together with other weapons, such as wedges. The effect is mostly visual, counting points with the judges and making the audience cheer. They are usually inefficient to disable other robots because most opponents are fireproof, except if the electronics is exposed or the wheels are flammable.

2.3.16. Multibots



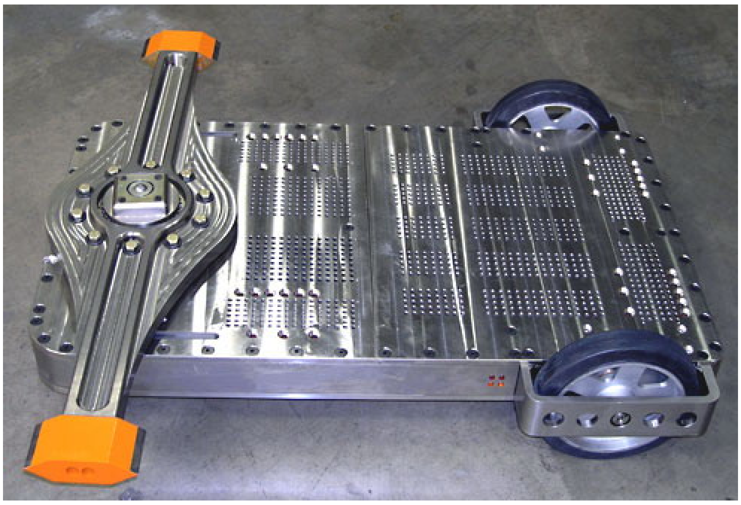
Multibots are robots made out of 2 or more sub-robots, with weights that must not add up beyond the limit of the category. Most of the competitions adopt the rule that says that it is necessary to incapacitate 50% or more (in weight) of the robot to win a round. Using 2 sub-robots is therefore risky, because it is enough to have the heavier one incapacitated to lose a match. For that reason, several multibots use 3 robots of similar weights, forcing the opponent to incapacitate 2 of them to win. For instance, you can use 3 middleweights, as long as one of them drops to 100lb, to compete as a single super-heavyweight multibot (120 + 120 + 100 = 340lb). In the same way that several small weapons are less efficient than a large one, multibots have little advantage over their opponents, unless the attack (usually controlled by 2 or more drivers) is very well coordinated. In practice, it is difficult to coordinate a simultaneous attack, the opponent ends up incapacitating the multibot one by one (in general going for the smallest one in the beginning of the match). Another technique is to use, for instance, a main robot with about 90% of the weight of the category and 2 small ones with 5% each, which serve as a distraction for the opponent. In practice, the small ones are ignored and the opponent goes for the bigger one (the multibot Chiabot used 1 small robot as a distraction, but it didn't help much in practice). Another idea is to use a swarm of small autonomous robots, which would climb the opponent, get inside and destroy them from the inside out. But they are still science fiction, like the Sentries from Matrix, or Star Wars' Buzz Droids.

2.4. Design Steps

After choosing the weight class and type of the robot, the next concern is with its cost.

2.4.1. Cost

A middleweight robot, to be competitive internationally, has a typical cost of about US$4,000, including the radio control and spare batteries. For lightweights, about US$3,000 [10], for heavyweights US$6,000, and for super-heavyweights US$8,000. The numbers can go much higher than that. The robot Buster (on the right) is a beautifully designed super-heavyweight, all made in milled titanium, with an estimated cost of about US$30,000. This doesn't mean that it is not possible to win an international competition with a much less expensive robot, everything depends on creativity. But, statistically, the above numbers are reasonable estimates. The opposite is also true, there is no guarantee that an expensive robot will win a competition.



In summary, this is not a cheap sport. However, for many sponsors such numbers are low if compared with what it is usually invested in other sports. In addition, featherweights and other lighter robots can be quite inexpensive.

2.4.2. Sponsorship

A few great tips about sponsorship and several other combot subjects can be found at The Robot Marketplace (http://robotmarketplace.com/tips.html). Basically, it says that it is not an easy task to find a sponsor that will help you out if you haven't built any combot before. Probably the only exceptions are companies whose owners or directors you know well or who are your friends. Most big companies do not bother with sponsoring robots, it's a better bet to look at smaller local shops near you that might like to help out. You might be able to get sponsorship from big companies, but it is important to meet the right people, the ones who are able to make the decisions. For instance, presenting your robot to a public relations intern won't help you a lot, he/she won't probably be as enthusiastic as you would be when presenting the proposal to their boss.

Also, you have to call and visit them in person, nobody will give you sponsorship over e-mail. Bring with you business cards with your team's logo, for a more professional look, as pictured to the right.

Prepare a presentation folder with lots of nice photos, such as the one pictured to the right. Clearly show the potential sponsors how and where their name and logo would be made visible, such as in a T-shirt layout (pictured below), on the robots, at the team website, in YouTube videos, etc. Show as well which newspapers, magazines and TV news programs have already covered the events you plan to attend. Showing videos from the fights is also a great idea, several potential sponsors have no idea of what robot combat is. They might fall in love as soon as they watch it.

Attached to the presentation folder, you should include your annual budget. Don't forget to include the cost of parts, machining time, taxes (especially if any component must be imported), marketing material (such as T-shirts with sponsor logos), event entry fees, and travel expenses. Do not cut down expenses at this stage, ask for everything you might possibly need – there's a chance you get full sponsorship for that value. If you ask for too little in the beginning, you might not be able to increase the budget later on during the same year.

But let the potential sponsors know that they don't need to provide the entire budget, that you will take partial sponsorship. You may even come up with sponsorship levels, such as bronze sponsorship for 10% of the budget, silver for 25%, gold for 50%, and platinum for 100%.

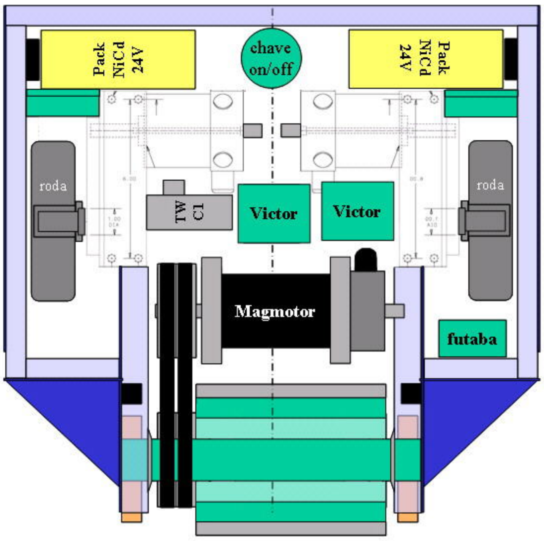
It is important to show the potential sponsors which benefits they get depending on the sponsorship level. For instance, in the T-shirt layout from the previous page, a gold sponsor would get advertising space on the areas 1, 2, 3, 6 and 9, while silver would get 4 and 7, and bronze would get 5 and 8. Needless to say, a platinum sponsor would get all areas from 1 to 9. Note that area 3 is better than areas 4 or 5, because it has a higher chance of being caught on camera during a TV interview, as pictured to the right. Usually, the silver sponsor logo in area 4 is only partially shown during an interview.

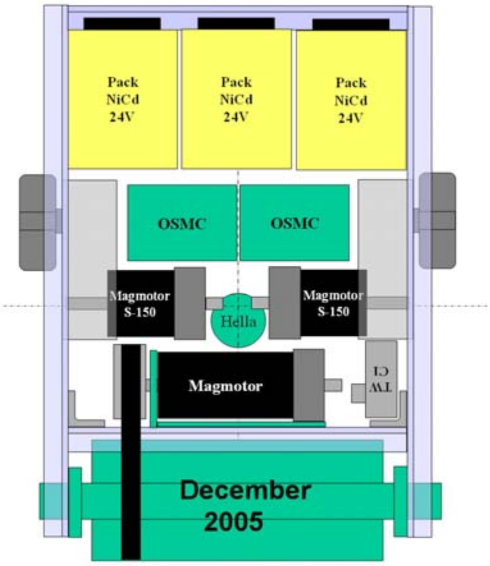
Any sponsorship help is welcome. Unless you are very well established with your sponsors, you will find it difficult to get cash from them, more often they might contribute with parts or machining time. And don't give up after getting turned down a few times, you need to put a lot of effort into it.

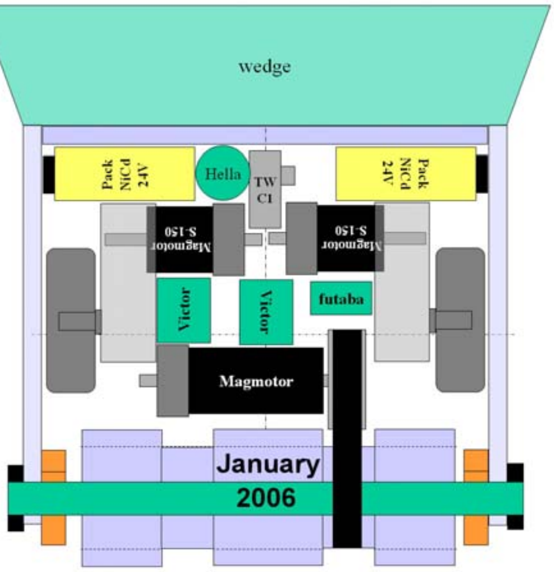
2.4.3. Designing the Robot

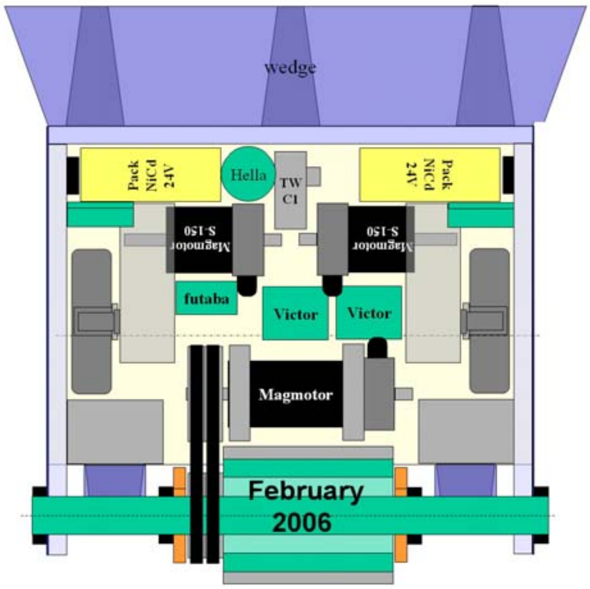
The next step is to get an estimate of the robot weight. If, after adding all the motors, wheels, structural components, weapons and batteries, the robot is way above its weight class limit, this means that it is necessary to reduce the entire scale of the robot or to use lighter components. To distribute well the robot's weight, a very useful tip is to use the 30-30-25-15 rule [10]: 30% of the robot weight should be devoted to the drive system (motors, transmissions and wheels), 30% to the weapons (weapon, motor, transmission), 25% to the structure and armor, and 15% to the batteries and electronics. Of course those numbers can vary a lot depending on the type of the robot, but they are representative average values.

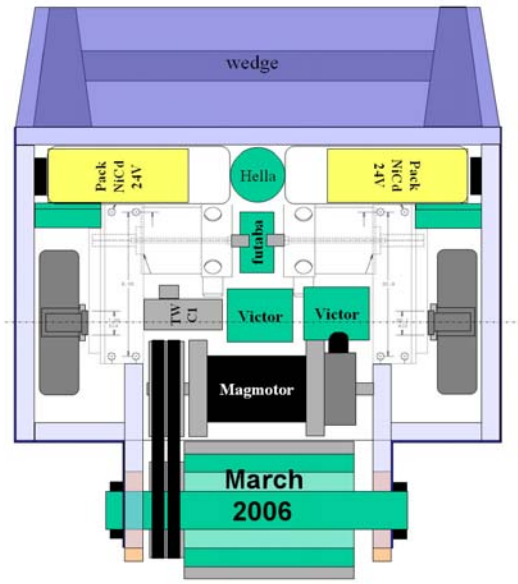
When designing and sketching the robot, always have in mind the principle known as KISS: Keep It Simple, Stupid! In other words, don't complicate your design too much if not necessary, design your robot in the simplest possible way, but never simpler than that. Sketches can be made by hand, using a CAD program, or in any way that makes it quick to update and share it with all your teammates. The first sketch of our middleweight Touro was made, believe it or not, in MS Powerpoint, see the figure to the right. It is a program that the entire team had in their personal computers, either at home or in the University, unlike most CAD programs. In this way, the entire team could think anytime anywhere about improvements in the robot design, using any personal computer. This technique is also known as PAD (Powerpoint Aided Design), making it easy to generate vaporbots, which are virtual robot designs that haven't been built yet. Vaporbots help a lot to stimulate creativity and to evolve your design without any building cost. The next page shows 4 vaporbots that helped generate the RoboGames 2006 version of Touro.



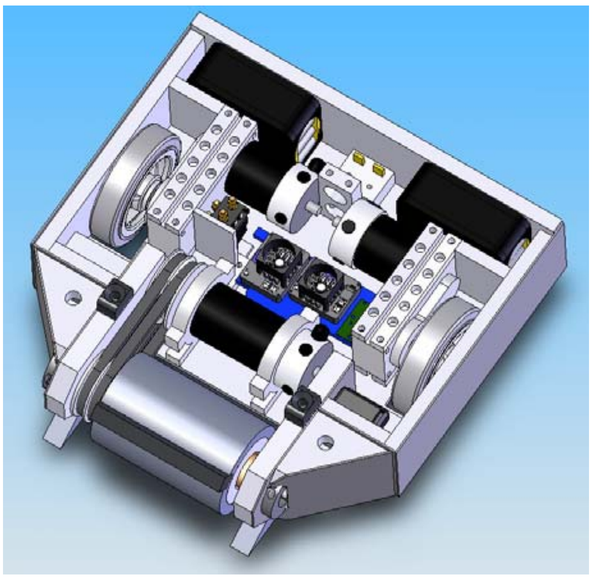








If you have access to CAD programs such as Solidworks or Rhino3D, then you can use them to create a 3D view of the robot, see the figure to the right (created using Solidworks). CAD programs are also useful to make cutting and drilling marks: just print out the layout in 1:1 scale, glue it directly onto the piece/plate with an adhesive spray (such as Spray 77), and mark the holes with a center punch.



During the design phase, it is necessary to have in mind that fragile items such as electronic components should be placed well inside the robot, to be protected from cutting weapons. The robot should also be the most compact possible, so that its armor can have larger thicknesses without going over the weight limit. But don't forget that too compact robots are difficult to repair during a pitstop, the parts that need to be changed may be inaccessible, so it is important to use common sense.

2.4.4. Calculations

After the first sketches, it is recommended to perform a stress analysis to calculate the resistance of each component from the robot. This subject is too vast, it is beyond the scope of this tutorial. Books about mechanics of solids and mechanical behavior of materials [8] are very useful for that. The analysis consists basically of calculating the tensile, bending, torsion and shear stresses in the structure and components, including the stress concentration factors of the eventual notches (such as holes, abrupt changes of geometry), and combining them to obtain an equivalent stress, usually known as Mises or Tresca stresses. With the equivalent stress, it is possible to design the parts against yield, rupture, plastic collapse, fatigue, etc. Finite element software, such as Abaqus, Ansys, Nastran, Adina, or several others, can be used to aid in the numerical calculation of the robot's resistance. Most of them are capable to import drawings directly from CAD programs. Their license is usually expensive, however these programs are not indispensable. With a little common sense and mechanical background it is possible to make "back of the envelope" stress analyses, which are approximate but accurate enough for design purposes. Chapter 6 will show a few examples of such dimensioning techniques.

2.4.5. Optimization

Most combat robots are born overweight. You must prepare yourself to deal with that, sooner or later. If it is too much overweight, you might need to redesign it completely. Otherwise, a few optimization techniques can be used to lose weight, improve strength, or even to do both at the same time.

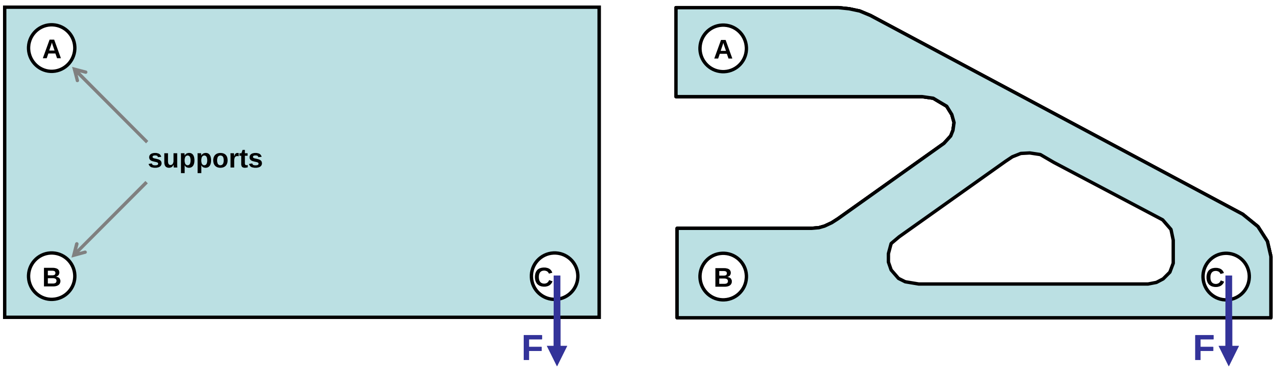
One way to do that is to optimize the shape of the robot parts. This is usually done in an ad-hoc manner, using common sense, and sometimes even with the aid of finite element software to check the resulting strength, such as in the spinning disk of the middleweight Vingador (pictured to the right). The holes and voids in the disk were positioned not too close to its center, where out-of-plane bending stresses can get very high, and not too close to the outer perimeter, to avoid lowering the moment of inertia or the strength of the teeth. This process usually involves trying several hole configurations, and using finite element and CAD programs to calculate the disk strength and moment of inertia.

Shape optimization can also be seen in the spinning bar of the hobbyweight Fiasco, pictured to the right. Pockets were milled in the bar to relieve weight, except at the middle section, not to compromise strength, and at the ends, not to compromise its moment of inertia.

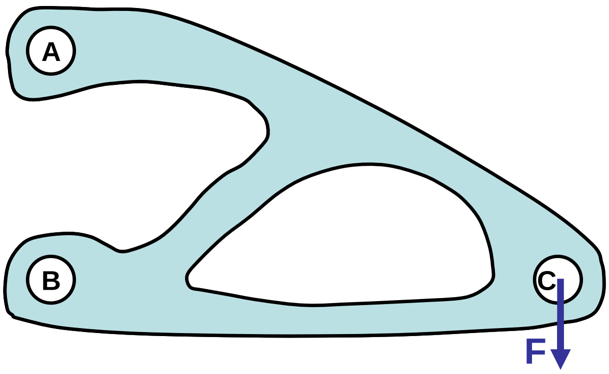
The lifter arm from BioHazard’s four-bar mechanism (pictured to the right) is another example of clever shape optimization to selectively remove weight. Note that the weight saving holes near the middle pivot, where the bending moments are maximum, have smaller diameters not to compromise strength. The diameters of the holes are also directly proportional to their distance to the middle pivot, trying to evenly distribute the stresses at the bar, because the bending moment in this system is directly proportional to the distance to the bar ends.

Such optimization tasks can also be performed automatically. Sophisticated software can perform shape and topology optimization of structural parts, to minimize their weight or maximize some property. Shape optimization software like Tosca (http://www.fe-design.de) can be run together with finite element programs to find the optimal shape of a part that will minimize its weight while achieving desired values for stiffness, strength or even moment of inertia, for instance.

For instance, suppose you need to design a single-piece bracket to be fixed inside the robot by two holes A and B, to support some vertical force F that acts at another hole C, as pictured in the next page to the left. The optimization program will require you to inform the relative positions of the holes, their diameters, their contour conditions (such as whether they allow rotations, as if attached by pins, or whether they don’t, as if attached by keyed shafts), the bracket material, the direction and intensity of all the applied forces and moments, and the performance requirements. These requirements can be, for instance, the maximum allowable stress in the bracket (a strength requirement) and, at the same time, its maximum allowable deflection (a stiffness requirement), while minimizing its weight. The optimization programs usually require you to inform as well the topology of the component, which is basically the number of voids it may have. And a few programs also allow you to minimize weight together with manufacturing complexity as well, trying to achieve an optimum shape using only straight lines and circular arcs, avoiding generic curves or very small voids.

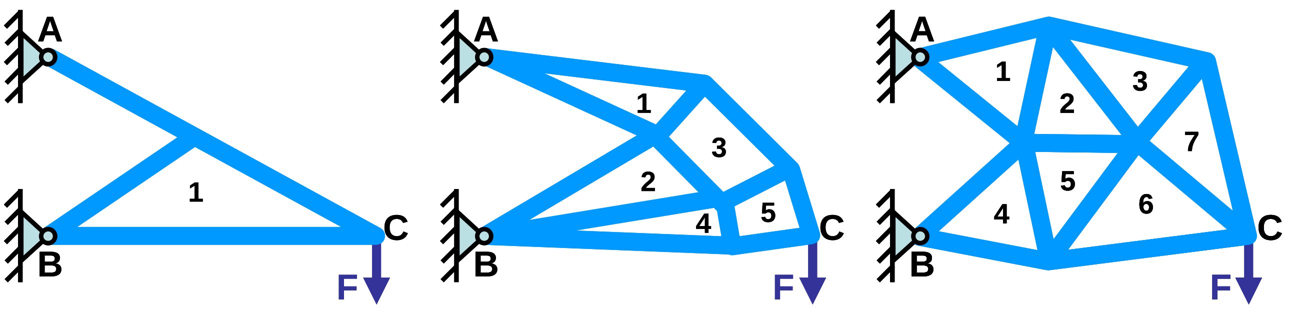


The figure above to the right shows the resulting shape for minimum weight with minimum manufacturing complexity for a version of our bracket with only one void (besides the voids from the fixed holes A, B and C). Note that this resulting shape is only optimal for specific input values, because it depends on all the given parameters. If, for instance, the maximum allowable deflection increases while the maximum allowable stress decreases, the shape will be different. Also, if you turn off the minimum manufacturing complexity requirement, you might end up with an even lighter bracket (such as the one pictured to the right), but you'll probably need a numeric control laser or waterjet cutting system to fabricate the resulting intricate part.

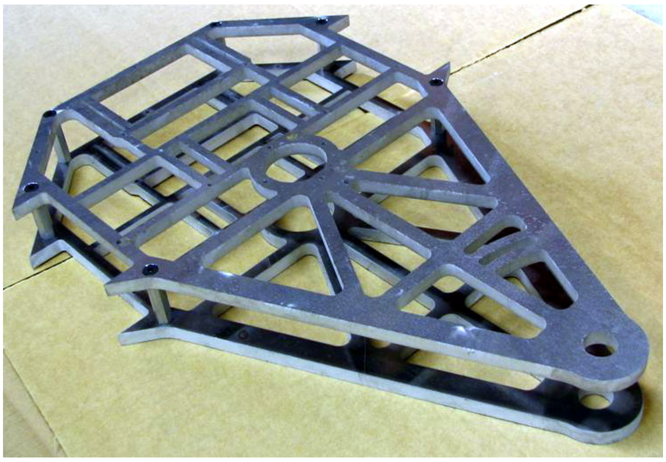


A few programs are also able to optimize both shape and topology, finding not only the shape but also the ideal number of voids in the component. This can be useful, for instance, to find optimal number of voids and their shapes for a spinning disk with maximum strength-to-weight and moment of inertia-to-weight ratios.

Pictured below are a few examples of bracket topologies with 1, 5 and 7 voids (not counting the voids from the holes A, B and C). The above results were obtained after choosing the 1-void topology seen below. A topology optimization program wouldn't need such user choice, it would find out by itself which topology would be the best option, and then optimize its shape.

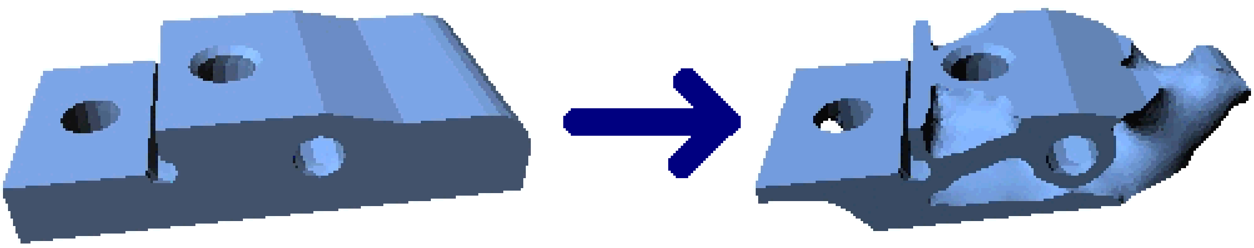


Note that the topology representations above look a lot like trussed structures, but they'll result in single-piece components, such as in the plates the form the structural frames of the hobbyweight Fiasco (pictured below to the left) and lightweight K2 (to the right). Note also that, for armor plates or other external unprotected structural elements, you'll probably want to turn off topology optimization to force a solution with zero voids. Armor plates with voids would probably be a bad idea against spearbots and flamethrowers.



The topology and shape optimization analyses are not limited to planar problems such as parts with uniform thickness. They can also obtain the shape of optimized tri-dimensional (3D) parts, as pictured to the right. Laser or waterjet cutting won't be enough to fabricate these optimal 3D parts, you'll probably need a mill or even a CNC system.

The 3D optimization process is quite similar to the planar case. You'll feed the software with an initial guess of the shape of the desired component (as pictured below to the left), along with all the required holes and contour conditions, material information, applied forces and moments, and performance requirements. The software will then optimize the topology of the component, adding voids if necessary, and finally output the optimized shape that meets the requirements with minimum weight (as pictured below to the right).



Another approach to optimize the robot is to change the material of its components. Material optimization, either to improve performance or to reduce weight, is seen in detail in chapter 3. Other weight saving techniques can also be found in chapter 9.

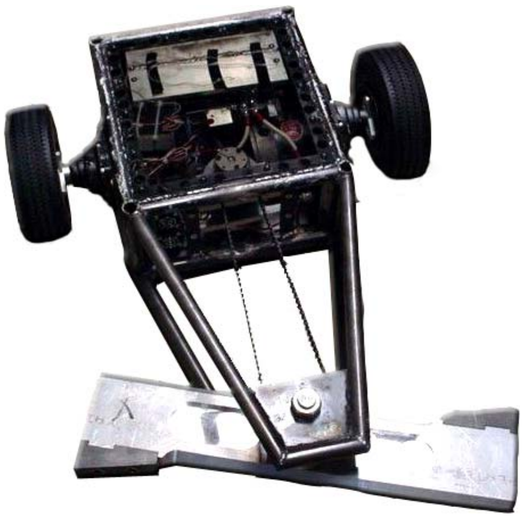
2.4.6. Building and Testing

During the robot design, building a full scale model is also very useful. We've already built several models of our robots and their components. For instance, while we were waiting for an Etek motor to arrive in Brazil during its import process, we've built a one-to-one scale model (pictured to the right) using Styrofoam, cardboard, and an old snorkel. These models guarantee that your hand will fit everywhere inside the robot, which is fundamental for quick pitstops. Unfortunately, Solidworks doesn't allow you (yet) to reach your hand inside the monitor. Always recalculate the robot weight, combots tend to easily get overweight.

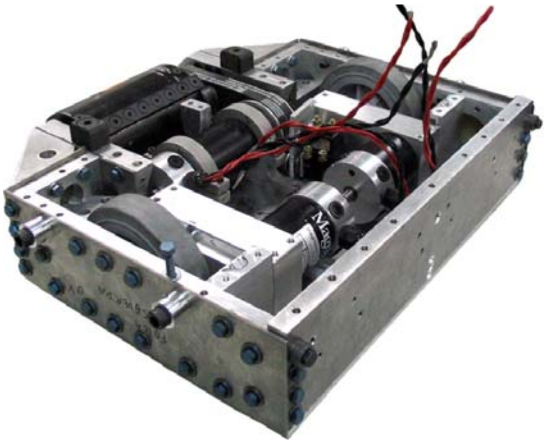
At least in our experience, we've realized that the design phase usually takes most of the robot development time, perhaps about 60% or more. The other 40% would be the construction itself. In order not to waste money and material, it is a good idea to make sure that the design won't suffer huge changes before starting to build it (small changes during construction will almost always happen). Check the CAD drawings - or the cardboard prototypes - before starting to cut metal. Follow the "measure twice, cut once" rule. A lot of information on building the robot will be covered in the following chapters of this tutorial.

Finally, after finishing the robot, there's the part that everybody forgets about (including us): testing. Follow Carlo Bertocchini's law: "Finish your robot before you come to the competition." Many times the robot is finished just before the competition, leaving not enough time to test it. This is a fatal mistake, there are several things that can go wrong. With a few tests most problems can be identified and corrected. Besides, during the tests the driver is able to acquire experience in driving that specific robot, which can make all the difference during a match. This leads to one of Judge Dave Calkins' main advices: LTFD – Learn To *Freaking* Drive! Drive a lot. Hundreds of hours, not a few. Several opponents drive maybe two hours a day. This can and will make a huge difference.

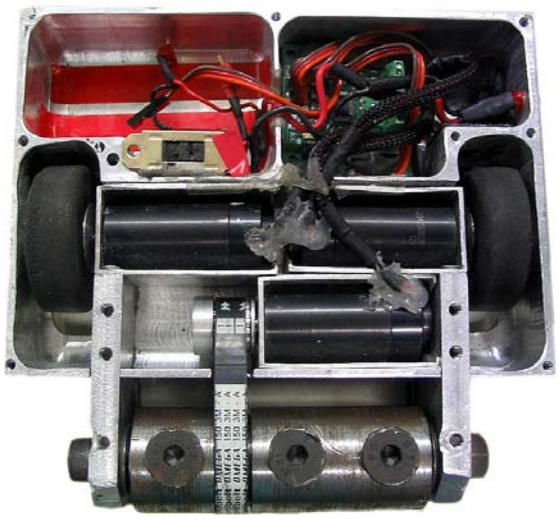
2.5. Robot Structure



As for the robot structure, the three main types are: the trussed, the integrated, and the unibody. The trussed robots (such as The Mortician, pictured to the right) are built using several bars, in general welded together, resulting in a very rigid and light structure. The armor is made out of several plates, usually screwed to the bars, sometimes using rubber sandwich mounts (see chapter 4) to provide damping against impact weapons. They are the fastest type of structure to build, it is enough to use a hacksaw and welding equipment to quickly assemble the chassis. Trussed robots are also easy to work with during pitstops because, if one of the plates gets damaged, it is easy to unscrew it and change it for a new one. The greatest disadvantage is to depend on the welds, which are in general the weak point. Besides, the armor plates are prone to be ripped off in combat.



The integrated robots (such as our middleweight Touro, pictured to the right) receive such name because the structure and armor are integrated into a single set, using screws or welds. The same plates that work as armor are the ones where the internal components are mounted to. Sometimes there is a thinner armor layer on top of the integrated structure. Building such robots is not an easy task, however they generate very compact and resistant systems.



The unibody robots (such as our beetleweight Mini-Touro, pictured to the right) have their structure milled out of a single solid block. Through milling, it is possible to create the side walls, the bottom, and pockets to fit batteries, motors, etc. In this way, it is not necessary to weld or to use screws in the structure, except to install the components and to attach the top cover. These are the lightest and most resistant robots. However, you lose about 80% to 90% of the material from the solid block to carve its interior, not to mention the hours (or days) hogging the milling machine. The cost and material waste makes this solution attractive only to very light robots such as the insects. Another disadvantage is that there is no way to replace a damaged part of the structure, as it is done with the armor plates from the trussed robots. If there’s too much damage, it might be necessary to mill an entirely new unibody.

A unibody can also be made out of a composite frame, as in the hobbyweight VD2.0 (pictured to the right). Composite frames are basically a foam body with the shape of the unibody, covered with some fiber such as glass, carbon and/or aramid (Kevlar) fibers, which are epoxied to the surface. Carbon fibers are an excellent choice to obtain very high stiffness, while Kevlar gives high impact toughness, see chapter 3. Composite frames are not very popular because they’re expensive and difficult to manufacture, in special if the robot design requires the structure to have a high precision to mount, for instance, weapon systems.

2.6. Robot Armor

There are basically three types of armor: traditional, ablative and reactive, presented next.

2.6.1. Traditional Armor

Traditional armor plates are usually made out of very tough and hard materials that try to absorb and transmit the impact energy without getting damaged. The high hardness of the armor plate is used to break up or flatten sharp edges from the opponent weapon (which is good against very sharp horizontal spinners), while its high toughness allows the plate to withstand the blow without breaking. This sometimes can be achieved using a composite armor, which means using several layers of different materials. For instance, you can use very hard (but brittle) ceramic tiles sandwiched between two very tough (but relatively soft) stainless steel plates to use as armor.

Due to their high hardness, traditional armors need to be changed less often, and they look nicer after a match. However, traditional armors transmit a lot of the impact energy to the rest of the robot structure, as shown in chapter 6, and they usually produce sparks, which may count as trivial or cosmetic damage points depending on the judges.

2.6.2. Ablative Armor

Ablative armor plates, on the other hand, are designed to negate damage by themselves being damaged or destroyed through the process of ablation, which is the removal of material from the surface of an object by vaporization or chipping. They're also made out of tough materials, but with low hardness and low melting point to facilitate the ablation process.

Ablative armor plates are much more efficient dissipating the impact energy, which is mostly absorbed by the ablation process, transmitting much less energy to the rest of the robot. They are a good choice especially against blunt or not-so-sharp horizontal spinners. They are also good against drumbots, even the ones with sharp teeth, because most of the drum energy will be spent "eating out" chunks of the armor instead of launching the robot. Also, you won't get sparks if you're using an aluminum ablative armor, which is good even though they are only counted as trivial damage.

Thick wooden plates are also very efficient as ablative armor, however they result in a lot of visual damage that may award damage points to your opponent (even though the destruction of ablative armors should only count as cosmetic damage). Make sure that the judges know if you have an ablative armor. A disadvantage of ablative armors is that they need to be changed very often because of the ablation, and you might need to use gloves to handle your deeply scarred robot.

2.6.3. Reactive Armor

The third armor type is the reactive. Such armor reacts in some way to the impact of a weapon to prevent damage. Most of them are very effective against projectiles, which have a relatively low mass and extremely high speeds, but not much against regular combot weapons, which have much more mass but much lower speeds than projectiles.

One example is the explosive reactive armor, which is made out of sheets of high explosive sandwiched between two metal plates. During the impact, the explosive locally detonates, causing a bulge of the metal plates that locally increases the effective thickness of the armor.

Another example is non-explosive reactive armor, which basically consists of an inert liner, such as rubber, sandwiched between two metal plates. Against most combot weapons, this basically works as a shock-mounted armor, dissipating energy in the elastic liner. And against spearbots this armor has an additional advantage: during an angled impact, the outer metal plate will move laterally with respect to the inner plate, which may deflect or even break up any spear that eventually penetrates.

There are also studies on electric reactive armors, which would be made up of two or more conductive plates separated by air or some insulating material, creating a high-power capacitor. This could be implemented in practice using three metal layers, separated by rubber liners (acrylic tape such as VHB 4910 is also a good option due to its high dielectric breakdown strength), which would also work as a shock-mount. The middle plate is then charged by a high-voltage power source, while the other 2 plates are grounded. When the opponent's weapon penetrates the plates, it closes the circuit to discharge the capacitor, vaporizing the weapon tip or edge, or even turning it into plasma, significantly diffusing the attack. Note, however, that this system might be very difficult to implement in a combat robot, not to mention the increased battery requirements. Also, most competitions forbid the use of electric or explosive reactive armors.

2.7. Robot Drive System

The three usual types of drive systems are based on wheels, tank treads and legs, discussed next. There are also other types, based on rolling tubes (moving as a snake), rolling spheres, or air cushions (hovercrafts), but they're not very effective in combat. Flying is usually forbidden.

2.7.1. Tank Treads and Legs

Robots with tank treads are beautiful, they have excellent traction, however they waste a lot of energy when turning due to ground friction. They are also slow when turning, which allows an opponent to drive around and catch them from behind. Besides, treads can be easily knocked off by opponents with powerful weapons.

Legs have also several disadvantages. They are complex to build and control, and they usually end up not sturdy enough for combat, in special against undercutters. They tend to leave the robot with a high center of gravity, making it easy to get flipped over. Their only advantage is the weight bonus, usually 100%, allowing for instance a 240lb legged combot to compete among 120lb middleweights. But note that shufflers, which are rotational cam operated legs, are not entitled for the weight bonus. Legs are usually good options for robots in very rough and uneven terrain, which is not the case in flat floored combat robot arenas. This is why the international combat robot community has converged to the wheel solution.

2.7.2. Wheel Types

There are several types of wheels in the market. A few robots use pneumatic wheels, however they are filled internally with polyurethane foam so that they don't go flat if punctured.

Another good solution is the use of solid wheels. To maximize traction, it is recommended that solid wheels have an external layer of rubber with hardness around 65 Shore A, at most 75 Shore A. Harder wheels tend to slide. Wheels with hardness measured in Shore D units are probably too hard.

Several robots, as well as our middleweights Touro and Titan, use the Colson Performa wheels (pictured to the right). These wheels are very inexpensive: each 6” wheel from Touro costs only US$7.25. Besides the low price, this Performa model from Colson has hardness 65 Shore A, a very good value for traction.

An interesting wheel solution was used by our team during the RoboCore Winter Challenge 2005 competition, held on an ice arena. When driving on ice, the wheel hardness is irrelevant. The important thing is the presence of sharp metal tips to generate traction. The secret of walking on ice is to know that it is not friction (very low in this case) that generates traction, but normal forces. The solution for the problem was very cheap: we’ve inserted several self-drilling flat head screws at angles of about 60 degrees with respect to the wheel radius (as pictured to the right). The screw caps were also sharpened to improve traction performance. Those sharp tips generate a very small contact area with ice, generating a very high contact pressure. That high pressure makes the ice melt locally, allowing the tips to slightly sink in and lock in place. Then, when the motors spin the wheels, the “fixed” tips sunk in the ice apply normal *horizontal* forces, generating traction without sliding. The traction on ice ends up even better than the one from a regular wheel on metal. See in the picture above that we chose to use a single row of screws: our tests with 2 parallel rows generated worse traction, because with twice the number of screws to distribute the load, the pressure on the ice drops in half, and the screws sink in much less. A single well sunk screw generates much better traction than two half-sunk screws. Also notice that we’ve alternated the screw angles on the wheel, to guarantee that in average the traction was identical in both forward and reverse directions.

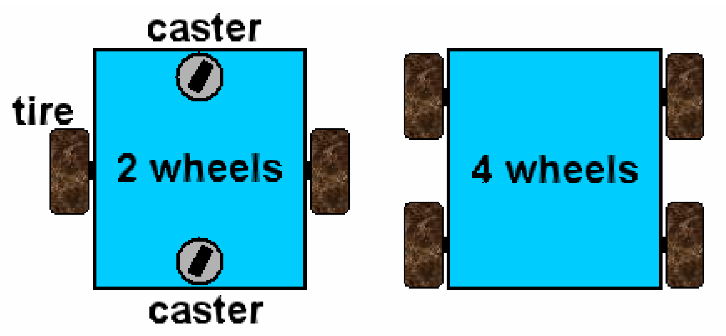
2.7.3. Wheel Steering

There are two main types of wheeled vehicles: the ones with Ackerman steering and the ones with tank (or differential) steering. Ackerman is the solution adopted by the automobile industry: a large motor is used to move the system forward or backward, and another smaller motor controls the steering of the front wheels to make turns. This is very efficient for high speeds, because it is easy to drive straight, however it demands several maneuvers for the robot to spin around its own axis. Besides, the steering system is usually a weak point, needing to be very robust and, consequently, very heavy.

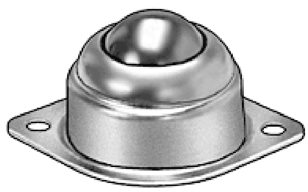
Tank steering receives that name for being used in war tanks. The entire left side of the robot is driven independently from the right side. To drive on a straight line, it is necessary that both sides have the same speed, which is not always easy to guarantee. Turns are accomplished when those speeds are different. The great advantage of that method is that if the speeds of both sides are equal in absolute value but have opposite senses, the robot can turn on a dime. This is perfect to always keep facing the opponent.

2.7.4. Two-Wheel Drive

There are two common options in tank steering, which are using 2 or 4 active (power driven) wheels, as pictured to the right. With 2 active wheels, it is possible to turn very fast and with less waste of energy. In addition, the robot saves weight by not needing the extra set of active wheels, shafts and bearings.



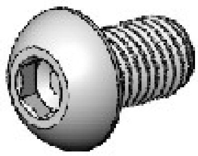
With only 2 active wheels, the robot will probably need at least another ground support, ideally 2. This is usually accomplished with skids, which are passive elements such as ball transfers or caster wheels (pictured to the right). Try to place the axis of the 2 active wheels as close as possible to the robot center of gravity, and the ball transfers or casters in the front and in the back, arranged in a cross configuration (see the previous figure for a 2-wheeled robot). In this way, you guarantee that almost the entire reaction force from the ground will go through the 2 active wheels, where you need traction. Our middleweight Ciclone, due to lack of internal space, could not use the cross configuration. The 2 active wheels ended up in the back, as pictured to the right, supporting only half of the robot weight, compromising traction. But be careful with the cross configuration, make sure that the ball transfers or casters won't lift the active wheels off the ground, especially in an arena with uneven floor. To avoid lifting the active wheels and losing traction, these robots should have their passive elements in a plane a couple of millimeters higher than the active wheels. You can also spring mount the ball transfers and casters, creating a suspension system that prevents the active wheels from being lifted off.



A disadvantage of using only 2 wheels is that it is more difficult to drive on a straight line. Several electric DC motors do not have neutral timing, which means that they spin faster in one sense, making it harder to drive on a straight line. If possible, try to set the drive DC motors in neutral timing (see chapter 5) or, if the radio control system is programmable, try to compensate the speed differences through the trim settings. A few robots use gyroscopes to drive straight, more details can be seen in chapter 7.

If your robot continues with problems to move on a straight line, try to use rigid casters (pictured to the right) instead of the swivel ones. You will have a harder time turning, but the robot will drive straighter.

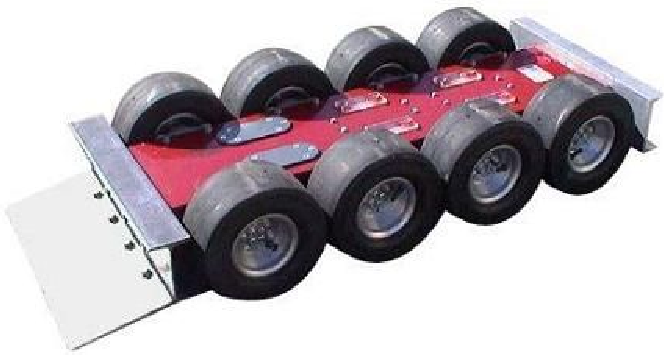
In robots with very violent weapons, the ball transfers and casters may not take the extreme forces transmitted to the ground during an impact against the opponent (these forces can easily exceed a few metric tons for middleweights). In this case, you can replace these passive elements by, for instance, button-head cap screws (pictured to the right), mounted upside down at the bottom of the robot. The round head slides very well on the arena floor. This is the technique that we use in our middleweight spinner Titan. Use hardened steel screws, the ones with high class (see chapter 4), because they are harder and do not easily wear away due to friction with the arena floor. A few robots also use wide pieces of Teflon (PTFE) for ground support with reduced friction.



2.7.5. All-Wheel Drive

Another wheel steering option is the use of 4 (or more) active wheels. Four-wheeled robots drive better on a straight line, they are good against wedges and lifters (because in general they guarantee at least 2 wheels on the ground to be able to escape if they've been lifted), and they have redundancy in case a few wheels are destroyed during a match. Experienced drivers, such as Matt Maxham from Team Plumb Crazy, are still able to drive even after 3 out of 4 wheels have been knocked off!

A few robots use 6 or 8 wheels to maximize traction as well as to increase redundancy, such as the 8-wheeled super-heavyweight New Cruelty and the famous 6-wheeled heavyweight Sewer Snake, pictured to the right. The problem with 4 or more wheels is the waste of energy while making turns, besides the additional drivetrain weight needed by the additional axes, bearings, pulleys, etc.



An interesting solution to help 6-wheeled robots to make turns more easily is to have two middle (compliant) wheels with a slightly larger diameter. In this way, the ground normal forces on the 4 outer wheels are reduced, decreasing their friction resistance while turning on a dime.

2.7.6. Omni-Directional Drive

A very specific type of drive system is the omni-directional drive. It can be accomplished with omni-directional wheels (a.k.a. Mecanum wheels), which can move sideways without changing their direction. Those wheels have several small passive rollers, which can rotate freely, as pictured to the right.

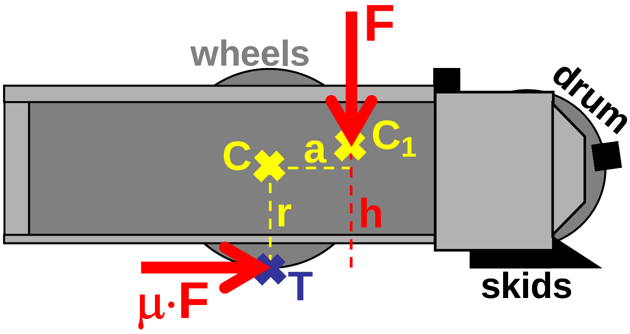
The most common configurations are 4 parallel wheels, or 3 wheels at 120^o angles. The rollers provide the wheel with traction in only the circumferential direction, rotating freely in the shaft axial direction. Coordinating the movement of the 3 (or 4) wheels, it is possible to move sideways without changing the direction of the robot. In the case of 3 wheels at 120^o, the omni-directional control system is not so simple to implement, you need to program a few calculations involving sines and cosines. An off-the-shelf solution is the OMX-3 Omni-Directional Mixer (pictured to the right), a small US$45 board from Robot Logic (www.robotlogic.com), which does all these calculations automatically. This system is excellent for robot soccer competitions: the robot with the ball can move sideways to dribble an opponent without losing sight of the goal. It is possible to kick towards the goal immediately after dribbling the opponent, without wasting time changing direction and making turns.

However, in combat robots such omni-directional capability is not necessary, because during a match you do want to be pointed towards your opponent. This is usually your goal. Moving sideways can be a good idea to dodge from an attack, but the cost-benefit is not good: the omni-directional wheels have worse traction than regular ones, they are less efficient (they waste more energy), and the rollers don’t stand violent impacts.

2.7.7. Wheel Placement

Another important factor in the design of the drive system is the location of the center of mass of the robot. If it is shifted to the left of the robot, for instance, the wheels on this side will receive a larger reaction force from the ground. Because of that, they would have better traction than the right side, and the robot wouldn’t move straight. Try to distribute the weight equally on both sides.

For robots with only 2 active wheels, it would be ideal to have the robot center of mass C_1 very close to the center C of the line that joins the wheel centers, as pictured to the right. In that case, each wheel would receive about half the robot weight, guaranteeing good traction.



Even better would be to place C_1 slightly ahead of C, at a horizontal distance $a = \mu \cdot h$, where μ is the coefficient of friction between the tires and the ground, and h is the height of C_1, as pictured to the right.

If the combined torque of both wheels is large enough to guarantee an initial traction force of $\mu \cdot F$, the maximum value without wheel slip, where F is the robot weight, then the robot won’t tilt backwards while it is accelerating if $a \geq \mu \cdot h$. It won’t tilt because the forward gravity torque $F \cdot a$ with respect to the contact point T between the wheel and the ground becomes greater than or equal to the backward inertial torque $\mu \cdot F \cdot h$ (with respect to T) caused by the forward acceleration of C_1, since $F \cdot a \geq \mu \cdot F \cdot h$.

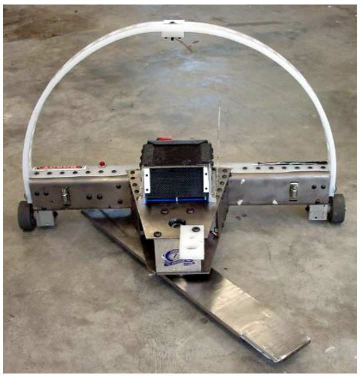
Our middleweight Touro uses this principle. Not tilting backwards is good to prevent wedges from entering underneath the skids that support Touro’s drum. In addition, during the initial drivetrain acceleration, 100% of the robot weight goes to both wheels if $a = \mu \cdot h$, maximizing the initial traction force. The front skids will only feel part of the robot weight after the wheel motors drop their traction force below $\mu \cdot F$, which happens as they speed up. So, with $a = \mu \cdot h$, Touro achieves its maximum possible initial drivetrain acceleration while the front skids are barely touching the ground, until it acquires enough speed to make the front skids get some downward pressure right before they get in contact with the opponents, trying to get under them using the skids as if they were wedges. Note that, due to the almost symmetric and invertible design of Touro, the height h of its center of mass C_1 is almost equal to its wheel radius r, resulting in $a \cong \mu \cdot r$.

But it is important not to make this distance much higher than $\mu \cdot h$. As discussed before, our middleweight Ciclone, due to lack of space, had its 2 active wheels far in the back of the robot (as pictured to the right), away from the center of gravity, resulting in a large value for the distance a. Each wheel ended up just bearing about one fourth of the robot weight, the other half went to the front ground supports. With this reduced applied load on the active wheels, Ciclone had poor traction, with a lot of wheel slip. Note that magnet wheels and suction fans would be two possible solutions, although unusual, to increase the normal forces at the wheels.

The distance between the robot bottom and the arena floor is also important, this clearance needs to be large enough to avoid being trapped in debris or in uneven seams of the arena floor. If your poor featherweight will fight right after the super-heavyweight hammerbot The Judge, it will probably have to overcome arena conditions such as the one pictured to the right. But the ground clearance cannot be too large, otherwise your robot might be vulnerable to wedges, lifters and launchers. It is also important to keep low the robot center of gravity to avoid being flipped over. In our experience, a minimum suggested clearance for any class from hobbyweight to super-heavyweight is about 1/4” (or 6mm).

2.7.8. Invertible Design

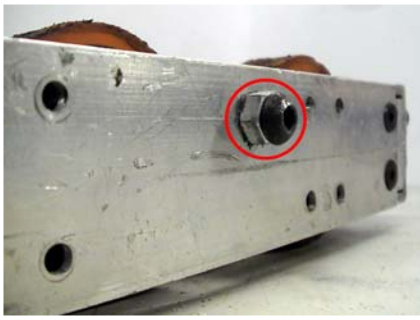
Most successful combat robots are invertible, which means that they can be driven while upside down. With the high number of wedges, drumbots and vertical spinners that we see today, not to mention launchers and lifters, it is just a matter of time until your robot gets flipped over.



If your robot is not invertible, or if its weapon has limited or no functionality when upside down, then it is a good idea to have some self-righting mechanism (SRiMech). A SRiMech is an active system that returns an inverted robot to its upright state. This mechanism can be an electric or pneumatic arm, or a passive extension on the upper surface of the robot to roll or flip it upright, such as the large white hoop on top of the featherweight Totally Offensive, pictured to the right. Launching or lifting arms, or even vertical spinning weapons, can also be used as a SRiMechs if properly designed.

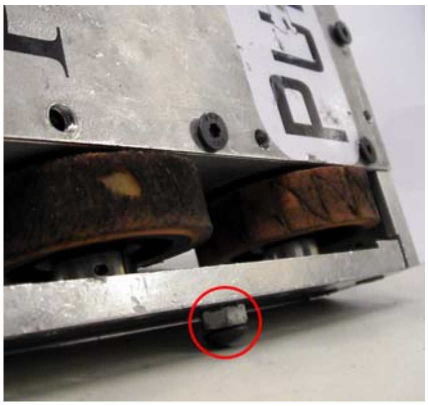
The easiest way to implement an invertible design is to use wheels that are taller than the robot chassis. If the front side of your robot has a tall chassis, but not its back side, then another option is to use 2 drive wheels in the back, and skids in the front.

Another solution is to have two sets of active wheels, driven together using chains or belts, one of them for driving the robot when not flipped, and the other to be used when upside down. But note that this solution usually adds a lot of weight to your drive system.



Also, it is important to remember that your robot does not have only 2 sides. If it is box-shaped, it actually has 6 sides. But it is very simple to avoid losing a match because your robot ended up standing on its side. You only need to avoid having perfectly flat and vertical front, back and side walls.

This can be accomplished, for instance, using bolts sticking out of the walls, as pictured to the right, circled in red, in our wedge Puminha.



The bolts should not stand out too much, to avoid being easily knocked off, but enough to make sure that the robot will tilt back, as shown in the bottom picture to the right.

If the robot is invertible, without a preferential side, then you can place the screw in the mid-height of the chassis. Otherwise, you’ll probably want to place it near the top of the chassis, as in both pictures to the right, to increase the chance of tilting back in the upright position. But this screw will need to stand out approximately twice as much as in the mid-height design to make sure that the robot will indeed tilt back.

2.8. Robot Weapon System

The wide range of weapon systems makes it difficult to give general suggestions that would apply to all of them. So, the weapon system of each robot type needs to be studied on a case by case basis. This topic is extensively covered in chapter 6, which deals with Weapon Design. You can also find several weapon design tips in sections 2.3 and 2.4. In addition, chapter 3 will show a thorough discussion on material selection for all kinds of weapon systems. Chapter 5 also deals with this subject, showing spin-up calculations for kinetic energy weapons such as spinning bars, disks and drums.

There are also very good books on the subject. For instance, Combat Robot Weapons [6] is entirely dedicated to weapon systems. Build Your Own Combat Robot [3] and Kickin' Bot [10] have chapters explaining the design details of each weapon type and the related strategies. And Building Bots [4] even presents basic physics equations. There are also a lot of weapon-related questions and answers at http://members.toast.net/joerger/AskAaron.html.

Note that there are several weapons that are usually not allowed in combat. This includes, but is not limited to, radio jamming, noise generated by an internal combustion engine (ICE), significant electro magnetic fields, high voltage electric discharges, liquids (glue, oil, water, corrosives, etc.), foams, liquefied gases (if used outside a pneumatic system), halon gas fire extinguisher (to stop an opponent's ICE), unburned flammable gases, flammable solids, explosives, un-tethered projectiles, dry chaff (powders, sand, ball bearings), entanglement weapons (nets, strings, adhesive tape), lasers above 1 milliwatt, and light, smoke or dust based weapons that impair the viewing of robots (such as the use of strobe lights to blind the opponent driver).

2.9. Building Tools

The following chapters will present the several materials and components necessary to build a combat robot. But for that it is desirable to have access to a series of tools. Below, there is a comprehensive list with everything that could be useful in the construction of a combat robot. Most of the items can be found, for instance, at McMaster-Carr (www.mcmaster.com).

The book Kickin' Bot [10] has very good sections on how to effectively use most of these tools. There's also a great 43-minute video at http://revision3.com/systm/robots, featuring RoboGames founder Dave Calkins, teaching how to use basic tools to build a combot, as well as presenting a primer on the involved components.

Of course it is not necessary to own the entire list of tools presented below to build a combot. If your robot has some special part that you're not able to build by yourself, either due to lack of experience or to restricted access to a machine shop, you can have it machined straight from its CAD drawing through, for instance, the www.emachineshop.com website.

Mechanical

- safety: safety glasses, goggles, face shield, gloves, ear muffs, first aid kit;
- wrenches: Allen wrench (L and T-handle), combination wrench, open-end wrench, socket wrench, adjustable-end wrench, monkey wrench, torque wrench;

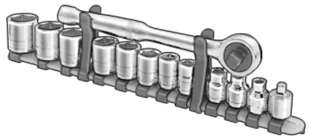
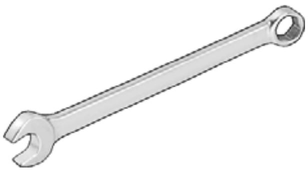
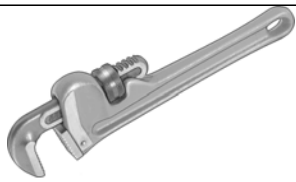
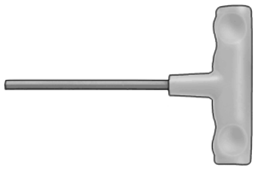
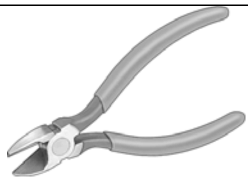
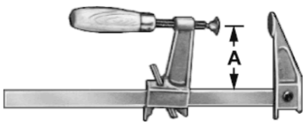
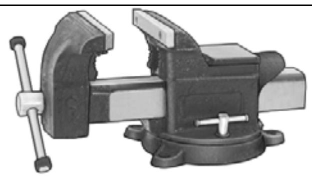
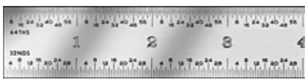
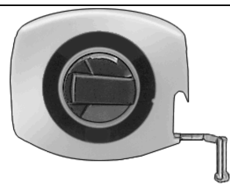
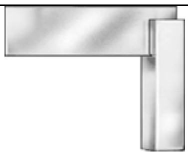
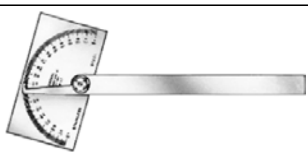
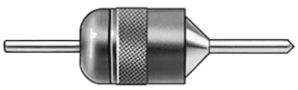
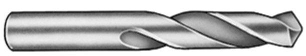
- screwdrivers: flathead and Phillips;
- pliers: needlenose plier, cutting plier, vise-grip, slip-joint plier, retaining ring plier;
- clamping: C-clamp, bar clamp, bench vise, drill press vise;
- measuring: caliper, micrometer, steel ruler, tape measure, machinist’s square, angle finder, level;
- marking: metal scriber, center punch, automatic center punch, hole transfer;
- cutting: scissors, utility knife, Swiss army knife;
- drilling: drill bit, unibit, countersink, counterbore, end mill, hole saw, reamer;
- tapping: tap, tap wrench;
- hand tools: hacksaw, file, hammer, jaw puller, keyway broach, collared bushing, telescopic mirror, telescopic magnet;
- weighing: dynamometer, digital scale;
- power tools: power drill (preferably 18V or more), jigsaw, Dremel, angle grinder, orbital sander, disc sander, circular saw;
- large power tools: lathe, bench drill, bench grinder, vertical mill, bandsaw, miter saw, belt sander, guillotine, CNC system, water jet system, plasma cutter;
- welding: oxyacetylene, MIG and TIG;
- cleanup: air compressor, air gun, vacuum cleaner (metal bits can short out the electric system).

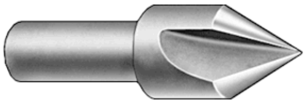
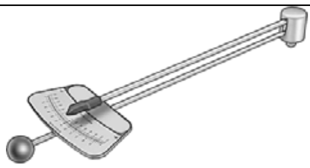
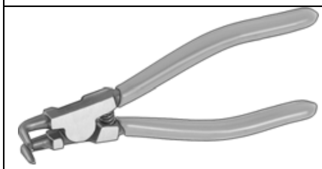
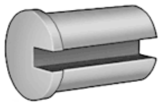
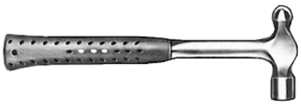
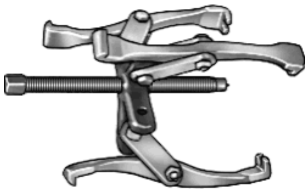
Electrical / Electronic

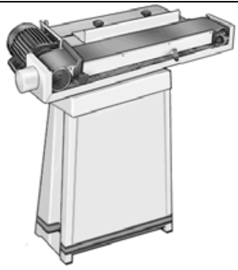
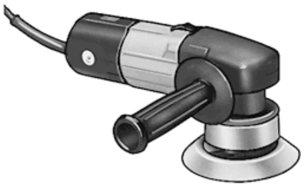
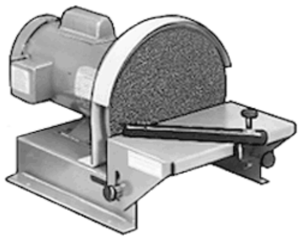
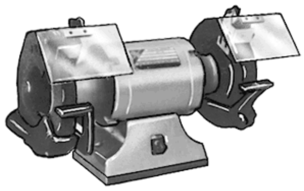
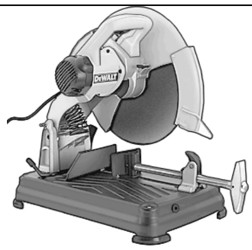
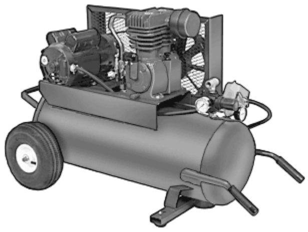
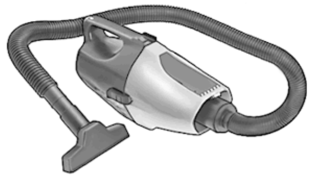
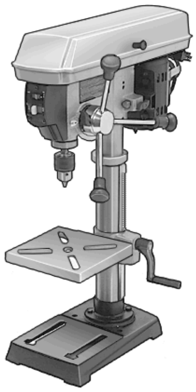
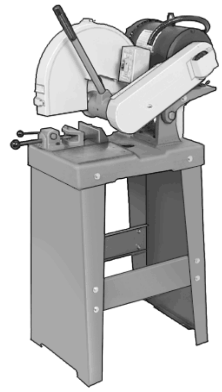
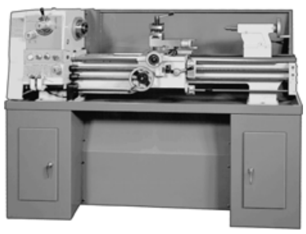
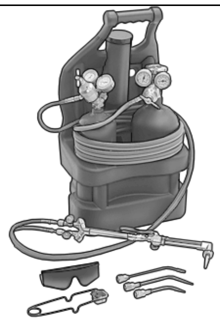
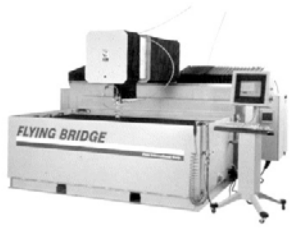
- pliers: flush cutter, needle plier, crimper, wire stripper;
- soldering iron and support with sponge, desoldering tool;
- tweezers, magnifying glass, board support;
- digital multimeter, power supply, oscilloscope, battery charger;
- hot air gun, glue gun.

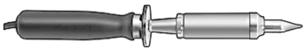
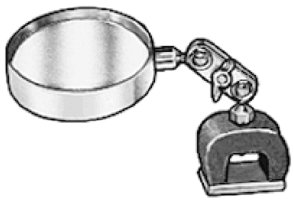
Fluids

- WD-40 (lubricant, it can be used to cut, drill and tap, and to clean Colson wheels);
- stick wax (to lubricate cutting discs);
- threadlocker (Loctite 242, it locks the screw in place);
- retaining compound (Loctite 601, it holds bearings);
- professional epoxy (the 24 hour version), J.B. Weld (even stronger metallic bonds);
- alcohol and acetone (metal cleanup before applying epoxy);
- layout fluid (to paint the parts and later mark holes or draw lines for cutting);
- penetrant dye (to inspect the presence of cracks);
- adhesive spray (3M Spray 77, to glue layout printouts onto plates);
- citrus-based solvent (Goo-Gone);
- solder paste and liquid electrical tape;
- wheel traction compound (Trinity Death Grip).

 safety glasses/goggles	 face shield	 gloves	 ear muffs
 first aid kit	 flathead screwdriver	 Phillips screwdriver	 socket wrench
 open-end wrench	 monkey wrench	 L-handle Allen wrench	 T-handle Allen wrench
 needlenose plier	 cutting plier	 vise-grip	 slip-joint plier
 C-clamp	 bar clamp	 bench vise	 drill press vise
 caliper	 micrometer	 steel ruler	 tape measure
 machinist’s square	 angle finder	 center punch	 automatic center punch
 metal scriber	 hole transfer	 drill bit	 unibit

 countersink	 counterbore	 end mill	 hole saw
 tap	 tap wrench	 hacksaw	 file
 telescopic mirror	 telescopic magnet	 torque wrench	 air gun
 retaining ring pliers	 level	 keyway broach	 collared bushing
 scissors	 utility knife	 Swiss army knife	 reamer
 hammer	 jaw puller	 dynamometer	 digital scale
 power drill	 jigsaw	 Dremel	 angle grinder

 belt sander	 orbital sander	 disc sander	 bench grinder
 guillotine	 miter saw	 air compressor	 vacuum cleaner
 bench drill	 vertical mill	 bandsaw	 miter saw
 lathe	 oxyacetylene welder	 MIG welder	 TIG welder
 horizontal saw	 plasma cutter	 waterjet system	 CNC system

 flush cutter	 needle plier	 crimper	 wire stripper
 soldering iron	 support with sponge	 desoldering tool	 tweezers
 digital multimeter	 power supply	 oscilloscope	 battery charger
 board support	 magnifying glass	 hot air gun	 glue gun
 Loctite 242	 J.B.Weld	 layout fluid	 penetrant dye

Chapter

3

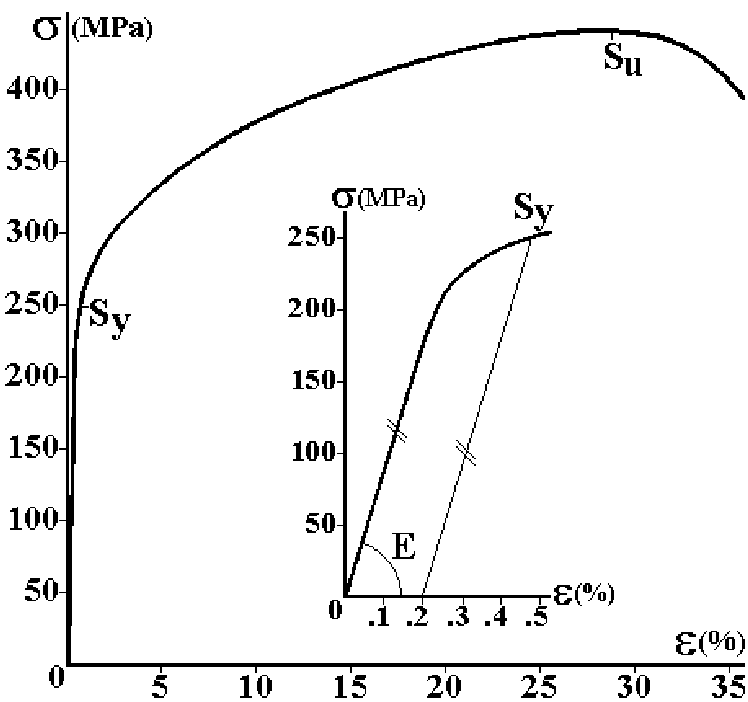
Materials

The choice of structural materials is an important step to guarantee the robot's resistance without going over its weight limit. It is not a simple task to choose among the almost 100 thousand materials available, and for that it is necessary to know their mechanical properties.

3.1. Mechanical Properties

Mechanical properties quantify the several responses of a material to the loads it bears. These loads generate stresses, denominated σ, usually measured in MPa (units similar to pressure, $1\text{MPa} = 10^6\text{Pa} = 1\text{N/mm}^2$). In English units, 1MPa is equivalent to 0.145ksi, where ksi stands for kilo pound-force per square inch (1 ksi = 1,000psi). For a uniform tensile stress distribution, stresses can be defined as the applied force divided by the material cross section area. These stresses also generate strains, denominated ε, which are a measure of deformation, of how much the material is elongated or contracted. The main mechanical properties can be obtained from the stress-strain curve.

The small graph to the center of the figure to the right shows the stress-strain curve of a material under small ε – in the example, smaller than 0.5% (it is the same graph as the large one, but zoomed in the region close to the origin). Note that, initially, the material has linear elastic behavior, in other words, the dependence between σ and ε can be represented using a straight line. The material stiffness is quantified by the modulus of elasticity E, or **Young modulus**, which is equal to the slope of this straight line (see figure). The larger the slope, the more rigid the material is.

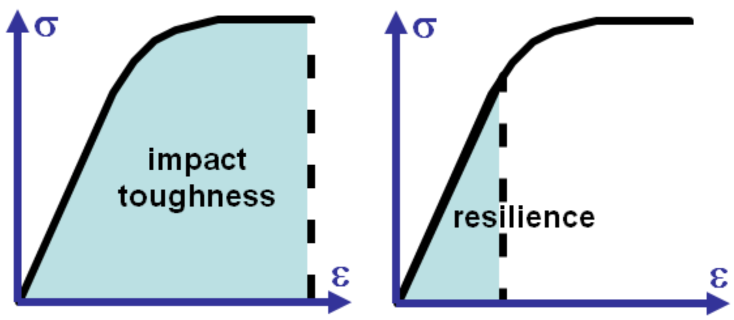


When applying increasingly larger loads, the plotted curve becomes no longer straight, becoming curved. This happens when the material begins to yield, which means it suffers permanent plastic deformations. When the stress reaches the **yield strength** S_y, the material already has 0.2% of permanent (plastic) deformation. In the previous graph, S_y is equal to 250MPa.

Looking now at the larger graph in the figure, note that the material continues yielding until the stress reaches a maximum value S_u, known as the **ultimate strength**, after which the material breaks (in the above example, S_u is about 450MPa). The **fracture strain**, ε_f, is the maximum strain that the material can tolerate before breaking. Beware that, although related, there are subtle differences between fracture strain and **ductility**. Ductility is the material capacity to plastically deform without breaking, while the fracture strain includes both elastic and plastic deformation components. So, if a material is ductile, then it has a high ε_f, but the opposite is not necessarily true: brittle tool steels can achieve a high purely elastic ε_f with almost no ductility.

The stress-strain curve is measured in slow traction tests. Therefore, S_u measures the material resistance to static loads. The resistance to dynamic loads is measured by two other properties of interest: **impact toughness** and **resilience**. Both measure the resistance of the material to impacts. But the impact toughness measures how much impact energy the material absorbs before *breaking*, while the resilience measures such energy before it *starts to yield* (plastically deform).

The impact toughness depends not only on the material strength, but also on its fracture strain. The more it can deform while resisting to high stresses, the more impact energy it can absorb. This is why it is possible to estimate the impact toughness from the area below the entire stress-strain curve (as pictured to the right). Higher values of S_u end ε_f result in a larger area under the entire curve, resulting in a higher impact toughness. The resilience can also be estimated from the area below the curve, but only in the linear elastic region, where the stresses are below S_y (see figure above). That area is approximated by $S_y^2/2E$.



But a tough material is not necessarily resilient, and vice-versa. For instance, the stainless steel (SS) type 304, the most used SS, tolerates large deformations but it is easily yielded. Therefore, it is very tough (because of the large ε_f), being good for armor plates that can be deformed. However, it has low resilience (because its S_y is low), and thus it should not be used in shafts (which should not get bent or distort) or in wedges (because if their edges are bent or nicked they lose functionality).

On the other hand, the steel from a drill bit, for instance, is very hard, it has a very high yield strength S_y, and thus it has a high resilience. However, its ε_f is small and therefore its impact toughness is low. This is why drill bits do not make good weapons for combat robots, because they easily break due to impacts. Titanium is an excellent choice for use in combat robots because it is very tough (good for armor) and resilient (good for wedges) at the same time, as it will be discussed further on.

Fracture toughness, K_{Ic} (pronounced "kay-one-see"), is the resistance of the material to the propagation of cracks. It is measured in cracked specimens, under static loads that are slowly increased until the material fractures (breaks). K_{Ic} is measured using the unusual units MPa√m or ksi√in. The higher the K_{Ic} of the material of an already cracked component, the higher the stresses it can withstand before fracturing. In most metals, it is observed that the impact toughness is very much related to the fracture toughness, even though the first is measured in dynamic and the other in static tests. More specifically, several experiments suggest that the impact toughness is directly proportional to K_{Ic}^2 / E, where E is the Young modulus. However, this is not always true for non-metals. Lexan, for instance, has a relatively high impact toughness for a polymer if cracks are not present. However, its fracture toughness is low, easily propagating cracks once they are initiated, usually around holes, which concentrate stresses.

Note that fracture toughness must be measured for very thick specimens to be called K_{Ic}. This is because fracture toughness has some thickness dependence, thinner plates can deform more easily and absorb more energy per volume than thick plates. It is found that the apparent fracture toughness of a very thin plate can reach up to twice the value of K_{Ic}. So, when searching for fracture toughness data, make sure you're getting K_{Ic} from thick specimen tests, and not a higher apparent value that cannot be compared to the K_{Ic} of other materials.

Finally, the **hardness** of a material is the resistance to penetration by other harder materials. If we press a very hard material (for instance the tip of a diamond) onto the surface of a softer one, the softer one will become dented. The larger and deeper the dent, the softer the material is. A very common hardness unit for hard metals is Rockwell C (HRc). The larger the value, the harder the material is. Another common hardness unit is Brinell (HB), measured in kg/mm^2. A conversion table between HRc and HB hardnesses can be found in Appendix A.

In general, among metals from the same family (such as among steels), the ones with higher hardness tend to have proportionally higher S_u. For instance, you can estimate within a few percent $S_u \cong 3.4 \cdot HB$ for steels, where HB is in kg/mm^2 and S_u is in MPa. This estimate is very useful in practice, because hardness tests are non-destructive and very fast to perform. For steels, this estimate is so good, with a low dispersion, that its coefficient of variation CV is less than 4%. Aerospace aluminum alloys have a relatively good correlation, $S_u \cong 3.75 \cdot HB$, with CV = 6%. There are also estimates for other alloys, but the results have higher scatter (as seen from their higher CV). For instance, aluminum alloys from the 6000 series (such as 6061) have $S_u \cong 3.75 \cdot HB$ (CV = 12%), titanium alloys have $S_u \cong 3 \cdot HB$ (CV = 16%), and magnesium alloys have $S_u \cong 4.2 \cdot HB$ (CV = 20%). These estimates are very good for quick calculations, but use them at your own risk.

Among all the properties presented above, the most important ones in combat robots, as well as in most engineering applications, are without a doubt the impact and fracture toughnesses. Robots need to tolerate impacts and cracks without breaking.

Once having presented the main mechanical properties, we can analyze the main materials used in combat robot construction, as follows.

3.2. Steels and Cast Irons

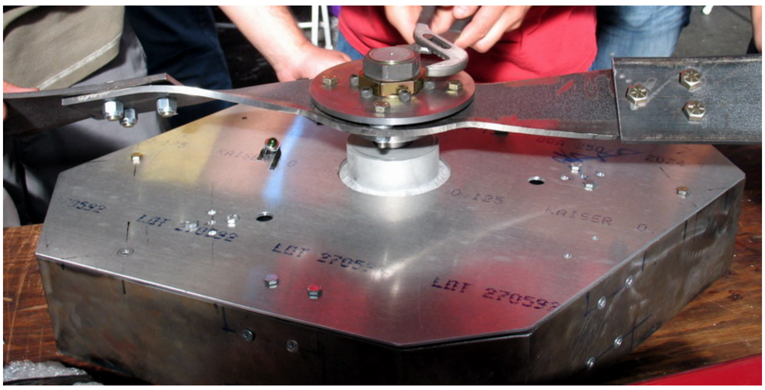
Steels are metals composed basically of iron and of some other (in general few) alloy elements. Depending on the type, they can be extremely resistant, however their high density would make an all-steel robot very heavy. The density of steels does not vary much, between 7.7 and 8.0, with average 7.8 (which means 7.8 times the density of water, or 7.8kg per liter of the material).

Their stiffness also varies very little, around $E \cong 200GPa$ (notice that 1GPa = 1000MPa). This means, for instance, that to deform a piece of any steel in 0.1% it would be necessary to apply a stress of 200GPa × 0.001 = 0.2GPa = 200MPa (29ksi), the equivalent to a force of 200N for each mm^2 of cross section of the material. On the other hand, the strengths of steels can vary a lot: the best steels get to be 10 times more resistant than low strength ones, therefore it is important to know them very well.

Low strength steels are ready to be used soon after being machined. However, many steels need to go through heat treatment (HT) after machining to reach high strengths. For instance, in steels, the HT consists of heating up the material to a high temperature (typically 800 to 900°C, or 1472 to 1652°F, but it varies a lot with the steel type) and cooling it in water, oil, powder or even air (the quenching process), and later heating it up for a few hours in a not so high temperature (typically 200 to 600°C, or 392 to 1112°F, the temper process). HT can be performed in your shop with just a torch and water or oil, however specialized companies are recommended for a better result with larger reliability in the resulting mechanical properties. It may cost around US$50 to heat treat a small batch of the same material.

The following are a few of the main types of steel used in combat robots.

- 1018 steel, 1020 steel: they are mild steels, they have low carbon content, about 0.18% to 0.20% in weight respectively. They have low strength, but they are easily conformed, machined, and welded. They're usually used in shafts and in a variety of components. They are used in the robot structure due to their low cost, however their low yield strength S_y makes them easily bendable (therefore avoid using them in spinning weapon components that need to be well balanced, as pictured to the right). HT only gets to increase the strength and hardness of the surface of those low carbon materials, their interior continues with low strength.



- 1045 steel: steel with medium carbon content (0.45%), it is used when larger strength and hardness are desired. It is used in high-speed applications, gears, shafts and machine parts. It is a cheap solution for the robot shafts, however it needs HT after machining.

- 1095 steel: steel alloy with high carbon content (0.95%), with hardness and strength elevated after HT. It tends to be brittle, with low impact toughness. It is typically used in springs or cutting tools that require sharp cutting edges.

- 4130 steel: steel with 0.30% carbon, with addition of chrome and molybdenum (also called chromoly) to increase strength. The low carbon content makes them a good choice for welding, allowing robots to have their structure formed by 4130 bars and tubes, which are welded together and then heat treated to reach great strengths.

- 4340 steel: steel with 0.40% of carbon, with nickel in addition to chrome and molybdenum (chromoly), with even higher strength and impact toughness after HT than 4130 or 4140 (4140 is equivalent to 4130 but with 0.40% carbon). The typical applications are for structural use, such as components of the landing gear of airplanes, gears for power transmission, shafts and other structural parts. It is an excellent material for shafts, the weapon shaft of our middleweight spinner *Ciclone* is all made out of tempered 4340 steel. To reach high impact toughness, HT the 4340 in a way to leave it with final hardness between 40 and 43 Rockwell C – much more than that and the shaft becomes brittle, breaking under a severe impact, and much less than that will allow the shaft to easily yield. Our recipe for 4340 steel is to heat it up and keep it at 850°C (1562°F) for 30 minutes, quench in oil until reaching 65°C (149°F) (important: in the case of shafts, dip it in vertically to avoid distortions), and soon afterwards temper at 480°C (896°F) for 2 hours.

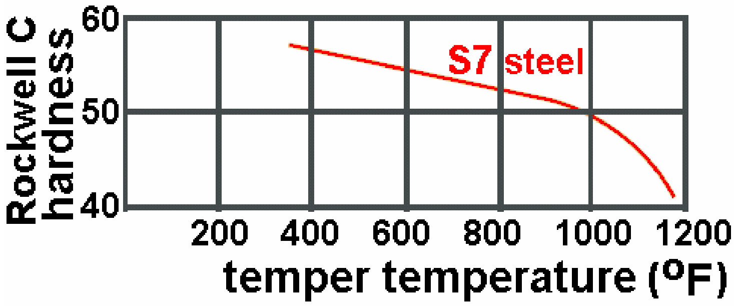
- AR400 steel: high hardness steel once used in the wedge of the famous middleweight Devil's Plunger, until it was replaced with titanium. AR stands for abrasion resistant, and 400 is its Brinell hardness. AR400 has almost the same mechanical properties as 4340 steel hardened to 43 Rockwell C, which is equivalent to 400 Brinell. It is also known as Hardox AR400 steel.

- 5160 steel: steel with 0.60% of carbon, it contains chrome and manganese. Called spring steel, it has excellent impact toughness. It is usually used in heavy applications for springs, especially in the automotive area, such as leaf springs for truck suspension systems. The spinning bars of our middleweights *Ciclone* and Titan are made out of heat treated 5160 leaf springs. Be careful with the HT, the harder it gets, the lower the impact toughness – during the RoboCore Winter Challenge 2005 competition, *Ciclone*'s spinning bar was severely HT to reach a 53 Rockwell C hardness, so hard that it broke against the rammer *Panela* due to the reduced impact toughness. After that, we changed the HT without having any problems. The ideal hardness for 5160 steel in combat applications is between 44 and 46 Rockwell C, this is what we use now for *Ciclone* and Titan. Our recipe is to heat it up and keep it at 860°C (1580°F) for 30 minutes, quench in oil until reaching 65°C (149°F) (important: in the case of spinner bars, dip it in horizontally to keep any spring-back effects symmetrical, preventing unbalancing effects), and soon afterwards temper at 480°C (896°F) for 2 hours.

- stainless steels: they are steels with more than 12% in weight of chrome, which forms a protective film that prevents corrosion. There are 60 types of stainless steel (SS), the most used one is the SS type 304, also called 18-8 for having 18% of chrome and 8% of nickel. It has an excellent combination of impact toughness and resistance to corrosion, and it doesn't need to be HT. SS 304 is a good material for the robot armor (despite being heavy) because, besides being very tough, it increasingly hardens after suffering impacts and deformations. However, SS 304 is easily deformed, making its resilience low, therefore avoid using it in parts that significantly lose functionality if bent or distorted such as shafts. There are other SS with higher resilience, they are the martensitic SS, the most famous of them are the types 410, 420 and 440: they need to be HT, after which they reach high S_y and S_u, however their impact toughness is usually much lower than the one from 304. High end stainless steels are the precipitation hardened (PH) types, such as 17-7PH and 15-5PH, which are necessary mostly in high temperature applications.

- tool steels: tool steels can reach very high hardness values after HT. They are used to make tools and metal dies, however most of them have low impact toughness. The exceptions are the tool steels from the S series (S meaning Shock), which have a high impact toughness in addition to hardness, to be used in chisels, hammers, stamping dies, and applications with repetitive impacts. The S1 and S7 steels are the most used tool steels in combat robots, respectively in Brazil and in the US. They are mainly used in the weapon parts that get in contact with the opponent. The teeth from *Touro*'s drum are made out of S7 steel, as well as the spinning blade of the middleweight Hazard, pictured to the right. They are not too expensive, S1 steel can be found in Brazil for about US$13/kg (almost US$6/lb), while S7 steel can be found in the US at, for instance, www.mcmaster.com. Regarding HT, several robot builders adopt hardnesses varying between 52 and 60 Rockwell C (HRc) for S7 steel. Our recipe for S7 steel is to pre-heat up to 760°C (1400°F), equalize the temperature throughout the entire piece, continue heating up and keep it at 950°C (1742°F) for 30 minutes, then quench in oil (S7 can also be quenched in air, which is good to avoid warping due to the thermal shock with the oil) until 65°C (149°F), and immediately temper at a certain temperature for 2 hours. After cooling, it may be tempered again for 2 hours at the same temperature, what is

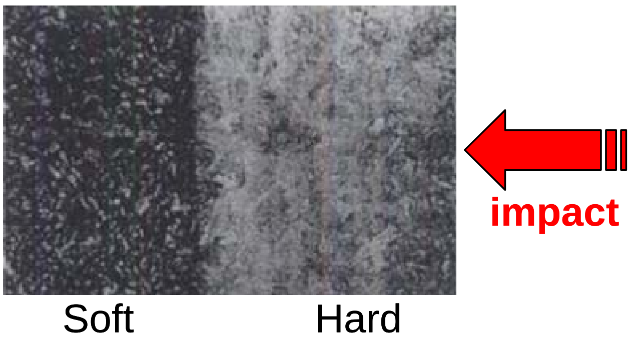
called a double temper, instead of a single one. The temper temperature depends on the desired hardness, see the graph to the right for single-tempered S7 steel: for a hardness value close to 60 HRc, use 392°F (200°C), while for values close to 52 HRc use 752°F (400°C). We've realized that there is a peak in impact toughness of the S7 steel at exactly 54 HRc, which can be achieved with a single temper with temperature around 600°F (315°C). Impact tests performed on standard unnotched Charpy specimens made out of S7 at different tempers showed that they would absorb 309 J (Joules) of impact energy before breaking when at 54 HRc. "Nothing more, nothing less than 54 Rockwell C," as experienced builder Ray Billings once told us. This is because at either 56 or 52 HRc the absorbed energy drops to less than 245 J. This energy would rise back again beyond 300 J only for lower hardnesses, below 51 HRc (324 J for 50HRc and 358 J for 40HRc). Therefore, the best cost-benefit to have both impact toughness and hardness at high levels, to prevent the component from breaking while retaining its sharpness, is to use S7 steel at exactly 54 HRc. Not 55 HRc. Not 53 HRc.



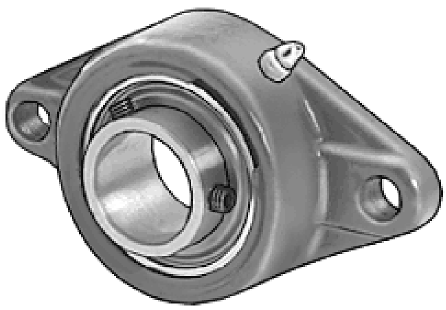
- AerMet steels: it is a class of special high strength steels with high nickel and cobalt content, patented by the Carpenter company (www.cartech.com). There are 3 types with increasing hardness but decreasing toughness: AerMet 100, AerMet 310 and AerMet 340. The most famous of them, AerMet 100, is replacing older special nickel-cobalt steels such as AF1410 and HP-9-4-30. After HT it reaches hardnesses from 53 to 55 Rockwell C, with 2.15 times higher impact toughness than S7 steel. It is probably the metal with best ultimate strength and fracture toughness combination in the world at the present time, with S_u = 1964MPa and K_{Ic} = 130MPa$\sqrt{m}$ (after HT). AirMet 100 is used in the lifting mechanism of the heavyweight BioHazard, enabling it to save weight using a compact 3/4" diameter shaft. It was also used in the output shaft of the 24V DeWalt Hammerdrill gearbox, as pictured to the right. As one would expect, it is very expensive, more than US$55/kg (US$25/lb) in the US. To obtain its best properties, heat it up to 885°C (1625°F) for 1 hour, cool to 66°C (150°F) in 1 to 2 hours using either oil quenching or air cooling, then refrigerate to –73°C (–100°F) and hold for 1h. Then heat at 482°C (900°F) for 5 hours, never below 468°C (875°F), and finally air cool.

* maraging steels: it is a class of special high strength nickel-cobalt-molybdenum steels with very low carbon content. There are four commercial types, all of them with 18% nickel: 18Ni(200), 18Ni(250), 18Ni(300) and 18Ni(350), with S_y equal to 1400, 1700, 2000 and 2450MPa, respectively, after HT. To obtain these S_y properties, heat to 900°C (1650°F) and hold for at least 1 hour, air cool to room temperature, then heat for 3 hours at 482°C (900°F), and finally air cool. The 18Ni(350) needs 12 hours (instead of 3) at 482°C. Together with the AerMet alloys, these are the best steels for high strength and high toughness applications, however they are also expensive, between US$42/kg (US$19/lb) and US$64/kg (US$29/lb) in the US, at www.onlinemetals.com. The 18Ni(200) can reach higher K_{Ic} than AerMet 100, but 24% lower S_u. The 18Ni(250) is a reasonable replacement for AerMet 100, but with 10% lower S_u and K_{Ic}. The 18Ni(350) is recommended for low impact applications because it has one third of the K_{Ic} of AerMet 100, but its S_u can almost reach the incredible mark of 2500MPa.

* K12 Dual Hardness steel: it is an armor plate with dual hardness sold by Allegheny Ludlum, with a high hardness front side to break up or flatten incoming projectiles, and a lower hardness back side that captures the projectile. The front side has a higher carbon content, reaching 58 to 64 Rockwell C hardness after heat treatment, metallurgically bonded to a lower carbon back side that reaches 48 to 54 Rockwell C, as pictured in the cross section to the right. With the hard front side facing out of your robot, you'll be able to break up or chip any sharp edges from your opponent's weapon, while the inner "softer" side will provide high toughness and prevent fractures. A careful and precise heat treatment is required to achieve optimum performance.



* cast irons: they are basically steels with more than 2.5% of carbon content. The carbon excess ends up generating graphite inside the microstructure, which is very brittle (anyone who's used a pencil knows that). In combat robots they are used in bearing housings and in a few gears. Be careful with this material, it has a low impact toughness – the 2004 version of our spinner *Ciclone* used cast iron flanged housings (pictured to the right) to hold the bearings of its weapon shaft, however one of them cracked from its own impact against other robots. Luckily, it still resisted until the end of the competition, despite the cracks. Since 2005 we've stopped using cast iron housings, and started to embed the weapon shaft bearings into the aluminum plates of the robot structure. We haven't had cracking problems with bearing housings ever since.



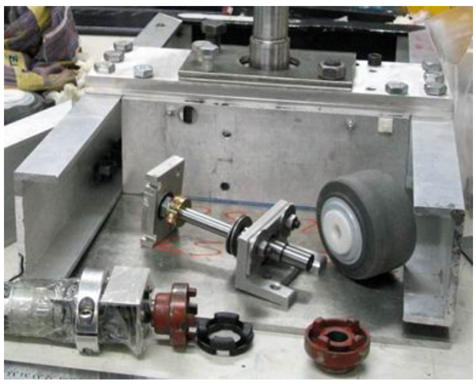
3.3. Aluminum Alloys

Aluminum is a very light metal, it has about 1/3 of the density of steels, about 2.8, which makes it very attractive for the robot structure. Its stiffness is also around 1/3 of the one of steels, with a Young modulus E ≅ 70GPa. Many types of aluminum exist, usually denominated by a 4 digit number. The aluminum alloys from the 1000, 3000 and 5000 series (for instance the aluminum 1050, used in electric equipment, the 3003, used in kitchen utensils, and the 5052, resistant to sea corrosion) are low strength and should not be used in combat. Cast aluminum is even less resistant, and it should be avoided – the wheels of the 2004 version of our middleweight *Ciclone* were made out of cast aluminum and rubber, luckily they didn't break but they most likely would if hit by another spinner.

A few aluminum alloys from the 6000 series (such as the 6061-T6 and 6351-T6) have medium strength, becoming a reasonable choice for the robot structure. The alloys from the 2000 and 7000 series (such as the 2024-T3 and the 7075-T6) are called aerospace or aircraft aluminum due to their extensive use in aircrafts. With high S_y and S_u, they are naturally the most expensive. The 7000 series alloys usually have higher S_y and S_u than the 2000 series, but sometimes this comes along with a lower fracture toughness.

Aluminum alloys already come heat treated from factory, which saves us time and money when building a combot. Be careful with the denominations with the letter T, the number after it indicates which heat treatment was used: for instance, the aluminum 6061-T6 has much higher strength than 6061-T4, which suffered a different HT. The main types of aluminum alloys are discussed next.

- 6063-T5 aluminum: it is the aluminum alloy used in almost all the architectural extrusions in the market, because it has high corrosion resistance, and it is relatively cheap. However, it has low strength, therefore avoid using it in the robot external structure. It can be used in the internal structural parts, to stiffen the robot or to support batteries. Because all aluminum alloys have roughly the same stiffness (due to their Young modulus always close to 70GPa), the 6063-T5 is as effective as any other more expensive aluminum alloy to stiffen the structure, its problem is just its low strength. Note that stiffness and strength are two different things: for instance, glass is much more rigid than Lexan (polycarbonate), however Lexan has a much higher ultimate tensile strength than glass. Several internal parts from our middleweight *Touro* are made out of 6063-T5 extrusions. Because it is difficult to find in Brazil C-channels or I-beams made out of structural aluminum such as 6061-T6, the side walls of our middleweight *Ciclone* ended up using 6063-T5 extrusions, as pictured to the right – but, to make up for that, they were reinforced with an outer layer of grade 5 titanium sheet. Depending on the quantity, 6063-T5 (or 6063-T52) costs between US$6 and US$13 per kg (between US$2.7 and US$5.9 per lb). A few stores only sell extrusions in 6 meter lengths.



- 6061-T6 aluminum: it is the most common structural aluminum alloy, used in several applications such as bicycle frames, structures, naval and truck components. It has medium strength, about twice the S_u of 6063-T5, and it can also be welded. Compared to aerospace alloys, 6061-T6 has lower S_y and S_u strengths, with a similar impact toughness. Its greatest advantage is its good weldability, much better than in most aerospace aluminum alloys. All the famous robots from Team Plumb Crazy are made out of 6061-T6 extrusions, as pictured to the right, as well as our hobbyweights *Tourinho* and *Puminha*. Extrusions can be found in the US, for instance, at Online Metals (www.onlinemetals.com).

- 5083-H131, 5086-H116, 5086-H32 aluminum: despite their low yield strength, common to the marine alloys of the 5000 series, they have such a high impact and fracture toughness that they are used as armor plates in light weight military vehicles. They are good material candidates for very thick armor plates.

- 2024-T3, 7050-T7451, 7075-T6, 7075-T73, 7475-T7351 aluminum: high strength aerospace alloys, with about 3 times the strength of 6063-T5. They are useful for structures that demand high strength-to-weight ratio, usually to manufacture truck wheels, fuselage of airplanes, screws, orthopedical belts, and rivets. They are the best commercially available aluminum alloys, in Brazil the 7050-T7451 and 7075-T6 cost around US$17/kg (almost US$8/lb). Considering that a middleweight with its entire structure made out of aluminum would need around 15kg (33lb) of this material, about US$250 would be enough to build it using the best aerospace alloys available, a good investment with a relatively low cost.

- 2324-T39 Type II, 2524-T3, 7039-T64, 7055-T74, 7055-T7751, 7085-T7651, 7150-T77, 7175-T736, 7178-T6 aluminum: high end aluminum alloys with improved mechanical properties over the traditional aerospace alloys. They are not readily available commercially.

- Alusion – very light aluminum foam (pictured to the right), available in several densities. Despite its low strength, it can be used as thick ablative armor plates mounted on top of the robot structure.

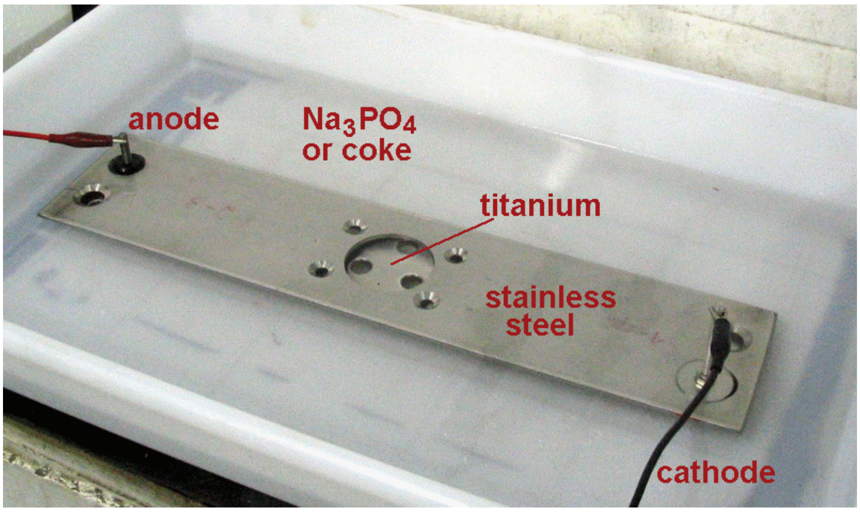
3.4. Titanium Alloys

Titanium is one of the best materials for combat robots. With little more than half the density of steels (between 4.4 and 4.6), it reaches strengths 2.5 higher than 1020 steel. Or up to four times higher in a few military grade titanium alloys, making their strength-to-weight ratio so attractive that they're used in 42% of the F-22 fighter aircraft. Its Young modulus is $E \cong 110GPa$, about half the one of steels. They are non-magnetic, non-toxic, and extremely resistant to corrosion, even in the presence of biological fluids, which explains their use in prosthetics and medical implants. Titanium generates beautiful white sparks when it is ground. Care should be taken with titanium chips from machining, they are flammable. We've carefully made several mini-bonfires with titanium chips in our lab, they generate a very intense white light.

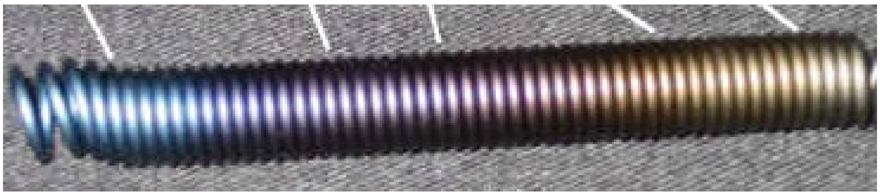
Titanium alloys are difficult to cut and drill. The secret to drill them is to use low spindle speeds in the drill and a lot of pressure on the part (always use a bench drill with them, never a manual one). And, most importantly, do not let the piece get hot, therefore use plenty of fluid. If there is heat build-up, titanium forms a thin oxide layer that is harder than the drill bit, and then several bits will be worn-out in the process. Use special cobalt drill bits to drill titanium, they will last longer. Practice is also important.

A curiosity about titanium (as well as niobium) is that its surface can be colored without paints or pigments, just using Coke (or Pepsi) in a technique called electrolysis or anodizing. The figure to the right shows an artistic painting made on a titanium plate. Note the range of colors that it is possible to obtain.

To color it, you need a piece of stainless steel (SS) with equal or larger area than the one of the titanium to be colored, a SS screw, a titanium screw, Coke, and a DC power source (of at least about 30V). The scheme is pictured to the right. Polish well the titanium surface and clean it with alcohol or acetone – do not leave any fingerprints. Place the titanium part (which will be the anode) and the SS one (the cathode) submerged in Coke (the electrolyte, which can also be replaced with Trisodium Phosphate Na_3PO_4), very close together but without making contact. Make sure the titanium screw is in contact with the titanium part to be colored but not with the SS plate (we used a rubber grommet to guarantee this, as shown in the picture), and the



SS screw only touches the SS piece. Connect the positive of the DC power source to the titanium screw and the negative to the SS one, without letting the wire contacts touch the electrolyte. Apply a certain DC voltage between 15 and 75V for a few seconds and it is done, the titanium part is colored!



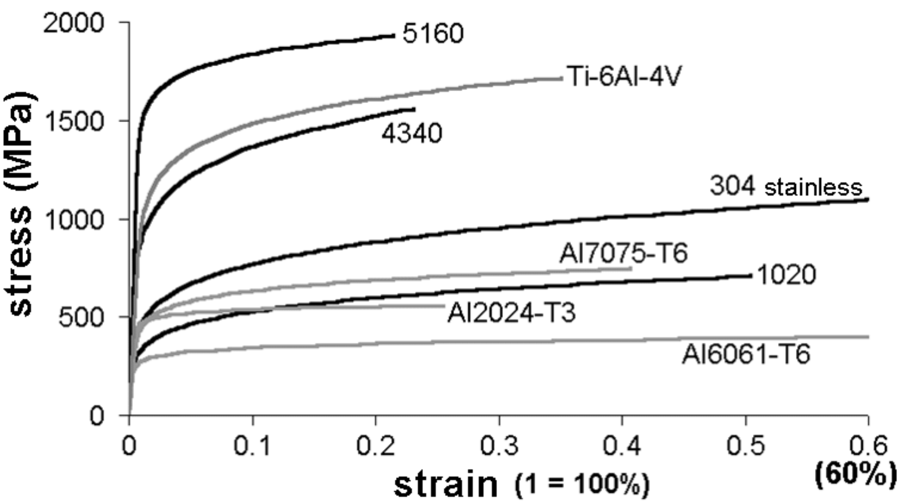
A few of the colors that can be obtained are pictured to the right. The titanium color obtained by the electrolysis process depends on the applied voltage. The higher the voltage, the thicker will be the titanium oxide layer that is formed on the plate (anode), changing its color. This color change happens because the oxide layer causes diffraction of the light waves. The colors are gold (applying 15V), bronze (20V), purple (25V), blue-purple (30V), light blue (35V), white bluish (40 to 45V), white greenish (50V), light green (55V), yellow-greenish (60 to 65V), greenish gold (70V) and copper (75V). There are other colors up to 125V, but they are opaque, not very brilliant.

Coke works well, but it is not the best electrolyte. We've discovered that Diet Coke is a little better because it doesn't have sugar, which accumulates on the contacts. But the best option would be to use Trisodium Phosphate (Na_3PO_4, known as TSP), diluted at about 100 grams for each liter of distilled water (about 13oz/gallon). Besides being transparent (which allows you to see the colors as you increase the voltage), TSP is a detergent that helps to keep the titanium surface clean during the electrolysis, resulting in a more uniform color. In the picture to the right you can see Titan's side walls, the top two plates before the process and the bottom one after being colored using TSP and 30V. Note the masking that we've used on the top plate, written TiTAN, made out of waterproof adhesive contact paper. The mask protects the region during electrolysis, leaving afterwards letters with the original color of the titanium (as it can be seen in "RioBotz" written on the bottom plate).

Commercially pure titanium, the most common of which is grade 2 titanium, has lower strength and higher density than aerospace aluminum, therefore it should not be used in combat robots. Use only high strength alloys such as grade 5 titanium, known as Ti-6Al-4V. Ti-6Al-4V has twice the strength of the best aerospace aluminum alloys and much higher impact toughness, with only 60% higher density. However, when welding grade 5 titanium, it is a good idea to use grade 2 as a filler material. This is because welds are prone to cracking due to thermally induced residual stresses, and grade 2 titanium filler, despite its lower strength, has a higher ductility that prevents such cracks and improves the overall impact and fracture toughness.

Ti-6Al-4V is also known as Ti-6-4, for having 6% aluminum and 4% vanadium in weight, mixed with 90% titanium. It is the most used high strength titanium alloy, combining excellent mechanical strengths and corrosion resistance with weldability. It is extensively used in the aerospace industry in a variety of applications in turbines and structural components up to 400°C (752°F). It can be heat treated (STA – Solution Treated and Aged), however the increase in ultimate strength is small, with the drawback of a 43% lower K_{Ic}. In practice, most combat robots use Ti-6-4 in the annealed condition, without further heat treating. It is usually available in the mill annealed condition. It can also be found in other two annealed conditions: recrystallization anneal (8% higher K_{Ic}) or beta anneal (33% higher K_{Ic} but much lower S_u). Unfortunately, titanium grade 5 is expensive, about US$55/kg to US$80/kg (US$25/lb to US$36/lb). Notorious resellers are Titanium Joe (www.titaniumjoe.com), President Titanium (www.presidenttitanium.com), and Tico Titanium (www.ticotitanium.com).

Ti-6-4 has an unbelievable impact and fracture toughness for its weight, we've used it in all side walls and bottom plate of our spinner Titan, as armor plates covering the aluminum walls of *Touro* and *Ciclone*, and in the wedges of Titan and *Puminha*. If you need an even higher fracture toughness, you could use the more expensive Ti-6Al-4V ELI (Extra Low Interstitial), which presents lower impurity limits than regular Ti-6Al-4V, especially oxygen and iron. The lower oxygen content increases the fracture toughness in 22% over mill annealed Ti-6Al-4V, however it lowers in about 10% the yield and ultimate strengths.



The graph to the right shows a comparison among steels, aluminum alloys and Ti-6Al-4V titanium used in combat robots, through their stress-strain curves. The curves stop at the strain where the material breaks. Remember that the higher the curve gets, the larger the S_u strength to static loads until rupture. The farther the curve gets to the right, the higher the material can be plastically deformed before breaking, in other words, the higher their ductility and their ε_f. Note that the 7075 and 2024 aluminum alloys behave in a similar way to the 1020 steel (except for their lower impact toughness), however with only 1/3 of the weight. The stainless steel 304 has the largest area under the curve, resulting in a very high impact toughness, however it begins to yield under relatively low stresses. Note from the areas under the curves that Ti-6Al-4V has similar impact toughness to 5160 steel, but with almost half the weight.

3.5. Magnesium Alloys

Magnesium is the third most used structural metal, after steels and aluminum alloys. The magnesium alloys ZK60A-T5 and AZ31B-H24 are excellent for the robot structure, because they have strength similar to 6061-T6 aluminum however with only 65% of its weight: the density of the magnesium alloys is only about 1.8, instead of 2.8 from aluminum. Their Young modulus is relatively low, $E \cong 45$GPa, however their low density allows the use of very thick plates, resulting in very high stiffness-to-weight ratios. The impact toughness of the best magnesium alloys is similar to the one of high strength aluminum alloys.

The largest drawback of magnesium alloys is their extremely poor corrosion resistance: magnesium is in the highest anodic position on the galvanic series. Also, when tapping magnesium, choose coarse instead of fine threads to avoid stripping.

The ZK60A-T5 (US$62/kg or US$28/lb for small quantities) is the commercially available magnesium alloy with highest fracture toughness, however it is difficult to find large plates of that material. The alloy AZ31B-H24 (US$42/kg or US$19/lb for small quantities) is a little less resistant, but it is easier to find. The heavyweight lifter BioHazard has used these magnesium alloys to stay under the weight limit.

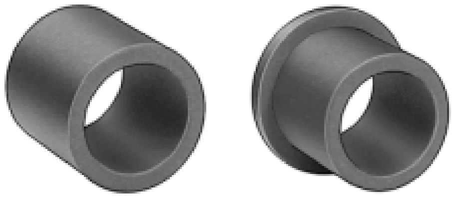
There are other magnesium alloys, such as Elektron WE43-T5 and Elektron 675-T5, however all of them have lower fracture toughness than ZK60A-T5 and AZ31B-H24. The new experimental alloy Elektron 675-T5, which was in its final stages of development in 2008, has the highest ultimate strength of all Mg alloys, $S_u = 410$MPa.

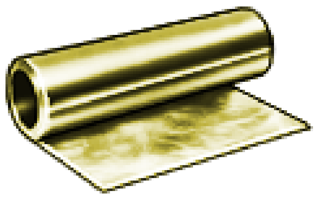
Note that there are often misconceptions regarding the flammability of magnesium and its alloys. It may ignite when in a finely divided state such as powders, shavings from magnesium fire starters (pictured to the right), ribbon or machined chips, exposed to temperatures in excess of 445°C (833°F, the lowest Solidus temperature of all Mg alloys). However, in solid form, magnesium is very difficult to ignite. It has a high thermal conduction, quickly dissipating any localized heat. Also, most alloys self extinguish in the event of ignition, because of the oxide skin that forms over any molten alloy (in special in the presence of yttrium, such as in the two mentioned Elektron alloys). In practice, magnesium alloy ignition only happens due to sustained major fires (such as major fuel fires following an accident), similarly to aluminum ignition. The US Army is starting to use thick magnesium alloy plates as armor in its light weight vehicles, without any problems even during severe ballistic tests.

3.6. Other Metals

A few other metals than can have structural application are:

- copper alloys: copper is an excellent electric conductor, and the bronze alloys (a copper alloy with, usually, tin) it generates are great for statues – but not for the structure of combat robots. Besides having lower strength than most steels, copper alloys are heavier, with density around 9.0. Bronze bushings (pictured to the right, showing the regular and flanged types), on the other hand, are a good option to be used as plain sleeve bearings in shafts for the wheels and weapons. The SAE 660 bronze, a.k.a. alloy 932, is hard, strong and nonporous, offering excellent resistance to shock loads and wear, it is the best option for sleeve bearings under high impact loads. Another option is the SAE 841 bronze, a.k.a. Oilite, a porous sintered material impregnated with roughly 18 percent SAE 30 oil – it is cheaper and it provides less friction than SAE 660, but it has lower strength and impact toughness. Brass (a copper alloy with zinc) also has low strength, but it is an excellent material for shim stock (pictured to the right), to be inserted in between parts to avoid slacks.





- nickel superalloys: they are a little heavier than steels, and they only present advantages if used at very high temperatures. The best superalloys can retain their high strength even at up to 80% of their melting temperatures. They can easily work at temperatures between 700 and 1000°C (1292 to 1832°F), which is great for components inside jet engines, but useless for combat, unless the competition is held in Venus or Mercury.

- beryllium alloys: theoretically, they are by far the best metals in the world to make a light and rigid structure. A few alloys such as the S-200 have Young modulus E = 303GPa (more than 4 times the stiffness of aluminum alloys) with density lower than 1.9. They find applications in nuclear reactors, inertial guidance instruments, computer parts, aircraft, and satellite structures. They would be a marvel in combat except for three problems: they are relatively brittle; beryllium must be processed using powder metallurgy technology, which is costly; and beryllium powder and dust, which can be released during the machining process, as well as in the wear and tear during combat, is highly toxic and cancerous. Because of that, competitions usually forbid their use. Do not use it, berylliosis disease can kill you. A curious fact is that beryllium and its salts taste sweet. Early researchers (who are not among us anymore) used to taste beryllium for sweetness to verify its presence. This is why it used to be called glucinium, the Greek word for sweet. Do not taste it, just take my word that it is sweet.

- tungsten alloys: very high density alloys, their application in combat robots is mainly for counterweights of spinning weapons. Tungsten, meaning "heavy stone" in Swedish, has in its pure form an amazing 19.35 density, with the highest melting point at atmospheric pressure among metals (3,422°C or 6,192°F), losing only to diamond's 3,547°C (or 6,416°F). It has also the lowest coefficient of thermal expansion of any pure metal. In its raw state, it is brittle and hard to work. However, when alloyed with 3% to 10% of nickel, copper and/or iron, it becomes relatively tough, extremely machinable, and it reaches ultimate strengths S_u between 758MPa and 848MPa. Their machining properties are similar to gray cast iron These tough high density alloys are known as ASTM-B-777-07 or Densalloy, with 4 different classes: class 1 (or HD17, with 90% tungsten, and a density of 17), class 2 (HD17.5, 92.5% tungsten, 17.5 density), class 3 (HD18, 95% tungsten, 18 density) and class 4 (HD18, 97% tungsten, 18.5 density). They can be found, for instance, at www.mi-techmetals.com, www.marketech-tungsten.com or www.hogenindustries.com, with a typical price between US$50 and US$100 per pound for special orders in small quantities. Small inexpensive tungsten weights can be found at www.maximum-velocity.com.

- other high density alloys: besides tungsten, there are several other high density alloys, however they're all extremely expensive. They usually have low strength, low toughness, or they are too dangerous to use in combat. The most famous high density materials are tantalum (with density 16.65 and reasonable mechanical properties with S_u greater than 450MPa), depleted uranium (density 18.95, reasonable S_u between 615MPa and 740MPa, toxic, used in tank armor and armor-piercing projectiles), gold (density 19.32, ductile but with low strength due to S_u = 120MPa), rhenium (density 21.04, good mechanical properties, S_u = 1070MPa), platinum (density 21.45, S_u = 143MPa, low strength), iridium (density 22.4, S_u = 1000MPa, brittle), and osmium (the material with highest density, 22.6, about twice the density of pure lead, with S_u = 1000MPa, very brittle and toxic).

- metallic glasses: they are amorphous metals, which have a disordered atomic-scale structure similar to common glasses, in contrast to most metals, which are crystalline with a highly ordered arrangement of atoms. They can be produced from the liquid state by a cooling process so fast that the atoms don't have time to organize themselves as crystals. They usually contain several different elements, often a dozen or more, causing a "confusion effect" where the several different sized atoms cannot coordinate themselves into crystals. Also, they don't have a melting point. Instead, they become increasingly malleable as the temperature increases, just like most plastics, making them good candidates for injection molding. Liquidmetal is a company that sells glassy metals such as Vitreloy, an alloy with mostly zirconium and titanium that reaches S_y = 1,723MPa, nearly twice the strength of Ti-6Al-4V. But since the atoms are "locked in" in their amorphous arrangements, most currently available glassy metals cannot plastically deform at room temperature, resulting in low impact strength, which limits their use in combat. They also have a coefficient of restitution close to 1, meaning almost perfectly elastic impacts. Versions with improved impact toughness could be created in the future by embedding ductile crystalline metal fibers into the metallic glass, forming a metal matrix composite (as discussed later). In 2004 the first iron-based metallic glass was created, called "glassy steel," with very high strength.

3.7. Non-Metals

Several non-metals need to be mentioned in combat robot design. The main ones are:

- polycarbonate: also known as Lexan, it is a polymeric thermoplastic (which softens and melts when heated, instead of burning), transparent to light waves and radio-control signals. It has high impact toughness, and it is very light, with density 1.2. It is used in combat robot armor, it absorbs a lot of energy as it is deformed during an impact. In spite of that, fewer and fewer robots have been using this material, because of its disadvantages: it has very low Young modulus (E = 2.2GPa, about 1% of the stiffness of steels, making the robot structure very flexible even for high thicknesses), it easily cracks (the cracks usually appear starting from the holes, and they propagate without absorbing much of the impact energy), and it is easily cut (becoming vulnerable to sawbots). To avoid cracking, chamfer all holes to remove sharp corners and edges, and provide the Lexan support with some damping, for instance using a thin layer of rubber or neoprene. Avoid tapping Lexan, if you must do it then guarantee that the hole is tapped very deeply with several threads, or else they might break. Never use threadlockers such as Loctite 242 in Lexan, because besides not locking, it causes a chemical reaction that makes it brittle. Acetone should also be avoided.

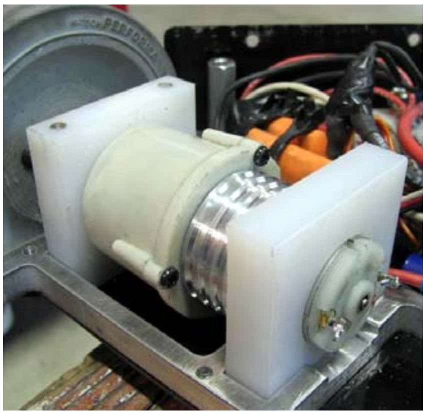
  Very thin sheets of Lexan make great drilling templates for top and bottom covers of the robot. This classic technique is very simple: once all the robot walls are finished and assembled, firmly attach the Lexan sheet on top of it, as if it were a robot cover. Since Lexan is transparent, it is easy to mark with a center punch the centers of the holes to be drilled, which must align with the already finished holes from the walls. If the Lexan sheet is very thin, it will bend as a cone into the holes from the walls as it is pressed by the center punch, improving the centering precision. After marking all hole centers, the Lexan sheet is ready to be fixed on top of the actual cover plates to be drilled.

- acrylic: good to build fish tanks, but do not use it in combat, because it has the same density as Lexan but with 20 to 35 times less impact toughness.

- PETG: it is a modified type of PET (polyethylene terephthalate) with an impact toughness in between the values for acrylic and Lexan. It is a cheap substitute for Lexan, but with worse properties. We've tried it in combat, and decided that it would be better used to make a nice transparent trophy shelf.

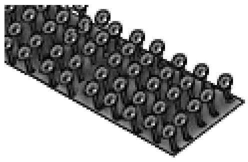
* Teflon (PTFE, politetrafluorethilene): very low friction, it can be used as a sliding bearing for moderate loads, or as a skid under the robot to slide in the arena. Its main problem is its high cost.

* UHMW: Ultra High Molecular Weight polyethylene is a high density polyethylene that also has very low friction. Known as the "poor man's Teflon," it doesn't slide as well as Teflon, but it is cheap and it has higher strength. Shell spinners, such as Megabyte, use internal spacers made out of UHMW (circled in red in the picture to the right) between the shell and the inner robot structure, guaranteeing that the shell won't hit the internal metal parts of the robot even if it is bent, allowing it to slide with relatively low friction in case it makes contact. The high toughness of UHMW makes it a good choice even for structural parts, such as the motor mounts of the hobbyweight Fiasco, as pictured to the right.



* nylon, delrin (acetal): they are thermoplastic polymers with high strength, low density and relatively high toughness. They are good for internal spacers in the robots, and even as motor mounts, similarly to UHMW.

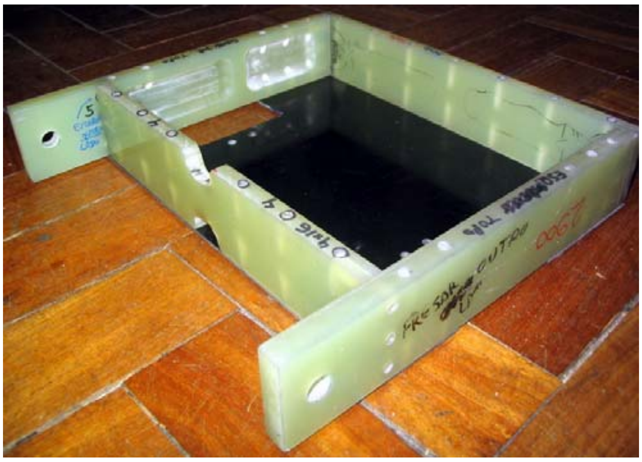
* rubber, neoprene, hook-and-loop (velcro): excellent materials to dampen the robot's critical internal components, such as receiver, electronics and batteries. High-strength mushroom-head hook-and-loop (pictured to the right) is also excellent to hold light components.



* epoxy: excellent adhesive, good to glue fiberglass, Kevlar and carbon fiber onto metals. Clean the metal part with alcohol or acetone before applying it, to maximize holding strength. Always use professional epoxy, which cures in 24 hours, not the hobby grade.

* phenolic laminate: it is an industrial laminate, very hard and dense, made by applying heat and pressure in cellulose layers impregnated with phenolic synthetic resins, agglomerating them as a solid and compact mass. Also known as celeron, it is an excellent electric insulator. We mount all the electronics of our robots on such laminates, which are then shock-mounted to the robot structure using vibration-damping mounts (see chapter 4) or mushroom-head

hook-and-loop, resulting in electrical insulation as well. The regular phenolic laminates are relatively brittle, but a high strength version called garolite (available at www.mcmaster.com) has already been used even in the structure of antweights and beetleweights. The top cover of our beetleweight *Mini-Touro* was made out of garolite, however it was replaced with a titanium cover with same weight. Although thinner, the titanium top cover has a higher impact strength than the garolite version, which is important when facing offset horizontal spinners that know how to skillfully pop a wheelie to deliver an overhead attack with their weapon. The first prototype of our hobbyweight *Tourinho* was made out of garolite (a green variety for the side walls and a black one for the top and bottom covers, as pictured to the right), transparent to radio signals and very resistant. However, we ended up changing it to aluminum for two reasons: the threads tapped in garolite, or in any other phenolic laminate, are brittle and easily break, and the better impact toughness of aluminum made up for its increased density (aluminum has density 2.8, and garolite 1.8).



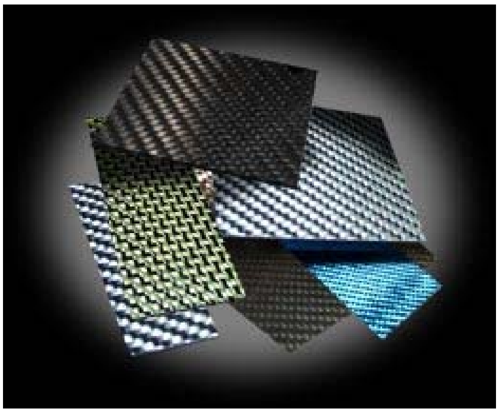
- wood: it has low impact toughness if compared to metals. It should not be used in the structure, unless your robot is very skillfully driven, such as the wooden lightweight The Brown Note, which got the silver medal at Robogames 2008 after losing to the vertical spinner K2 (pictured to the right). A few builders have mounted wooden bumpers in front of their robot when facing spinners, to work as ablative armor: while a shell spinner chews up the wooden bumper of its opponent little by little, it loses kinetic energy and slows down, becoming vulnerable.

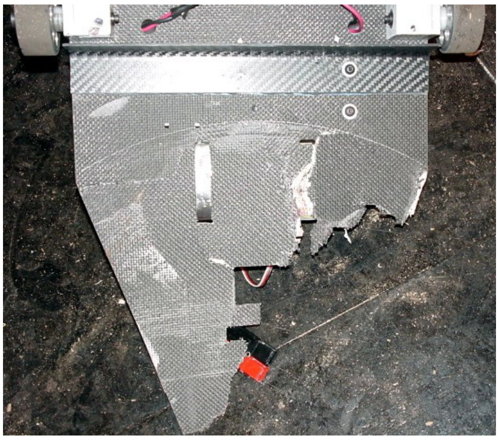
- ceramics: they are very brittle under traction, but under compression they are the most resistant materials in the world, so much that they are used underneath the armor plates of war tanks: the ceramic breaks up the projectiles, while their fragments are stopped by an inner steel layer. Ceramics are also extremely resistant to abrasion. The famous lifter BioHazard used 4” square 0.06” thick alumina tiles (Al_2O_3, which forms sapphires when in pure form) glued under its bottom to protect it against circular saws that emerged from the BattleBots arena floor.

* fiberglass: known as GFRP (glass fiber reinforced polymer), it is made out of very thin glass fibers held together by a polymeric adhesive (known as the polymer matrix) such as an epoxy resin. It is very used in boats. It has potential use in the robot structure for being rigid and light, however its impact toughness is low if compared with the one of most metals.

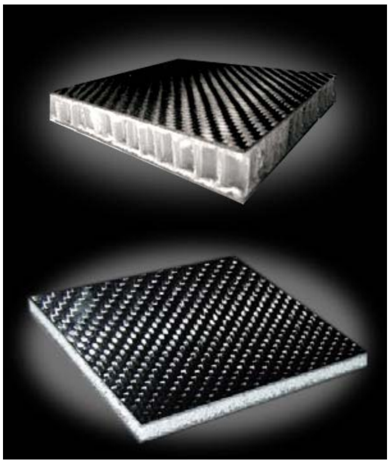
* Kevlar: known as KFRP (Kevlar fiber reinforced polymer), it is a yellow fabric (pictured to the right) made out of aramid fibers, a type of nylon, 5 times more resistant than steel fibers of same weight. Used in bulletproof vests, it has extraordinary impact toughness. *Touro* uses a Kevlar layer covered with professional epoxy (the polymer matrix) sandwiched between the aerospace aluminum walls of the structure and the external Ti-6Al-4V plates of the armor, to increase its impact toughness. The fabric is very difficult to cut, it is recommended to use special shears, found at www.mcmaster.com. Kevlar fabric is not expensive, we've used less than US$12 in *Touro* – more specifically, we've used the aramid fabric KK475, which costs about US$60/m^2 (less than US$6/ft^2) in Brazil.

* carbon fiber: known as CFRP (carbon fiber reinforced polymer), and available in several colors (as pictured to the right), it is very expensive but extremely rigid and light, and because of that it has been used in racing cars and in the fuselage of the new Boeing 787 and AirBus A350 (pictured in the next page). It is excellent to mount the robot's internal parts due to its high stiffness. But it is a myth that carbon fiber has high impact toughness. It surely has a high strength under static loads, but it does not take severe impacts. The undercutter Utterly Offensive is a good example of that, its carbon fiber baseplate (pictured to the right) self-destructed when it was scraped by its own spinning blade. The plate was later switched to titanium. Carbon fiber is not a good armor material, unless it is combined with Kevlar to achieve high impact toughness. Surely you could get away without Kevlar, using a very thick carbon fiber armor plate, but probably the added weight would have been better employed using, for instance, a titanium armor.





- other polymer matrix composites: there are several other composites that use a polymer matrix (such as epoxy or polyester) besides plain GFRP, KFRP and CFRP. For instance, you can tailor lay-ups of aramid and carbon fibers, cured (bonded) together with a polymer matrix, to achieve optimum impact toughness (due to Kevlar) and stiffness (due to carbon). It is possible to generate complex unibody structures by combining several parts into a single cured assembly, reducing or even eliminating the need for fasteners, saving weight and assembly time. This unibody can be joined together in three ways: cocuring, cobonding, or adhesive bonding. In cocuring, the uncured composite fabric plies are cured and bonded together at the same time using the same polymer matrix. In cobonding, an already cured part, usually a stiffener, is bonded to an uncured one, usually a skin, at the same time the skin is cured. In adhesive bonding, cured composites or metals are bonded to other cured composites, honeycomb cores, foam cores or metallic pieces. The pictures to the right show two very rigid sandwich panels with respectively a polypropylene honeycomb core and a polymethacrylimide foam core, sandwiched by CFRP sheets (available at The Robot MarketPlace). Besides increasing the panel bending stiffness, the foam core also works as a shock mount, increasing the impact strength, becoming a good option for the robot structure and even armor. An even higher stiffness-to-weight ratio can be obtained if the core is made out of balsa wood, as in the DragonPlate pictured to the right, however its impact toughness is relatively low.



- metal matrix and ceramic matrix composites: instead of having their fibers embedded and held together in a polymer matrix, these composites use either a metal or a ceramic matrix. The fibers (or even tiles in a few cases), which can also be made out of metal or ceramic, tend to increase the ultimate strength and stiffness of the matrix material. However, most ceramic matrix composites have low impact strength, which limits their use in combat, not to mention their very high cost. On the other hand, when part of a multi-layer composite armor plate, such as the Chobham armor, ceramic tiles embedded in a metal matrix can be very effective to shatter kinetic energy weapons.

3.8. Material Selection Principles

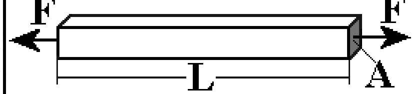
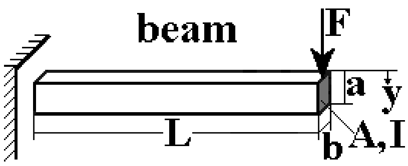
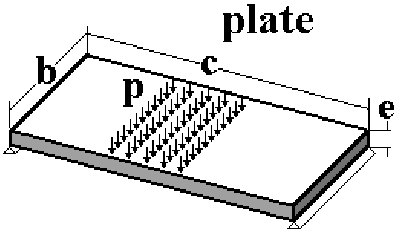
After presenting the main materials used (or not) in combat robots, the question is: which material should I use? "The most resistant" is not the correct answer. The most resistant materials per volume are steels, but a robot entirely made out of steel would be very heavy.

For instance, a 4mm (0.16") thick steel plate weighs as much as an 11mm (0.43") thick aluminum one. Which one is better, the 4mm steel or the 11mm aluminum?

The answer is not so simple. It depends on the function that the material will have, as it will be seen next.

3.8.1. Stiffness Optimization

Classic solid mechanics calculations (summarized in the table to the right) show that a beam under traction, working as a trussed element (such as in the structure of trussed robots), has the largest possible stiffness with minimum mass if the material has the largest possible ratio between the Young modulus E and the density ρ. Steels have in average E = 200GPa and ρ = 7.8, therefore E/ρ ≅ 26. Aluminum (Al) alloys usually have E = 72GPa and ρ = 2.8, thus E/ρ ≅ 26. Titanium (Ti) alloys have E = 110GPa and ρ = 4.6, resulting in E/ρ ≅ 24. And, in magnesium (Mg) alloys, E = 45GPa and ρ = 1.8, resulting in E/ρ ≅ 25. In summary, there is almost no difference in choosing among steels, aluminum, titanium or magnesium alloys for a trussed element if the only requirement is to have a high stiffness-to-weight ratio, their E/ρ ratio is very similar, between 24 and 26.

structural element type or function	min. mass for max. stiffness	strength
truss  Young modulus E specific mass ρ elastic strength S	$\Delta L=\frac{FL}{EA}$ $m=\rho LA=$ $=\frac{FL^2}{\Delta L}\frac{\rho}{E}\therefore$ maximize $\frac{E}{\rho}$	$\sigma=\frac{F}{A}$ $m=\rho LA=$ $=FL\frac{\rho}{\sigma}\therefore$ maximize $\frac{S}{\rho}$
beam  $b=\alpha a$ $A=\alpha a^2$ $I=\alpha a^4/12$	$y=\frac{4FL^3}{E\alpha a^4}$ $m=\rho L\alpha a^2=$ $=2\sqrt{\frac{\alpha FL^5}{y}}\frac{\rho}{\sqrt{E}}$ maximize $\frac{\sqrt{E}}{\rho}$	$\sigma=\frac{6FL}{\alpha a^3}$ $m=\rho L\alpha a^2=$ $=L\alpha\left[\frac{6FL}{\alpha}\right]^{\frac{2}{3}}\frac{\rho}{\sigma^{2/3}}$ maximize $\frac{S^{\frac{2}{3}}}{\rho}$
plate  load: pressure p $b=\alpha c$	$y=\frac{5pc^4}{32Ee^3}$ $m=\rho e\alpha c^2=$ $=\alpha c^3\left[\frac{5pc}{32y}\right]^{\frac{1}{3}}\frac{\rho}{\sqrt[3]{E}}$ maximize $\frac{\sqrt[3]{E}}{\rho}$	$\sigma=\frac{3pc^2}{4e^2}$ $m=\rho e\alpha c^2=$ $=\frac{\alpha c^3}{2}\sqrt{3p}\frac{\rho}{\sqrt{\sigma}}$ maximize $\frac{\sqrt{S}}{\rho}$

$S=S_y$ if material is ductile or $S=S_u$ if fragile

However, for a plate under bending, which would be the case of most of the robot structural parts, such as side walls and top/bottom covers, stiffness is maximized with minimum weight if the material has the largest possible $E^{1/3}/\rho$ ratio. In this case, magnesium alloys are much better, with ratio 2.0, against 0.8 for steels, 1.0 for titanium alloys and 1.5 for aluminum alloys. The results are summarized in the table to the right.

material	E/ρ	$E^{1/2}$/ρ	$E^{1/3}$/ρ
Steels	26	1.8	0.8
Al alloys	26	3.0	1.5
Ti alloys	24	2.3	1.0
Mg alloys	25	3.7	2.0
Lexan	2	1.3	1.1
Delrin	2	1.3	1.0
UHMW	0.7	0.9	0.9
wood	3 - 19	2 - 5.1	1.8 - 3.4
GFRP	8.6 - 16	2.2 - 3	1.4 - 1.7
CFRP	44 - 96	5.3 - 7.9	2.6 - 3.4
Be alloys	164	9.4	3.6

As seen in the table, beryllium (Be) alloys would result in extremely light and rigid structures, however its use is usually prohibited in combat due to health issues.

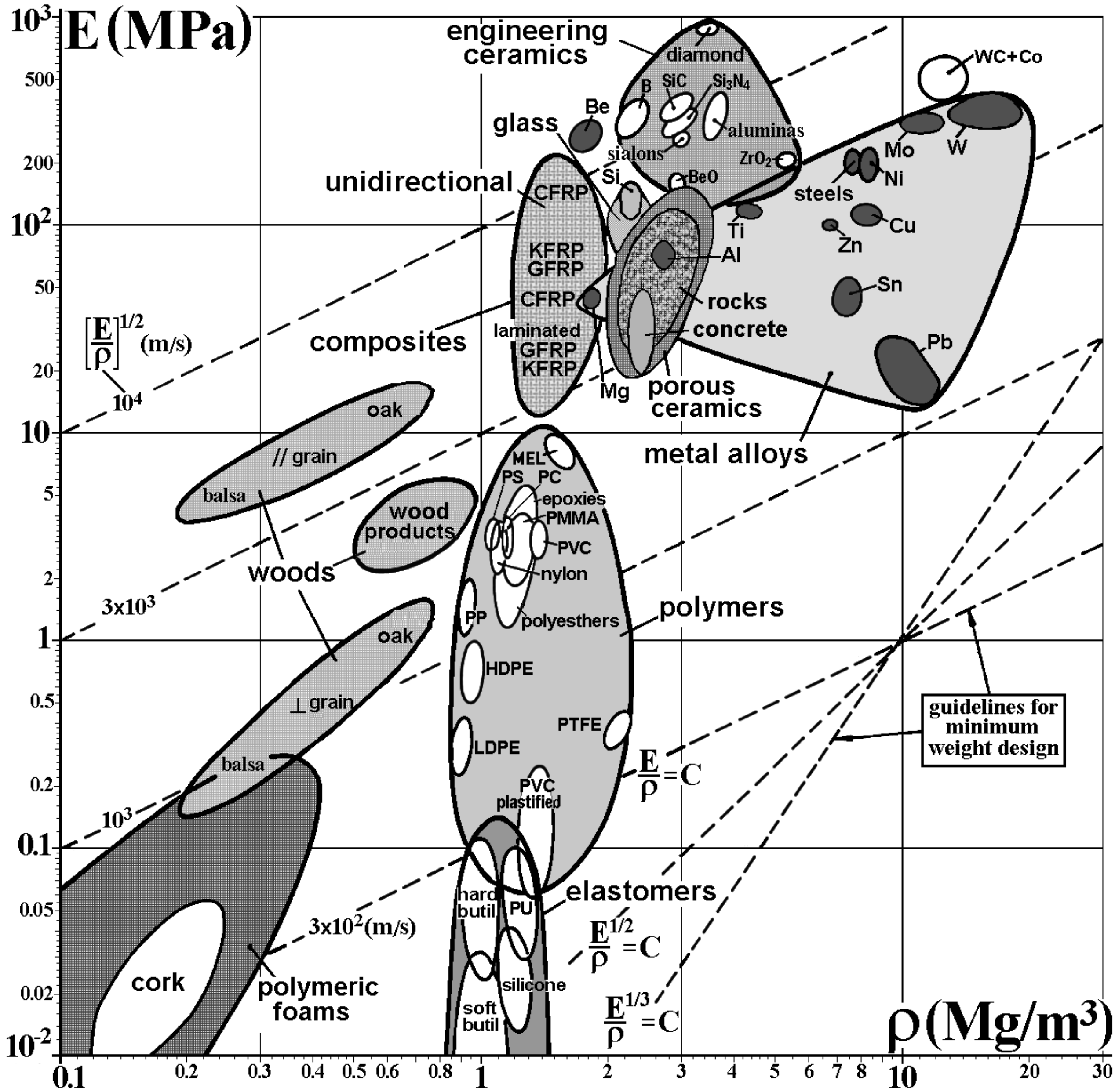
Among the allowed materials, carbon fiber (CFRP), Kevlar (KFRP) and fiberglass (GFRP) are the best choices for stiff and light beams and plates, however there are still the problems with the low impact toughness of carbon fiber and fiberglass, and the challenge in making an entire structure out of Kevlar fabric. In addition, their properties are not the same in all directions, they vary considerably. This is also true for woods, their stiffness and toughness perpendicular to their fibers are almost 10 times lower than parallel to them.

Lexan (polycarbonate) or delrin (acetal) would be awful as a trussed element under traction, their E/ρ is only 2. UHMW is even worse in that sense. Aluminum (Al) and magnesium (Mg) alloys have excellent stiffness with minimum weight, much better than Lexan, delrin, UHMW, steels, and even titanium alloys, for use in beams under bending, maximizing $E^{1/2}/\rho$, and for use in plates under bending, maximizing $E^{1/3}/\rho$.

Note from the weight optimization equations that the beam element in the previous figure assumes that both its width *b* and thickness *a* can be changed, only their aspect ratio $\alpha = b/a$ is assumed fixed. This could be true for internal structural components and for shafts, however all the robot's walls and covers cannot change their length *c* and width *b* without changing the robot design, only their thickness is a free design parameter.

Therefore, the plate element in the previous figure, which only allows its thickness *e* to change to optimize weight, without modifying *b* and *c*, is more appropriate for most structural parts. In summary, except for trussed elements, which are optimized by E/ρ, most of the robot's structural parts have their stiffness optimized by $E^{1/3}/\rho$ (as with plates), while shafts depend on $E^{1/2}/\rho$ (as with beams).

Since E and ρ do not vary much within the same type of material, it is possible to generate a large diagram comparing the applicability of each one. We've generated a graph in logarithmic (log-log) scale for several types of materials, whose ρ are represented in the horizontal axis and E in the vertical one. Using the log-log scale, we obtain guidelines that show materials with same E/ρ, $E^{1/2}/\rho$ and $E^{1/3}/\rho$ ratios, as explained below.



To choose materials to be used in light and stiff truss elements, consider the dashed guideline associated with constant E/ρ (labeled E/ρ = C). All the materials in the same straight line are equivalent, in other words, trusses of same weight made out of these materials would have the same stiffness. Now, draw parallel lines to this guideline. The higher the parallel line, the better will be the material. For instance, in the lowest guideline with constant E/ρ, we can see that plastified PVC is equivalent to cork. Going up to the next parallel E/ρ guideline, we reach the polyesters. The next parallel E/ρ guideline is a little below copper (Cu) alloys. A little above, note that, as expected, all steels, titanium (Ti), aluminum (Al) and magnesium (Mg) alloys are aligned, due to their E/ρ ≅ 25, as calculated before. The highest line with constant E/ρ in the figure goes through unidirectional carbon fibers (CFRP). A little further above we can see the infamous beryllium alloys (Be). This means that, to make a light and stiff truss, beryllium alloys would be better than CFRP, which is much better than copper alloys, which in turn is much better than polyesters, which are much better than corks (which have very low stiffness because they are foams).

To choose materials for light and stiff beams under bending, the procedure is similar, except that we'll use lines parallel to the guideline for constant $E^{1/2}/\rho$. And for plates under bending, use the guideline for constant $E^{1/3}/\rho$.

Note that steels, aluminum (Al), titanium (Ti) and magnesium (Mg) alloys are practically on the same straight line parallel to the guideline for trussed elements (constant E/ρ), so they are similar for such application, as we've already verified. However, when drawing parallel lines to the guideline for plates under bending (constant $E^{1/3}/\rho$), Mg is above Al, which is above Ti, and all of them are above steels. Therefore, it is not efficient to use steel to obtain light and rigid plates, as we had verified, it is much better to use Mg alloys.

An interesting result is that balsa wood can be the best material to make light and stiff plates (at least in a direction parallel to its grains). It is even better than titanium alloys or carbon fiber, you can easily check this from lines parallel to the constant $E^{1/3}/\rho$ guideline in the figure above. Anyone who's worked with model airplanes knows this very well. The internal structure of our fairyweight wedge Pocket is made out of balsa wood. Commercial airplanes would be much stiffer and lighter if they were made out of balsa wood, however aluminum alloys are used instead because of their higher impact toughness and weather resistance. Making a combat robot entirely out of balsa wood, including its external structure and armor, would be suicide. It would be extremely rigid, but it would break at the first impact. Thus, we must take into account other properties, not only stiffness.

3.8.2. Strength and Toughness Optimization

The yield and ultimate strengths S_y and S_u are also very important, and they need to be considered. High S_y is important for parts that should not have permanent deformations, such as shafts. And, naturally, high S_u is also important to avoid rupture and to increase the fatigue life. As the strength (denominated by the letter S) varies a lot within the same alloy family, it isn't possible to generalize conclusions to all steels, aluminum alloys, etc, as we did for stiffness. It is necessary to study each particular material separately. The best materials for trusses, beams and plates are, respectively, the ones with highest S/ρ, $S^{2/3}/\rho$ and $S^{1/2}/\rho$, as shown before in the solid mechanics calculation table.

material	S_y/ρ	$S_y^{2/3}/\rho$	$S_y^{1/2}/\rho$
UHMW	24	8	5.0
Delrin	44	11	5.6
Lexan	50	13	6.4
1020 steel	33	5	2.1
304 stainless	34	5	2.1
4340 (43HRc)	171	16	4.7
S7 (54HRc)	194	17	5.0
AerMet 100	215	18	5.2
18Ni(350)	303	22	6.1
Al 6063-T5	54	10	4.5
Al 6061-T6	102	16	6.2
Al 2024-T3	124	18	6.7
Al 7075-T6	169	22	7.8
Ti-6Al-4V	208	21	6.9
AZ31B-H24	84	16	6.9
ZK60A-T5	109	19	7.7
Be S-200	228	30	11

The results for yield strength ($S \equiv S_y$) are in the table to the right, for several representative materials. If we disregard CFRP, KFRP and GFRP, which would be the best options but they still have the problems mentioned before, it is noticeable that a trussed element under traction (such as in a trussed robot) has the largest yield strength with lowest weight if made out of 18Ni(350) steel (ratio $S_y/\rho = 303$, see the table), followed by the S-200 beryllium alloy ($S_y/\rho = 228$), AerMet 100 steel ($S_y/\rho = 215$) and Ti-6Al-4V ($S_y/\rho = 208$). If beams under bending are considered, the ranking is completely changed, the best choice against yielding would be S-200 beryllium ($S_y^{2/3}/\rho = 30$), followed by 7075-T6 aluminum and 18Ni(350) steel ($S_y^{2/3}/\rho = 22$). Plates under bending also have maximum yield strength with minimum weight if made out of S-200 beryllium ($S_y^{1/2}/\rho = 11$), followed by 7075-T6 aluminum ($S_y^{1/2}/\rho = 7.8$), however the third best option changes to ZK60A-T5 magnesium ($S_y^{1/2}/\rho = 7.7$). Note that, for plates under bending, most steels would be poor options, even worse than UHMW.

material	S_u/ρ	$S_u^{2/3}/\rho$	$S_u^{1/2}/\rho$
UHMW	43	13	6.8
Delrin	54	13	6.2
Lexan	54	13	6.7
1020 steel	56	7	2.7
304 stainless	77	9	3.1
4340 (43HRc)	184	16	4.8
S7 (54HRc)	251	20	5.7
AerMet 100	251	20	5.6
18Ni(350)	305	23	6.1
Al 6063-T5	69	12	5.1
Al 6061-T6	115	17	6.5
Al 2024-T3	174	22	7.9
Al 7075-T6	196	24	8.4
Ti-6Al-4V	224	22	7.1
AZ31B-H24	143	23	9.0
ZK60A-T5	169	25	9.6
Be S-200	415	45	15

A similar table can be generated for $S \equiv S_u$, to evaluate the best options for minimum weight if ultimate strength is considered. The trends are similar to the ones obtained from the S_y analyses, with the dominance of beryllium alloys, with high strength steels playing an important role in trussed elements (such as 18Ni(350) and its $S_u/\rho = 305$), with high strength Al, Ti and Mg alloys showing similar performance in beams ($S_u^{2/3}/\rho$ between 22 and 25), and with ZK60A-T5 magnesium as a good option for plates ($S_u^{1/2}/\rho = 9.6$).

A similar reasoning can be applied to optimize fracture toughness with minimum weight. The effect of a crack in a structure is directly proportional to the applied stresses. Therefore, the same analysis can be performed considering $S \equiv K_{Ic}$ in the previous equations. The results are shown to the right. It can be seen that 304 stainless steel is the best material to achieve tough trussed elements ($K_{Ic}/\rho = 27$). It is also great for tough beams, second only to high strength magnesium alloys, which have $K_{Ic}^{2/3}/\rho$ between 5.2 and 5.7. These magnesium alloys are also the best option for tough plates

material	K_{Ic}/ρ	$K_{Ic}^{2/3}/\rho$	$K_{Ic}^{1/2}/\rho$
UHMW	1.7	1.5	1.4
Delrin	2.1	1.5	1.2
Lexan	1.8	1.4	1.2
1020 steel	17	3.3	1.4
304 stainless	27	4.5	1.8
4340 (43HRc)	11	2.5	1.2
S7 (54HRc)	7.7	2.0	1.0
AerMet 100	17	3.3	1.5
18Ni(350)	5.2	1.5	0.8
Al 6063-T5	9.3	3.2	1.9
Al 6061-T6	10	3.3	1.9
Al 2024-T3	13	4.0	2.2
Al 7075-T6	8.7	3.0	1.8
Ti-6Al-4V	16	3.9	1.9
AZ31B-H24	16	5.2	3.0
ZK60A-T5	19	5.7	3.2
Be S-200	6.6	2.9	1.9

($K_{Ic}^{1/2}/\rho$ between 3.0 and 3.2), followed by 2024-T3 aluminum.

The material selection principles presented above allow us to choose a material to optimize a single mechanical property. For instance, the K_{Ic} calculations showed that 304 stainless steels and high strength magnesium alloys result in the toughest shafts with minimum weight, because shafts can be modeled as beams. But a 304 steel shaft would not be a good idea because of its low yield strength, allowing the shaft to easily get bent. And a magnesium shaft, despite being light, would need to have a very large diameter to achieve the desired toughness, which might not fit in the robot or require very heavy large diameter bearings and mounts. So, other considerations need to be introduced to decide which material is the best option for each part of the robot. This will be done next.

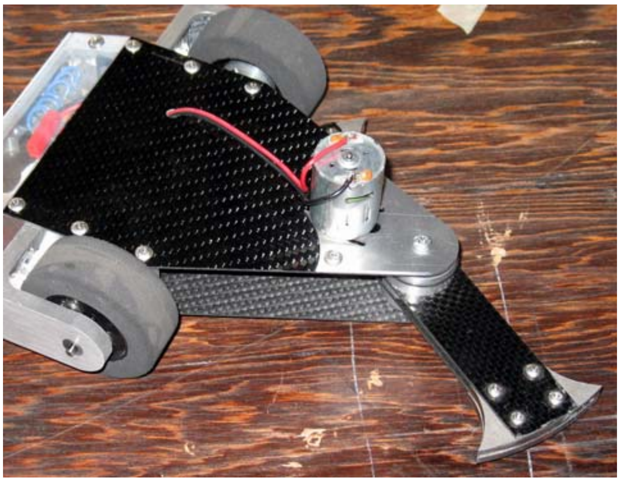
3.9. Minimum Weight Design

Minimum weight design has the goal to find the best dimensions and materials to optimize the performance of a component while minimizing its weight. It assumes that the dimensions of the component can be changed without interfering significantly with the robot design. If a component is performing as expected, then the idea is to reduce its weight by changing its materials and dimensions without losing functionality. Alternatively, if a component is failing in combat, then the idea is to improve its mechanical properties through material and dimension changes, while adding as little weight as possible. In this last case, if the redesign is wisely performed, it may be even possible to achieve the improved functionality and lose weight at the same time.

The following analyses will focus on typical structural materials that have potential use in combat. Note that beryllium alloys and composites won't be included in the following sections. Even though they would be, in theory, the best choices for minimum weight design, they have limitations in their use as structural elements.

Beryllium alloys would be a great option to maximize stiffness and strength of trusses, beams or plates, however they would not be the best choice in the presence of impacts, due to their low K_{Ic}. In addition, they are usually not allowed in combat due to health issues, as discussed before.

And composites, such as CFRP, despite their outstanding mechanical properties, also have several issues regarding their use. Composites are difficult to fabricate (in special high precision parts), they have poor mechanical properties perpendicular to the direction of the fibers, they may delaminate, and they lose toughness if drilled. Not to mention their high cost, which usually limits their application to insect weight classes. If these issues are addressed, then CFRP is the best option for light structures with high stiffness and strength. This is true not only for trusses, but also for beams (such as the CFRP spinning bar pictured to the right) and plates (such



as the CFRP structure of the same robot in the picture). If impact toughness is also necessary, then CFRP must be combined with, for instance, Kevlar. But unless you have experience with composites and a high budget, stick with the traditional structural materials: metal alloys.

The following analyses are also limited to general-purpose structural materials. Application-specific materials such as bronze, copper, PTFE (Teflon) and neoprene are not studied below. They are important in the robot to minimize friction (oil-impregnated bronze bearings, PTFE slide surfaces), to shock-mount parts (neoprene sandwich mounts), to lower electrical resistance (copper wires), and in several other tasks as described in the previous sections, but their applications are too specific for them to be compared with structural materials.

Finally, note that a few choices might seem subjective, but they are always backed up by measured properties. Note also that a few of the studied materials may be very difficult to find, such as the 2324-T39 Type II aluminum alloy used in the Boeing 777 plane, however they were included anyway for comparison purposes. Other alloys may also be unavailable in plates or bars, which might limit their applicability. For instance, the K12 Dual Hardness steel is only available in plates up to 1/2" thick, making it almost impossible to use it in shafts. And due to its dual hardness property, it will only be considered for plates that work as armor elements, its originally intended purpose.

3.9.1. Minimum Weight Plates

As seen above, magnesium (Mg) and aluminum (Al) alloys are excellent materials to increase the stiffness of structural plates that must have their weight minimized. So, if you need to lose weight, it is in general a good idea to replace steel plates with high strength Mg or Al alloy versions. But if in this case you simply change the material without increasing the plate thickness, it is easy to see that you will lower the robot stiffness and strength. To calculate the increased thickness to avoid that, we'll need to use the equations shown in section 3.8 for bending stiffness of plates. It is easy to show that the scale factor for the thickness to keep constant the plate stiffness is $(E_{old}/E_{new})^{1/3}$, where E_{old} and E_{new} are the Young modulii of the old and new materials.

So, to replace a steel plate without compromising its bending stiffness, you'll need, for instance, an aluminum one that is $(E_{steel}/E_{Al})^{1/3} \cong (205GPa/72GPa)^{1/3} \cong 1.42$ times thicker. This new thicker plate will still be lighter than the original one, because of the low density of Al alloys, which is 2.8 in average, instead of the steel average 7.8. The new plate will then have $1.42 \cdot 2.8 / 7.8 \cong 51\%$ of the weight of the original one, but with the same bending stiffness. This is a smart diet!

Similar calculations for constant bending stiffness can show that a steel plate can be switched to $(205/110)^{1/3} \cong 1.23$ times thicker titanium (Ti), weighing $1.23 \cdot 4.43 / 7.8 \cong 70\%$ of the original weight. So, if stiffness is your major concern, then switching to Al will save more weight than switching to Ti. Actually, the best choice would be Mg alloys: steel plates can be replaced with $(205/45)^{1/3} \cong 1.66$ times thicker Mg, weighing only $1.66 \cdot 1.8 / 7.8 \cong 38\%$ of the original weight, without changing their stiffness.

But other material properties besides E are also relevant, depending on the functionality of the component. The table below shows important mechanical properties of several relevant structural materials, such as S_u (measured in MPa), S_y (in MPa), K_{Ic} (in MPa√m), HB (hardness, using the Brinell scale), as well as E (in GPa) and the relative density ρ. Note that the hardnesses of the 3 polymers in the table are measured in Shore D, which would translate into very low Brinell values.

If we want to compare the performance of the listed materials as structural plates, then section 3.8 showed that we must calculate their $E^{1/3}/\rho$ ratio to evaluate stiffness, their $S_y^{1/2}/\rho$ for yield strength, $S_u^{1/2}/\rho$ for ultimate strength, and $K_{Ic}^{1/2}/\rho$ for fracture toughness. Note that hardness is a local property, it only depends on the material, not on the dimensions of the component, therefore it can be directly compared without the need to consider any ratio with the density.

		physical and mechanical properties						min. weight plate				
	material	ρ	E	S_u	S_y	K_{Ic}	HB	E*	S_u*	S_y*	K_{Ic}*	HB'
Mg alloys	AZ31B-H24	1.78	44.8	255	150	28	77	100	86	76	93	11
	ZK60A-T5	1.83	44.8	310	200	34	70	97	93	86	100	10
	Elektron WE43-T5	1.84	44	250	180	15.9	95	96	83	81	68	14
	Elektron 675-T5	1.95	44	410	310	16	114	91	100	100	64	17
Aluminum alloys	Al 6063-T5	2.7	68.9	186	145	25	60	76	49	49	58	9
	Al 6061-T6	2.7	68.9	310	276	27	95	76	63	68	60	14
	Al 2024-T3	2.78	73.1	483	345	32	120	75	76	74	64	18
	Al 2324-T39 Type II	2.77	72.4	475	370	48	118	75	76	77	78	18
	Al 5086-H32, H116	2.66	71	290	207	49	78	78	62	60	83	12
	Al 7050-T7451	2.83	71.7	524	469	31.5	140	74	78	85	62	21
	Al 7055-T74	2.86	71.7	524	469	39.6	140	73	77	84	69	21
	Al 7055-T7751	2.86	71.7	638	614	27.5	171	73	85	96	58	26
	Al 7075-T6	2.81	71.7	551	475	25	150	74	80	86	56	22
	Al 7075-T73	2.81	72	505	435	29.7	135	74	77	82	61	20
	Al 7175-T736	2.8	72	550	485	34	145	74	81	87	65	22
	Al 7475-T7351	2.81	71.7	496	421	45	135	74	76	81	75	20
Ti	Ti-6Al-4V (36HRc)	4.43	110	992	923	72	336	54	68	76	60	50
	Ti-6Al-4V ELI	4.43	110	896	827	88	326	54	65	72	66	49
Steels	1020 steel	7.87	203	441	262	130	108	37	26	23	45	16
	304 stainless	8.03	193	621	276	220	153	36	30	23	58	23
	4340 (43HRc)	7.85	205	1448	1344	88	402	38	47	52	38	60
	4340 (39HRc)	7.85	205	1310	1207	121	361	38	44	49	44	54
	4340 (34HRc)	7.85	205	1172	1069	148	320	38	42	46	49	48
	S7 (54HRc)	7.83	207	1965	1520	55	544	38	55	55	30	81
	AerMet 100 (53HRc)	7.89	194	1965	1724	118	530	37	54	58	43	79
	AerMet 310 (55HRc)	7.89	194	2170	1900	71	560	37	57	61	34	84
	AerMet 340 (57HRc)	7.89	194	2380	2070	37	596	37	60	64	24	89
	HP-9-4-30 (51HRc)	7.75	200	1585	1280	126	495	38	49	51	45	74
	18Ni(200) (46HRc)	8	183	1502	1399	142	426	36	47	52	47	64
	18Ni(250) (51HRc)	8	190	1723	1702	121	491	36	50	57	43	73
	18Ni(300) (54HRc)	8	190	2067	1998	80	544	36	55	62	35	81
	18Ni(350) (61HRc)	8.08	200	2467	2446	42	670	36	59	68	25	100
	K12 Dual Hardness	7.86	205	1785	1626	72	670	38	52	57	34	100
Polym.	Delrin	1.41	3.1	76	62	3	86SD	52	60	62	39	1
	Lexan	1.20	2.35	65	60	2.2	83SD	56	65	71	39	1
	UHMW-PE	0.93	0.689	40	22	1.6	66SD	48	65	56	43	1

To make things easier, we've normalized hardness and all the above ratios using the best materials from the table, resulting in a system of grade points between 0 and 100. The normalized hardness is called here HB', while the grades for minimum weight plates are represented by the property followed by the * symbol, namely E*, S_y*, S_u* and K_{Ic}*, shown in the table. For instance, the best material from the table for a stiff plate is the Mg alloy AZ31B-H24, therefore its stiffness grade for plates is E* = 100. Aluminum alloys have E* between 73 and 76, Ti alloys between 52 and 54, and steels between 36 and 38. With these low grades for minimum weight plate design, steels would certainly flunk a "Stiffness 101" course!

These grades are also proportional to the weight savings you'll get. For instance, a 4340 steel plate can be replaced with a 1.42 times thicker 7075-T6 aluminum one that is E_{4340}* / $E_{7075\text{-}T6}$* = 38 / 74 = 51% lighter, as calculated before, without losing stiffness.

The best material for light weight plates with high ultimate and yield strengths is the experimental Mg alloy Elektron 675-T5, therefore its S_u* = 100 and also S_y* = 100. Unfortunately, there is no material that can optimize all properties at the same time. For instance, this very same Mg alloy has only HB' = 17, a very low score for hardness. Regarding hardness, the best materials in the table are the 18Ni(350) maraging and the K12 Dual Hardness steel alloys, hardened to 61 Rockwell C, equivalent to a 670 Brinell hardness, resulting in HB' = 100. Finally, the best material for light weight plates that must sustain impacts and avoid fracture in the presence of cracks is the Mg alloy ZK60A-T5, with K_{Ic}* = 100.

To decide which material to choose from the table for a light weight plate, we must know as well which of the above properties are more important. This depends a lot on the functionality of the plate in the robot. Except for shafts, bars and trusses, most of the robot's structural parts can be modeled as plates for minimum weight design. This is because these parts usually have two fixed dimensions, width and length, obtained from the robot geometry, while their thickness and material can be changed. This is true for most internal mounts, structural walls, top and bottom covers, wedges, shields and armor plates. We'll study these plate-like structural members next.

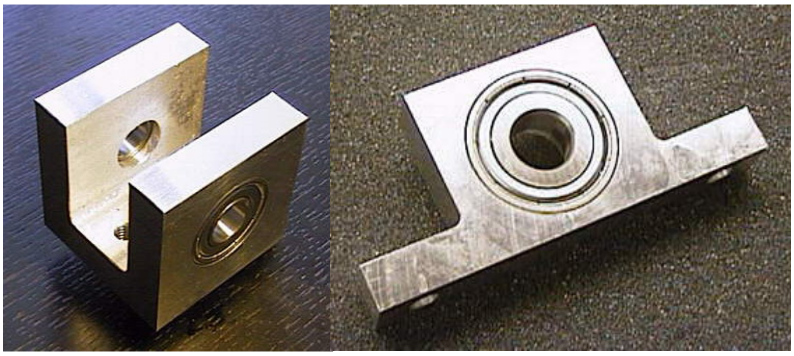
3.9.2. Minimum Weight Internal Mounts

The most desired property of internal mounts is stiffness. All the impacts they suffer are indirectly transmitted, being relatively damped by the chassis, so K_{Ic} is not that important. Usually, internal mounts that have sufficiently high stiffness are made out of plates that are thick enough to satisfy S_u and S_y requirements.

Therefore, if only the stiffness grades E* are considered, then all Mg alloys are by far the best choice, with grades between 91 and 100, followed by all Al alloys, grading between 73 and 76. Even the low strength 6063-T5 aluminum is a good choice if only stiffness is concerned. But forget about steel internal mounts, their low E* between 36 and 38 will end up adding unnecessary weight to your robot.

But if S_u and S_y are also critical, besides stiffness, then we must include them in the selection process. High S_u may be important for high stress mounts of heavy weapon motors, such as the 1/2" thick Etek and Magmotor mounts (pictured to the right, which can be found for instance at the Robot Marketplace).

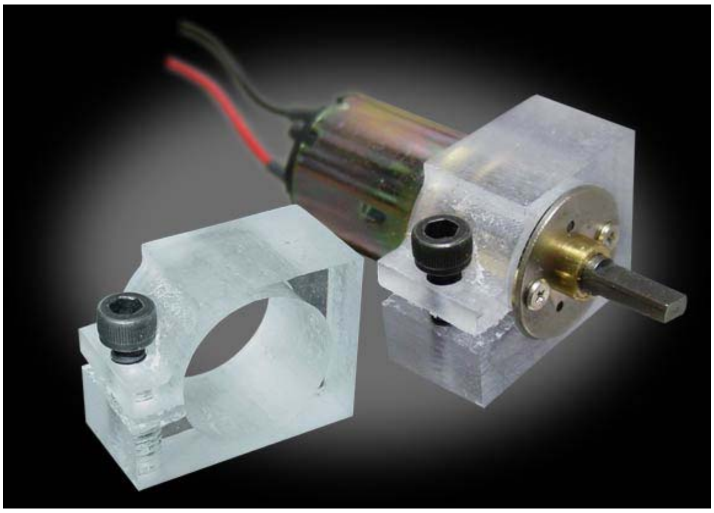
High S_y is also important for internal mounts that support wheel shafts, such as the drivetrain pillow blocks pictured to the right (sold at www.teamdelta.com), which must preserve a relatively accurate alignment without getting permanently bent.



If we (arbitrarily) choose to maximize the average between the grades E*, S_u* and S_y*, maximizing a certain grading parameter X* = (E* + S_u* + S_y*) / 3, then the best choices are the high strength Mg alloys Elektron 675-T5, ZK60A-T5, AZ31B-H24, Elektron WE43-T5, all of them with X* > 85. The next choices are high-strength Al alloys from the 7000 series, such as 7055-T7751, 7175-T736, 7075-T6, 7050-T7451 and 7055-T74, in that order, all with X* > 77. Steels and even Ti alloys usually result in unnecessarily heavy internal mounts, due to their lower E* and X*.

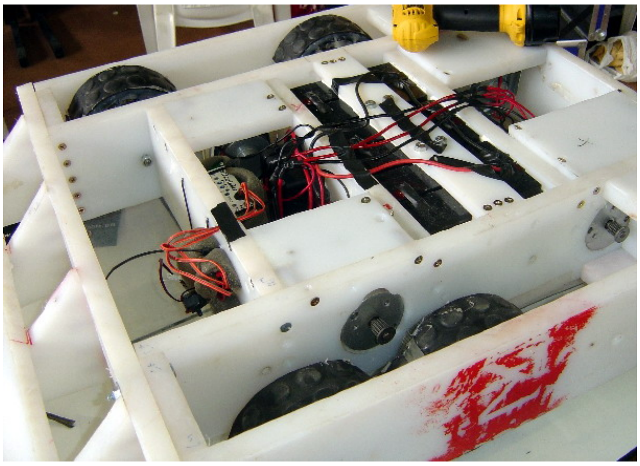
Lexan, delrin and UHMW mounts have much lower E*, between 48 and 56, but they can make good internal mounts for very small parts in insect weight robots, because their higher resulting thickness will allow them to have threaded holes.

For instance, the Lexan motor mount pictured to the right only weighs 4 grams, while its 1/2" thickness allows the use of a threaded hole for the 4-40 screw. If the mount was made out of aluminum, it would need to be $(E_{Al}/E_{Lexan})^{1/3} \cong (72GPa/2.35GPa)^{1/3} \cong 3.13$ times thinner to have same stiffness (or $\rho_{Al}/\rho_{Lexan} \cong 2.8/1.2 \cong 2.33$ times thinner to have the same 4 gram weight). The lower 0.16" thickness for same stiffness would make it impractical to use threaded holes to hold the 0.11" diameter 4-40 screw without compromising strength.



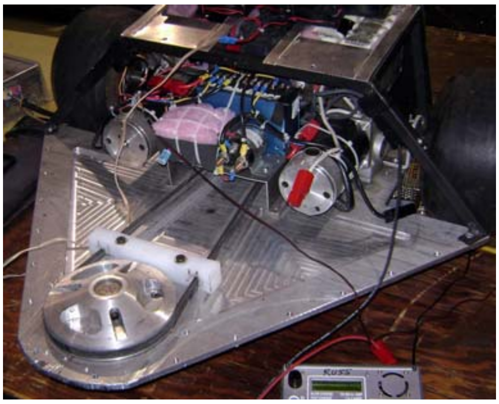
3.9.3. Minimum Weight Protected Structural Walls

Stiffness is very important for structural walls of robots with active weapons. Large structural deformations can make, for instance, a drum touch the floor when hitting an opponent, a spinning bar hit your own robot during a sloped impact, or even cause mechanism jamming due to severe misalignments.



This is why, unless you’re building a passive rammer or wedge (as pictured to the right), making your entire structure and walls out of plastic is a bad idea. For instance, a UHMW plate, despite its good impact toughness, would need to be $(70\text{GPa}/0.7\text{GPa})^{1/3} \cong 4.64$ times thicker than an aluminum one to have the same bending stiffness, and it would end up $4.64 \cdot 0.93 / 2.8 \cong 1.54$ times heavier, instead of lighter. A Lexan structure is also a bad idea, the plates would need to be $(70\text{GPa}/2.7\text{GPa})^{1/3} \cong 3$ times thicker than aluminum ones, they would end up $3 \cdot 1.2 / 2.8 \cong 1.29$ times heavier. The thicker plates would also require longer screws to be mounted, adding even more weight. Not to mention that Lexan has cracking problems around holes, and plastics in general are easily cut by sawbots. Trust in aluminum! And in magnesium alloys, if available.

If a structural wall is not exposed, such that the opponent cannot hit it directly, or if there's some shock-mounted armor plate over it, then this wall is considered to be protected. Protected walls, besides high stiffness, should have high S_u* to support static loads, and high S_y* to avoid getting permanently bent. Since they are protected, K_{Ic}* is not that important because they'll only suffer indirect impacts. Therefore, these walls basically behave as high stress internal mounts, being optimized by high strength Mg alloys and aluminum alloys from the 7000 series, as discussed in the previous sub-section. The pictures below show 7050-T7451 inner aluminum walls from our middleweight Touro, which are protected by titanium and Kevlar layers, shown in detail on the right.



Note that most bottom plates (as pictured to the right) can be modeled as protected structural walls, therefore high strength Mg and Al alloys are usually a good option for them.

But, if you have an invertible robot, these bottom plates could get exposed while the robot is upside down, so it is also a good idea to check the optimized materials for integrated structure-armor walls, in the next sub-section. This is especially useful against vertical spinners with large bars or disks, which could flip your robot upside down with one blow, mount on top of it, and then hit again with the blade on the now exposed bottom plate. It is also useful against vertical spinners with small diameter disks, such as K2, which can lift your robot and hit its bottom plate during the same attack, as pictured to the right.

We can conclude as well that the best materials for other internal structural components such as gearbox blocks (pictured to the right, from the TWM 3M gearbox) are also high strength Al and Mg alloys, as long as the gearbox is well protected inside the robot, of course.

If you're changing the material of an existing protected wall, you'll need to find its new thickness depending on what property you want to keep constant. If it is stiffness, then we've seen that the scale factor for the thickness in plates is $(E_{old}/E_{new})^{1/3}$. It is also easy to show that the scale factor for the thickness to keep constant the bending strength of a plate is $(S_{old}/S_{new})^{1/2}$, where S_{old} and S_{new} are the strengths (either the yield S_y or the ultimate S_u) of the old and new materials.

Because both strengths vary a lot within the same alloy family, it isn’t possible to generalize conclusions to all steels, aluminum alloys, etc, as we did in stiffness optimization calculations. It is necessary to study each material separately, evaluating its particular yield or ultimate strength, and its actual density (although the densities do not vary much within the same alloy family).

It is easy to see that all steels, even high strength steels such as a S7 steel tempered to 54 Rockwell C, are not a good choice for a light weight high strength structure. For instance, to replace a tempered S7 steel plate that works under bending without compromising its ultimate strength, you could use a 7075-T6 aluminum plate $(S_{S7}/S_{7075\text{-}T6})^{1/2} = (1965\text{MPa}/551\text{MPa})^{1/2} \cong 1.89$ times thicker, weighing $1.89 \cdot 2.81 / 7.83 \cong 68\%$ of the original weight. An almost equivalent choice would be to replace the S7 steel with Ti-6Al-4V, which would need to be $(1965\text{MPa}/992\text{MPa})^{1/2} \cong 1.41$ times thicker, with $1.41 \cdot 4.43 / 7.83 \cong 80\%$ of the original weight. Both 7075-T6 aluminum and Ti-6Al-

4V would have better ultimate strength-to-weight ratios than tempered S7, so both would be good options to replace any steel alloy in this case, with the high strength aluminum resulting in better values. This can be readily verified from the ultimate strength grade S_u* of S7 steel (equal to 55), Ti-6Al-4V (equal to 68) and 7075-T6 aluminum (graded 80). Magnesium alloys would be even better for plates, since ZK60A-T5 has S_u* = 93 and Elektron 675-T5 excels at S_u* = 100. The use of S7 steel would only be wise if that part needed to remain sharp, which is not the case for structural walls.

But what if you want to increase some property by a factor of n, instead of keeping it constant? Well, the first step is to optimize the material, finding the new material and thickness that keep constant the desired property. After the material has been optimized, you'll need to increase its thickness to improve the property by the n factor. From the analysis of plates under bending, it is easy to show that the scale factor for the thickness is $n^{1/3}$ for improved stiffness, and $n^{1/2}$ for improved yield strength, ultimate strength, or fracture toughness.

For instance, if you want to double the bending stiffness of a 1/4" thick 4340 steel plate, the first step is to switch it to a better material, such as the Mg alloy AZ31B-H24, which has E* = 100, instead of E* = 38 from that steel. The same stiffness of the original plate would be obtained using a Mg alloy plate that was $(E_{4340}/E_{AZ31B\text{-}H24})^{1/3} = (205GPa/44.8GPa)^{1/3} \cong 1.66$ times thicker (0.415" thick). Now, to improve the stiffness by a factor of n = 2 with the same Mg alloy, just multiply the thickness by $n^{1/3} = 2^{1/3} \cong 1.26$, resulting in a 0.523" thick plate. This new plate, even with twice the stiffness of the original 4340 plate, would only have $1.26 \cdot 1.66 \cdot 1.78 / 7.85 \cong 47\%$ of the original weight of the steel version. Clearly, since there is no commercially available 0.523” thick plate, you’ll probably have to choose between a lighter 1/2” or a stiffer 5/8” or 9/16” thick plate, or mill it down to the desired thickness. The numbers are even more interesting if you don't need to lose weight: a 1.1" thick Mg alloy plate would have the same weight as the original steel version, but its bending stiffness would be 18.75 times higher!

Note that, if the material is already optimized, then you’ll need to add thickness and weight to the plate to improve its mechanical properties. If you can’t afford the extra weight, then you’ll have to start optimizing the entire geometry, not only the thickness. A simple way to do that is by getting a thicker plate and milling pockets in it, until the final piece has the same weight of the original thinner one. We had to mill very deep pockets in the inner walls of our hobbyweight Touro Jr not to go over its weight limit, as seen on the right. The idea is to make the plate work as an I-beam, with thick outer sections (where the bending stress is maximum) and thinner mid-sections. But to calculate the new stiffness, strengths and toughnesses, you’ll probably need the aid of computer software such as Finite Element or even CAD programs.

3.9.4. Minimum Weight Integrated Structure-Armor Walls

If the external structural walls of your robot are unprotected, working as well as armor (such as in our lightweight Touro Light, pictured to the right), then fracture toughness K_{Ic} plays a major role. To be used in the robot structure, the material must have high E* and S_y*, as discussed before. But now K_{Ic}* is more relevant than S_u*, because while also working as armor the plate will mostly suffer dynamic loads (impacts) instead of static ones.

Top cover plates are also included in this category, because they must have high K_{Ic}* to survive the attacks of vertical spinners, hammerbots and overhead thwacks. If they also act as structural elements, helping for instance to support the drive system, then stiffness E* and yield strength S_y* grades are also important, so the following analysis also applies to them.

Since K_{Ic}*, E* and S_y* are the most relevant properties for structure-armor walls, we'll (arbitrarily) choose the average of their grades, $X^* = (K_{Ic}^* + E^* + S_y^*) / 3$, to evaluate the best materials. We'll also choose only the materials with $K_{Ic}^* > 50$, $E^* > 70$ and $S_y^* > 70$, to avoid any distortions that the average X* might carry. For instance, the 5086-H32 aluminum alloy has a relatively good X* = 73.5, however it has an undesirably low $S_y^* = 60$.

It is found that the Mg alloys continue in the lead, with the best alloy from the studied table being ZK60A-T5, followed by AZ31B-H24, Elektron 675-T5 and Elektron WE43-T5. Aerospace aluminum alloys follow in this ranking: 2324-T39 Type II, followed by 7475-T7351, 7175-T736, 7055-T7751 or T74 and 7050-T7451, all of them with X* > 73.

Interestingly, 2024-T3, which is not one of the best options for protected walls, is a good option for structure-armor plates, with X* = 71, despite its lower S_y*. It is almost as good in this application as 7075-T6, which has X* = 72. This is because 2000 series Al alloys have lower S_y than 7000 series, but they usually make it up with better K_{Ic}, which is crucial for armor elements.

Forget once again about steels. Although steels have high K_{Ic}, their high density results in plates with relatively low K_{Ic}-to-weight ratios, with K_{Ic}* between 24 and 58 for the ones in the studied table. These low ratios, together with their very low E*, makes them very unattractive, due to their $35 < X^* < 47$.

Titanium Ti-6Al-4V, despite its relatively good $S_y^* = 76$ and $K_{Ic}^* = 60$ (or 66 for the tougher ELI version), is not one of the best choices for an integrated structure-armor because of its relatively low stiffness-to-weight ratio, which results in E* = 54 and thus X* = 63.4. This lower stiffness could be good enough to make a very tough all-titanium rammer or wedge, but it would be a poor choice for an integrated structure-armor robot with active weapons. In fact, even medium strength 6061-T6 is a better choice than titanium, despite its lower $S_y* = 68$: it combines the same $K_{Ic}* = 60$ of Ti-6Al-4V with a much better $E* = 76$, resulting in a higher $X* = 68.2$. In addition, 6061-T6 is much cheaper than high strength Ti and Al alloys, it is easier to machine, it has good weldability, and it is readily available in extrusion forms. No wonder Matt & Wendy Maxham love this material!

3.9.5. Minimum Weight Wedges

Wedges and integrated structure-armor plates behave in a similar manner. They must have high $K_{Ic}*$ to withstand impacts. They must have high S_y* to avoid getting permanently bent, because bent wedges won't remain flush to the ground to scoop the opponents. And they must have high E* to become very stiff and launch the opponents. A very flexible wedge can be effective as an armor element, as a defensive element damping the impact, however it won't be able to effectively use the opponent robot's kinetic energy against it, as an offensive element. Stiff wedges will transmit much higher reaction forces from the arena floor to the opponent.

So, good material choices for wedges must have, similarly to structure-armor plates, a high average grade $X* = (K_{Ic}* + E* + S_y*) / 3$. The main difference here is that wedges must keep their edges sharp to stay effective, so high hardness is also important. We'll choose materials with hardness higher than 32 Rockwell C, which translates to grades HB' > 45. Higher hardness materials will rule out Mg and Al alloys, so we'll need to relax a little the restrictions on the minimum values of the other properties, to be able to find any match. We only choose then materials with $K_{Ic}* > 25$, $E* > 35$ and $S_y* > 40$, as well as HB' > 45, that maximize X*.

The result is that Ti-6Al-4V ELI and Ti-6Al-4V (pictured to the right) are by far the best choices from the table, with X* equal to 64 and 63, respectively. High strength steels would be the next choice, the best one being AerMet 100, followed by 18Ni(250), HP-9-4-30, 18Ni(200), 18Ni(300), tempered 4340, AR400 and tempered 5160, all of them with X* > 42.

3.9.6. Minimum Weight Traditional Armor

If a structural plate only works as armor, such as a rammer shield (pictured to the right), then there are basically three mechanical properties of interest: fracture toughness, impact toughness, and hardness.

The armor needs to withstand impacts, as well as tolerate the cracks that will eventually be formed after receiving some serious hits, therefore K_{Ic} is a major concern. Armor plates usually do not carry any static loads besides their own weight, they're just "hanging out” waiting to be hit, so S_u is not nearly as important as K_{Ic}. Also, they do not lose functionality after yielding, as long as their permanent deformations do not interfere with the inner structure, drivetrain or weapon system, so S_y is not that important either. And the armor plates are already mounted either over stiff internal structural walls or over shock mounts (as pictured to the right, with shock mounts made out of curled steel cables), therefore they don’t need too much stiffness themselves.

Top cover plates can be included in this category if they do not act as structural elements, if they are just plates used to protect the robot interior, without having to support any internal components such as the drivetrain system. So, stiffness and yield strength are not that important, as long as the robot has a few internal supports that will prevent the top cover from bending too much into the robot and smash some critical component. Therefore, non-structural top cover plates that are well supported can be modeled as traditional armor elements, so the following analysis also applies to them.

Note that we’re assuming here that the fracture toughness K_{Ic} can also be a measure of impact toughness. This is true for most metals, unless they have notch sensitivity problems, explained later. In addition, the value of K_{Ic} depends on the loading rate (the impact speed). All K_{Ic} measurements included in the previous table were made under very slow tests, therefore they are also called static K_{Ic}. If the tests had been performed at very high load rates, to evaluate the effect of the impact speed, the resulting dynamic K_{Ic} values would probably be much lower. For instance, one of the Ti-6Al-4V armor plates from our middleweight Touro shattered almost like glass due to a high speed impact from the bar spinner The Mortician, during RoboGames 2006. Very little plastic deformation can be seen in the remaining plate (pictured to the right), and the removed portion shattered into tiny pieces. At lower impact speeds, the very ductile Ti-6Al-4V would certainly absorb more energy, meaning that its static (low speed) $K_{Ic} = 72\text{MPa}\sqrt{\text{m}}$ is probably much higher than its dynamic (high speed) K_{Ic}.

However, if we assume that the ratio between dynamic and static K_{Ic} is similar for all materials (which is not completely true), then we can still compare them directly only using the available static K_{Ic} values.

As explained in chapter 2, traditional armors are usually made out of tough and hard materials that try to absorb and transmit the impact energy without getting damaged. They are a good option against very sharp horizontal spinners, since the high hardness will help chipping or blunting the edge of the opponent's weapon. So, in addition to a high grade K_{Ic}*, it is desirable that the armor plate has a high hardness grade HB'.

Thus, we'll choose materials that maximize the average X* = (K_{Ic}* + HB') / 2, while guaranteeing some minimum toughness and hardness requirements K_{Ic}* > 30 and HB' > 45. We find out that the best materials are, in that order, K12 Dual Hardness, AerMet 100, HP-9-4-30, AerMet 310, 18Ni(250), 18Ni(300), Ti-6Al-4V ELI, 18Ni(200) and Ti-6Al-4V, all of them having X* > 50. Tempered 4340 steel is not a bad option, it has X* > 48. Tempered 5160 steel could also be used, but it's not one of the best choices.

If you have trouble finding or heat treating AerMet, HP-9-4-30 or maraging steel alloys, then your best bet is to go for Ti-6Al-4V armor plates. Note that the above calculations assume that Ti-6Al-4V is in its commercially available annealed condition, because when heat treated to improve its ultimate strength it can end up with K_{Ic} lower than 45MPa√m, instead of 72MPa√m. If available, Ti-6Al-4V ELI (Extra Low Interstitial) is even better for armor plates, since K_{Ic} = 88MPa√m, despite its 10% lower yield and ultimate strengths. Titanium alloys with higher K_{Ic} are usually not commercially available, such as Ti-6Al-2Sn-4Zr-2Mo and Ti-11.5Mo-6Zr-4.5Sn.

If you want a low budget traditional armor, then 304 stainless steel is a reasonable choice. Its K_{Ic}* is 58, similar to annealed Ti-6Al-4V, but it is much cheaper. However, due to its low E* and S_y*, it will only be a good choice if backed up by a stiff structure. Touro has a few 304 steel spare armor plates, used when we're out of Ti-6Al-4V.

Forget about other steels, because their K_{Ic}* is usually below 50. With the same weight of the steel armor you can get a 77% thicker Ti-6Al-4V plate that will be much tougher. Even the high strength steels S7, 18Ni(350) and AerMet 340 should be avoided, because of their medium-low toughness grades K_{Ic}* ≤ 30. It is true that S7 tempered to 54 Rockwell C is one of the tool steels with highest toughnesses, with K_{Ic} = 55MPa√m, however this is a low value compared to most steels: for instance, the low strength 1020 steel can reach K_{Ic} = 130MPa√m. Beware, S7 steel is not a panacea! It may only be a good option when sharpness is also required.

3.9.7. Minimum Weight Ablative Armor

As explained in chapter 2, ablative armors are designed to negate damage by themselves being damaged or destroyed through the process of ablation, which is the removal of material from the surface of an object by vaporization or chipping. They're also made out of tough materials, but with low hardness and low melting point to facilitate the ablation. Most of the impact energy is absorbed by the ablation process, by breaking apart when hit by an opponent, transmitting much less energy to the rest of the robot.

To find out if a material will result in an ablative armor, you must consider its hardness and melting point. If you want a traditional armor, we've seen that a good option is Ti-6Al-4V, which has a 1660°C (3020°F) melting point and 36 Rockwell C hardness, equivalent to 336 Brinell. But if you want an ablative armor, we'll see that the best options are high toughness Mg and Al alloys, which have low Brinell hardnesses between 60 and 171, and relatively low melting points, close to 660°C (1220°F). Low hardness helps ablation by making the armor material deform during an impact, while low melting point helps ablation by allowing the armor material to locally melt or even vaporize during high energy impacts.

Ablative armors are a very good choice against blunt or not-so-sharp weapons. But, against very sharp horizontal spinners, very hard traditional armors are a better option, as discussed before. This is because ablative armor materials such as Mg and Al alloys have low hardnesses, not being able to blunt or chip the edge of the opponent's blade during combat. An opponent with a sharp spinning blade during the entire combat is not a pleasant thought. In special because Mg and Al alloys, used in the ablative armor, tend to be easily cut by sharp tools at high speeds, drastically reducing their K_{Ic}, S_u and S_y, which had been measured under static conditions. It's like cutting butter with a hot knife. Thus, traditional armor materials such as Ti-6Al-4V are better choices against very sharp spinners, their higher hardness and melting point prevent such weakening.

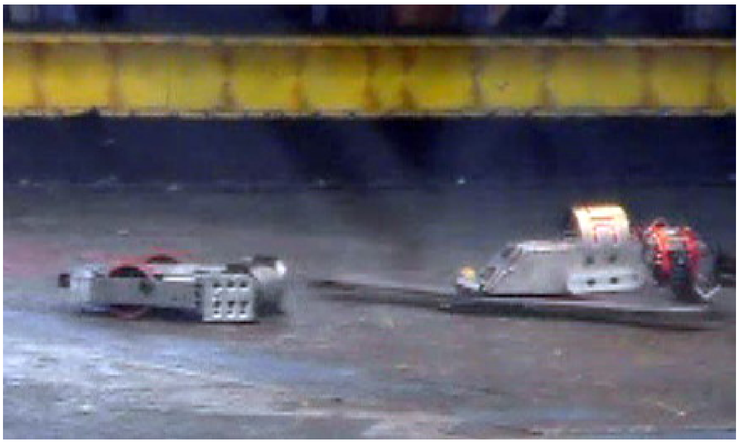
In addition to their ablative properties, high toughness Mg and Al alloys also have better fracture toughness grades K_{Ic}* than traditional armor materials. For instance, let's compare Ti-6Al-4V with 5086-H32 aluminum, used in armor plates of light weight military vehicles. In average, 5086-H32 has K_{Ic} = 49MPa√m, while Ti-6Al-4V has K_{Ic} = 72MPa√m. Section 3.8 showed that strength and toughness analyses have similar equations because the effect of a crack in a structure is directly proportional to the applied stresses. Therefore, for plates under bending, it is not a surprise that the scale factor between old and new plate thicknesses for a minimum weight design with constant fracture toughness is $(K_{Ic,old}/K_{Ic,new})^{1/2}$. Because almost all armor plates don't have restrictions about having their thickness increased, since they are outside the robot, they can be analyzed using a minimum weight design.

So, a Ti-6Al-4V plate would have the same toughness as a 5086-H32 aluminum plate that was $(72/49)^{1/2} \cong 1.2$ times thicker. This aluminum replacement would only have $1.2 \cdot 2.66 / 4.43 \cong 72\%$ of the weight of the Ti-6Al-4V version. In summary, we can conclude that, for weight optimization, high toughness titanium alloys (such as Ti-6Al-4V) are not as good as high toughness aluminum alloys when it comes to fracture toughness.

This conclusion might seem weird, but it is true. Surely a titanium plate would be a better armor than an aluminum one with same thickness, but remember that this is a weight (and not a volume) optimization problem. An aluminum plate with the same weight as a titanium one is about 1.6 times thicker, this is what makes the difference. This is easily seen from the fracture toughness grades K_{Ic}* = 60 for Ti-6Al-4V and K_{Ic}* = 83 for 5086-H32 aluminum.

To find out the best ablative armor materials from the table, we'll choose the ones with low hardness HB' < 30 and rank them by their K_{Ic}*. For instance, depending on the impact orientation, 7475-T7351 can have K_{Ic} from 36 to 55MPa√m, resulting in average in K_{Ic}* = 75. The 7000 series aluminum alloys have K_{Ic}* between 55 and 75.

But the ultimate ablative armor would be made out of, believe it or not, the Mg alloys ZK60A-T5 (K_{Ic}* = 100) and AZ31B-H24 (K_{Ic}* = 93). And their very low hardness, between 70 and 77 Brinell (HB' between 10 and 11), helps even more in the ablation process. In summary, the best ablative armor materials are, in that order, the Mg alloys ZK60A-T5 and AZ31B-H24, followed by the Al alloys 5086-H32, 2324-T39 Type II, 7475-T7351 and 7055-T74, all of them with K_{Ic}* > 69.



Touro Feather can testify the effectiveness of aluminum ablative armors. At Robogames 2008 it withstood several powerful blows from the featherweight undercutter Relic on its 3/4” thick 7050 aluminum front armor plates (pictured to the right). These scarred plates worked as an ablative armor, slowing down Relic’s weapon and allowing Touro Feather to go for the knockout.

Avoid using polymer armor plates, such as Lexan or UHMW, they have K_{Ic}* < 45. Wood might be a good option for ablative armor, although its K_{Ic} varies by a factor of 10 depending on the impact direction. In average, wood would grade K_{Ic}* = 77, a very high score. But hope that your opponent doesn't have a flamethrower, and that the opponent robot doesn't hit you in the brittle transverse direction of the wood fibers. And be careful with wood splinters when handling your robot, it will have plenty of them.

3.9.8. Minimum Weight Beams

The previous components were all modeled as plates, because they have by design 2 fixed dimensions (width and length), while only thickness can be changed. However, there are other components (such as shafts) that might only have one fixed dimension, their length, while their diameter can be varied. If a beam basically works under bending and/or torsion, then we’ve seen in section 3.8 that its mechanical properties are optimized for minimum weight using materials with high $E^{1/2}/\rho$ ratio for stiffness, high $S_y^{2/3}/\rho$ for yield strength, high $S_u^{2/3}/\rho$ for ultimate strength, and high $K_{Ic}^{2/3}/\rho$ for fracture toughness.

Similarly to what we did for plates, we've normalized all the above ratios using the best materials from the table, resulting in a system of grade points between 0 and 100 for beams. The normalized hardness is still HB’, because it is a local property, while the grades for minimum weight beams are represented by the property followed by the ** symbol, namely E**, S_y**, S_u**

and K_{Ic}**, shown in the table below. Note that the beam grades can differ a lot from the plate grades. For instance, the best material from the table for a beam with high yield strength is not a Mg alloy, as it was for plates, but the 7055-T7751 Al alloy, grading S_y** = 100. Note that steels are poor choices for high stiffness elements not only for plates, but also for beams, with E** < 50.

In the table there are also properties followed by the *** and ’ symbols, they will be used respectively in minimum weight truss design and in minimum volume design, discussed later.

		min. weight beam				min. weight truss				minimum volume				
	material	E**	S_u**	S_y**	K_{Ic}**	E***	S_u***	S_y***	K_{Ic}***	E'	S_u'	S_y'	K_{Ic}'	HB'
Mg alloys	AZ31B-H24	100	80	63	90	94	47	28	57	22	10	6	13	11
	ZK60A-T5	97	88	74	100	92	55	36	68	22	13	8	15	10
	Elektron WE43-T5	96	76	69	60	90	45	32	32	21	10	7	7	14
	Elektron 675-T5	90	100	93	57	85	69	53	30	21	17	13	7	17
Aluminum alloys	Al 6063-T5	82	43	40	55	96	23	18	34	33	8	6	11	9
	Al 6061-T6	82	60	62	58	96	38	34	37	33	13	11	12	14
	Al 2024-T3	82	78	70	63	99	57	41	42	35	20	14	15	18
	Al 2324-T39 Type II	82	78	74	83	98	56	44	63	35	19	15	22	18
	Al 5086-H32, H116	84	58	52	88	100	36	26	67	34	12	8	22	12
	Al 7050-T7451	80	81	84	61	95	61	55	41	35	21	19	14	21
	Al 7055-T74	79	80	84	71	94	60	54	51	35	21	19	18	21
	Al 7055-T7751	79	92	100	56	94	73	71	35	35	26	25	13	26
	Al 7075-T6	80	85	86	53	96	64	56	32	35	22	19	11	22
	Al 7075-T73	80	80	81	60	96	59	51	39	35	20	18	14	20
	Al 7175-T736	81	85	87	65	96	64	57	44	35	22	20	15	22
	Al 7475-T7351	80	79	79	79	96	58	49	58	35	20	17	20	20
Ti	Ti-6Al-4V (36HRc)	63	79	85	68	93	73	69	59	53	40	38	33	50
	Ti-6Al-4V ELI	63	74	79	78	93	66	62	73	53	36	34	40	49
Steels	1020 steel	48	26	21	57	97	18	11	60	98	18	11	59	16
	304 stainless	46	32	21	79	90	25	11	100	93	25	11	100	23
	4340 (43HRc)	49	58	61	44	98	60	57	41	99	59	55	40	60
	4340 (39HRc)	49	54	57	54	98	55	51	56	99	53	49	55	54
	4340 (34HRc)	49	50	53	62	98	49	45	69	99	48	44	67	48
	S7 (54HRc)	49	71	67	32	99	82	64	26	100	80	62	25	81
	AerMet 100 (53HRc)	47	70	72	53	92	82	72	55	94	80	70	54	79
	AerMet 310 (55HRc)	47	75	77	38	92	90	80	33	94	88	78	32	84
	AerMet 340 (57HRc)	47	80	81	25	92	99	87	17	94	96	85	17	89
	HP-9-4-30 (51HRc)	49	62	60	57	97	67	55	59	97	64	52	57	74
	18Ni(200) (46HRc)	45	58	62	59	86	61	58	65	88	61	57	65	64
	18Ni(250) (51HRc)	46	63	71	53	89	71	70	55	92	70	70	55	73
	18Ni(300) (54HRc)	46	72	79	40	89	85	83	37	92	84	82	36	81
	18Ni(350) (61HRc)	47	80	89	26	93	100	100	19	97	100	100	19	100
	K12 Dual Hardness	48	66	70	38	98	74	68	33	99	72	66	33	100
Polym.	Delrin	33	45	44	26	8	18	15	8	1	3	3	1	1
	Lexan	34	48	51	25	7	18	17	7	1	3	2	1	1
	UHMW-PE	24	44	33	26	3	14	8	6	0	2	1	1	1

To decide which material to choose from the table for a light weight beam, we must know which of the E**, S_y**, S_u**, K_{Ic}** and HB' properties are more important, which depends on its functionality in the robot. We'll study these beam-like structural members next.

3.9.9. Minimum Weight Shafts and Gears

Shafts are, basically, beams with circular cross-section under bending and torsion. They must have high K_{Ic}** grade to withstand impacts, high stiffness grade E** to prevent vibration and gear misalignment, and certainly high S_y** grade not to get bent. We'll look then at the average grade X** = (K_{Ic}** + E** + S_y**) / 3 to evaluate the fitness of each material.

It is easy to see that high strength Mg and Al alloys would be the best choices, with X** between 72 and 90. This is true for most beams, but not for shafts. It is true that Mg and Al shafts would have the best minimum weight properties, however they would need to have a much larger diameter than an equivalent one made out of steel or titanium, which would imply in larger bearings, larger gears and pulleys, and larger gearboxes, increasing the robot weight.

So, to avoid shafts with very large diameters, we'll limit our choices to denser materials such as steels and Ti alloys. We can easily do that by adding another restriction, which is HB' > 45. This medium-high hardness requirement will not only filter out polymers, Mg and Al alloys, but it will also help in the mounting process, since low hardness shafts would easily become dented, making it difficult to mount, for instance, a tight tolerance roller bearing. Also, higher hardness shafts will prevent wear due to, for instance, bronze bearing friction.

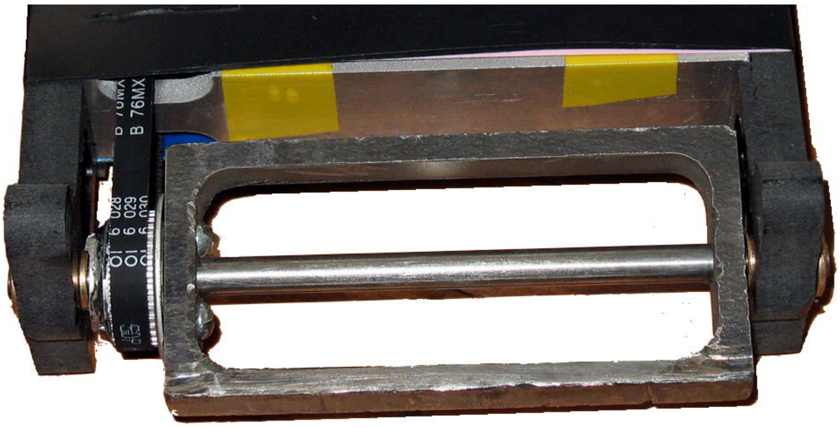
Also, to avoid distortions in the X** average, we'll also limit the choices to materials with K_{Ic}** > 25, S_y** > 40 and E** > 40. It is found that the best shaft materials from the studied table are Ti-6Al-4V ELI (with X** = 73) and Ti-6Al-4V (X** = 72, see the shaft pictured on the right). The next choices are, in that order, AerMet 100, 18Ni(250), 18Ni(200), HP-9-4-30, 18Ni(300), tempered 4340, AR400, and tempered 5160, all of them with X** between 50 and 58. Avoid using S7 steel shafts, they only grade X* = 49, and they're more expensive and with lower K_{Ic}** than 4340 steel.

Therefore, hardened steel shafts are better than Mg or Al ones. Note that high strength titanium is only better than high strength steels if the weight saved by the shaft is not gained by the slightly larger bearings, gearboxes, etc.

Note that minimum weight gears also fall in this very same category, if their thickness is a free parameter that can be changed. They also need high K_{Ic}**, E** and S_y**, for the same reasons. And a higher hardness grade HB' > 45 will prevent wear on the gear teeth. So, if the volume of the gear is not important, the best choice for minimum weight would be high strength Ti alloys. If you need more compact gears and with less tooth wear, go for the same high hardness steels chosen for shafts (such as in the hardened steel gear pictured above, from the TWM 3M gearbox).

3.9.10. Minimum Weight Spinning Bars and Eggbeaters

The material choice for the bars (blades) of horizontal and vertical spinners is very critical. Spinning bars can be modeled as beams or plates, depending on your design requirements. If their width and thickness are not restrained, which is usually true, then they can be analyzed as beams for minimum weight design. Eggbeaters (pictured to the right) also fall in this category, because they are basically two vertical spinning beams connected by two horizontal beams.



Note that minimum weight design does not mean that your spinning bar will have a low inertia, it only means that it will have high ratios between mechanical properties and weight. After optimizing your material, you'll be able to increase the bar thickness until reaching the desired weight or moment of inertia, and still have optimized mechanical properties.

All spinning bars need to have high K_{Ic}** grades, since they'll have to withstand their own inflicted impact, high E** grades to avoid hitting themselves due to excessive deflection at a sloped impact, and high S_y** not to get warped and therefore unbalanced.

There are several different material choices depending whether the bar itself needs to be sharp, blunt, or if it will have inserts made out of a different material at its tips, as discussed next.

Sharp one-piece spinning bars and eggbeaters

Sharp one-piece spinning bars (such as the one from the antweight Collision, to the right) and eggbeaters must have high hardness, to retain their sharpness. If we only select materials with HB' > 75, then we only have steels to choose from. The E** of steels is basically constant (it only varies between 45 and 49 for them). And all steels with very high hardness also have high yield strength, so we don't have to worry too much with S_y**, they would break before the yield deformations were high enough to cause unbalancing. We then decide to maximize the remaining grade, K_{Ic}**.

The result is that the best materials are AerMet 100 (K_{Ic}** = 53), 18Ni(300) (K_{Ic}** = 40) and AerMet 310 (K_{Ic}** = 38).

Other good choices are S7 steel at 54HRc (as in Hazard's sharp bar pictured to the right), 18Ni(350) and AerMet 340, but only if the bar or eggbeater is not heavily notched, because of their lower K_{Ic}** < 33.

If the bar or eggbeater is notched, it would probably be safer to use 5160 steel tempered to 46 HRc instead of S7, you will have a lower hardness (HB' = 65) but higher impact toughness. Note that these results also apply to sharp one-piece spears.

Blunt one-piece spinning bars and eggbeaters

If you want a minimum weight blunt one-piece spinning bar or eggbeater, then your hardness requirements can be somewhat relaxed. You still need medium-high hardness to be able to inflict damage, but it does not need to be too high since the weapon doesn't need to be sharp. This reasoning would also apply to one-piece hammers for hammer, thwack or overhead thwack bots.

We'll then choose materials with medium-high HB' > 45, with grade K_{Ic}** > 30, and order them by the average between these two grades, X** = (K_{Ic}** + HB') / 2, since both are important.

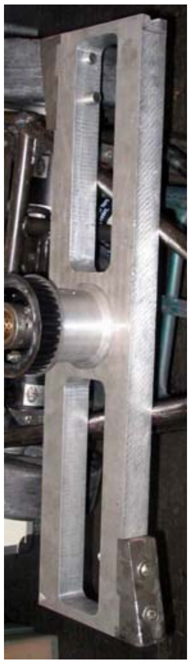
The result is that the best materials are AerMet 100, HP-9-4-30, 18Ni(250), Ti-6Al-4V ELI, 18Ni(200), 18Ni(300) and AerMet 310, all of them grading X** > 60. Ti-6Al-4V is the next choice (X** = 59). And 4340 steel is not too bad, as long as it is tempered to lower hardnesses between 34 and 39HRc to improve toughness (despite losing strength), instead of the usual 40 to 43HRc. But note that 4340 steel is usually sold in bar form, you might need to look for AR400 or 5160 steel plates.

Spinning bars and eggbeaters with inserts

If you want to improve the impact and fracture toughness of your spinning bar or eggbeater, then it is a good idea to use two different materials: a softer one for the bar itself, and a very hard one for inserts to be attached at its tips.

Now we have to worry again with E** and S_y**, since we won't be limiting our search to high hardness materials. So, to minimize the weight of spinning bars and eggbeaters with inserts, we'll choose materials with K_{Ic}** > 50, E** > 60 and S_y** > 60, and order them by the average grade X** = (K_{Ic}** + E** + S_y**) / 3.

The best choices are, in that order, ZK60A-T5, AZ31B-H24, Elektron 675-T5, 2324-T39 Type II, 7475-T7351, 7055-T7751 or T74, 7175-T736 and 7050-T7451, all with X** > 75. Other good options are Elektron WE43-T5, 7075-T73 or T6, Ti-6Al-4V ELI, Ti-6Al-4V and 2024-T3, all with X** > 70. Avoid using steels (X** < 58) or polymers (X** < 40).



The use of Mg and Al alloys has also the advantage of increasing the moment of inertia of the bar for a given weight. This is because you'll have a lighter material close to the spin axis, leaving more weight for heavier steel inserts at the tips, which will contribute much more to the moment of inertia due to their higher distance. Remember that the moment of inertia is proportional to the square of the distance of a certain mass to the spin axis. The aluminum spinning bars pictured to the right, from the middleweight The Mortician, not only have heavy steel inserts at their tips, but they also have pockets milled close to the spin axis or through-holes to optimize the weight distribution.

Note that the above optimum materials also apply to hammer handles (as pictured to the right), thwack or overhead thwack handles, and spears that have inserts.

Lifter and launcher arms would also be lighter if made out of these materials, since such arms are basically beams under bending stresses. But if using Mg or Al alloys in the lifter/launcher arm, make sure you'll have high hardness inserts at its tip to help wedge and scoop the opponent.

Low maintenance spinning bars and eggbeaters with inserts

As seen above, Mg and Al alloys make great spinning bars that have inserts. But, unless your inserts are large enough to shield and prevent any direct hits on such low hardness bar, you'll realize that the bar itself will need to be changed very often, due to ablation.

A low maintenance bar would need to have a higher hardness grade, for instance HB' > 45, in addition to the high average grade $X^{**} = (K_{Ic}^{**} + E^{**} + S_y^{**}) / 3$.

But these are exactly the requirements we used for minimum weight shafts and gears, so the optimum materials are the same: high strength Ti alloys are the best choice, followed by AerMet 100, 18Ni(250), 18Ni(200), HP-9-4-30, 18Ni(300), tempered 4340 (or AR400), and tempered 5160. Once again, avoid using S7 steel in the bar, leave it for the inserts. The spinning bar from the middleweight Terminal Velocity (pictured to the right) is an excellent example of optimum material choice: Ti-6Al-4V with S7 inserts.

Note that these materials also apply to low maintenance hammer, thwack or overhead thwack handles, to low maintenance spears that have inserts, and to low maintenance lifter and launcher arms, such as in the titanium hammer handle from the middleweight Deadblow (pictured to the right).

Spinning bars with minimum width restrictions

In all the above spinning bar analyses, it was assumed that both the bar width and thickness could be changed. But the bar must have a minimum width of, for instance, twice the diameter of its center hole, where the weapon shaft goes through. Smaller widths will probably compromise strength, as it will be shown in chapter 6. So, if the above calculations for minimum weight beam design result in a bar width that is smaller than, for instance, twice the center hole diameter, then the design strategy must be changed.

If this happens, then the bar width must be kept constant at this minimum value, while only the bar thickness can be changed in the design process. Thus, the problem is now a minimum weight plate design, instead of a minimum weight beam design. We'll have to use the plate grades K_{Ic}*, E* and S_y* instead of K_{Ic}**, E** and S_y**. The material choice for this bar with fixed width will then be the same as for a minimum weight spinning disk, as shown next.

3.9.11. Minimum Weight Spinning Disks, Shells and Drums

Spinning disks and shells usually have their diameter defined by the robot design, while only their thickness is a variable design parameter. The same is valid for drums, their external diameter and width are defined by the design of the robot structure, only leaving the drum thickness as a variable value. So, spinning disks, shells and drums are modeled as plates. Spinning bars with fixed width also fall in this category, as explained above.

Sharp one-piece spinning disks, shells and drums

One-piece spinning disks, shells and drums (pictured below) are usually a good option to maximize tooth strength and to minimize the number of parts.

The analysis is very similar to the one for sharp one-piece spinning bars, except that plate grades are used, instead of beam grades.

The disk, shell or drum also needs to retain its sharpness, so we choose materials with grades HB' > 75, K_{Ic}* > 20, S_y* > 50 and E* > 30, trying to maximize K_{Ic}*.

The best materials are then AerMet 100 (K_{Ic}* = 43), 18Ni(300) (K_{Ic}* = 35) and AerMet 310 (K_{Ic}* = 34). Other good choices are S7 steel at 54HRc, 18Ni(350) and AerMet 340, but only if the disk, shell or drum is not heavily notched, because of their lower K_{Ic}* ≤ 30. Note that these materials are exactly the same as the ones from the one-piece bar analysis, which is a coincidence, since different grades were used.

Blunt one-piece spinning disks and shells

Blunt one-piece spinning drums are not a good idea, they will have a hard time grabbing and launching the opponent. Sharpness is important for drums. But blunt one-piece spinning disks may be useful, in special if the one-piece disk has large teeth, and if it spins horizontally. Blunt one-piece spinning shells might also be useful.

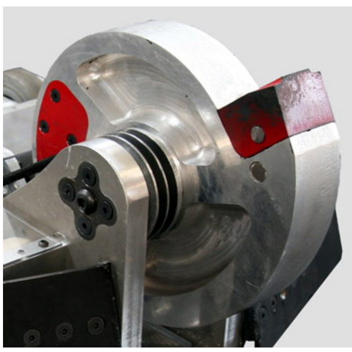
We can use the same material selection criteria from blunt one-piece spinning bars, as long as we change beam grades to plate grades, so we need HB' > 45 and K_{Ic}* > 30, ordered by the average X* = (K_{Ic}* + HB') / 2. Interestingly, these are exactly the same criteria that optimize traditional armor plates, resulting in almost the same materials.

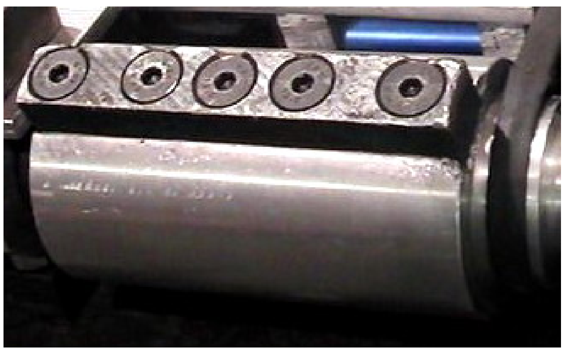
So, the best materials are then K12 Dual Hardness, AerMet 100, HP-9-4-30, AerMet 310, 18Ni(250), 18Ni(300), Ti-6Al-4V ELI, 18Ni(200) and Ti-6Al-4V, all of them with X* > 50. Tempered 4340 or 5160 steels are not bad options, but not one of the best. Avoid low hardness steels such as 1020 (which will yield very easily, as seen on the spinning disk tooth on the right), and medium-low toughness steels such as S7.

Note that the K12 Dual Hardness steel is probably a bad idea for disks. Although one of the disk surfaces would have HB’ = 100, the other one, which is also exposed, would only have HB’ = 73. K12 would be fine for shell spinners, as long as the harder surface is facing outwards.

Spinning disks, shells and drums with inserts

If your disks, shells or drums have inserts (as pictured below), then they can have a lower hardness to improve fracture toughness.





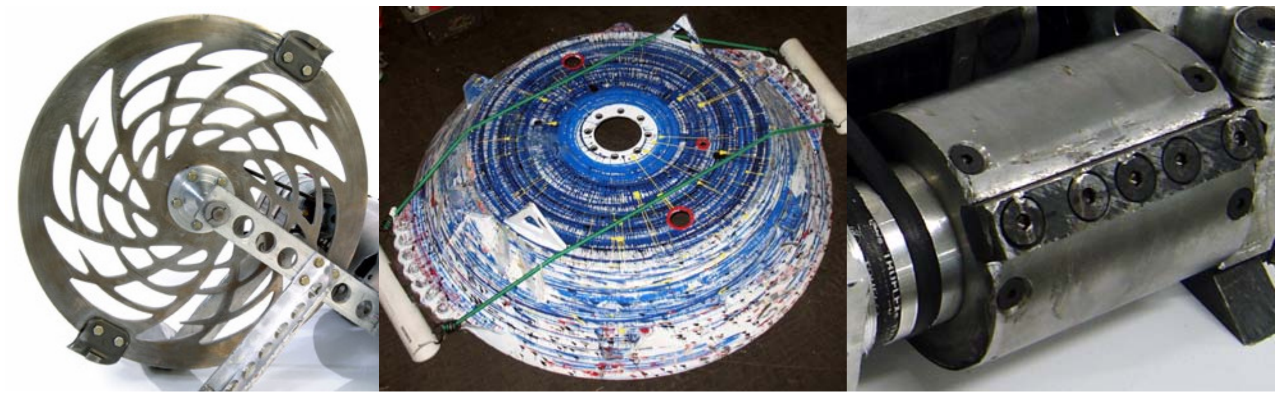
We can use material selection criteria similar to the ones for spinning bars with inserts, if the beam grades are changed to plate grades. So, we'll choose materials with $K_{Ic}^* > 50$, $E^* > 70$ and $S_y^* > 70$, and order them by the average grade $X^* = (K_{Ic}^* + E^* + S_y^*) / 3$. These are the same criteria used for integrated structure-armor plates, resulting in the same material choices: ZK60A-T5, AZ31B-H24, Elektron 675-T5, Elektron WE43-T5, 2324-T39 Type II, 7475-T7351, 7175-T736, 7055-T7751 or T74 and 7050-T7451, all of them with $X^* > 73$. The aluminum alloys 7075-T73 or T6 and 2024-T3 would be the next options. As we did with integrated structure-armor plates, avoid Ti alloys, steels and polymers.

Note that Ti-6Al-4V ELI is as good as most aerospace aluminum alloys for spinning bars with inserts, but it is significantly worse for spinning disks and drums with inserts. This is not an obvious conclusion, only after the above analyses we were able to show that.

So, the best spinning disks, shells and drums with inserts are made out of high toughness Mg and Al alloys. But these materials result in a high maintenance disk, shell or drum, due to ablation. The picture to the right shows that the aluminum drum of our featherweight Touro Feather, although still functional, has suffered a lot of ablation. This loss of material ends up unbalancing the drum, requiring it to be changed after a few tournaments. On the other hand, its tempered S7 steel teeth are high hardness inserts, with very little loss of material (despite some brittle chipping that can be noticed around their countersunk holes).

Low maintenance spinning disks, shells and drums with inserts

If you want a low maintenance disk, shell or drum, such as the ones pictured below, then you need to select a material with a higher hardness grade, for instance HB' > 45, in addition to the high average grade for plates $X^* = (K_{Ic}^* + E^* + S_y^*) / 3$.



If we also only choose materials with K_{Ic}* > 25, E* > 35 and S_y* > 40, to avoid distortions in the X* average, then we end up with exactly the same criteria for wedges. So, after having ruled out Mg and Al alloys due to their low hardness, the best materials would be Ti-6Al-4V ELI and Ti-6Al-4V, with X* equal to 64 and 63, respectively. The next choices would be AerMet 100, followed by 18Ni(250), HP-9-4-30, 18Ni(200), 18Ni(300), tempered 4340, AR400 and tempered 5160, all of them with X* > 42.

3.9.12. Minimum Weight Weapon Inserts

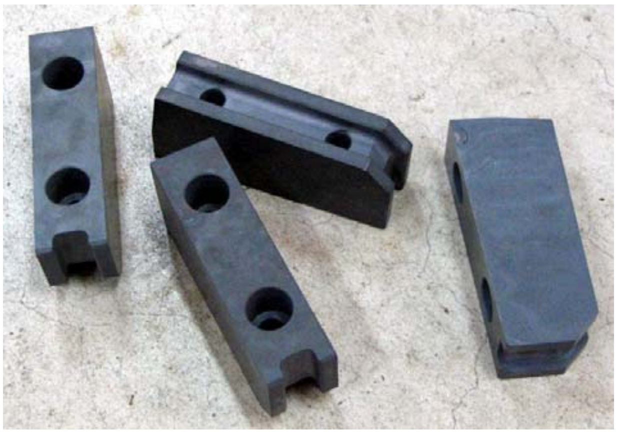
The most important properties of weapon inserts are high impact and fracture toughnesses. If they must remain sharp, then high hardness is also important. Three types of inserts are studied below.

Sharp plate-like weapon inserts

Clampers, lifters and launchers usually use sharp inserts at the tip of their arms to help scoop the opponent. These scoops are basically plates under bending, working as wedges. Therefore, the wedge design analysis can be used here, resulting in Ti-6Al-4V ELI and Ti-6Al-4V scoops. But the lower HB' between 49 and 50 of these alloys might require high maintenance to keep them sharp at every combat.

So, for a low maintenance scoop, a higher hardness is desired, for instance HB' > 75. With this new restriction, the same analysis used for sharp one-piece spinning disks can be applied for these scoops, resulting in AerMet 100 as the best material, followed by 18Ni(300), AerMet 310, S7 steel at 54HRc, 18Ni(350) and AerMet 340. Alternatively, 5160 tempered at 46HRc can be used, but it has a lower HB' = 65 than the other high strength steel options.

Sharp beam-like weapon inserts



Most weapon inserts, such as drum, disk, shell or bar teeth (pictured to the right), spear tips, or sharp thwack, overhead thwack or crusher tips, can be modeled as beams. This is because they usually have both their width and thickness (or their diameter) as free parameters.

To retain their sharpness, we need to select high hardness materials. Forget about Ti-6Al-4V inserts, its grade HB' = 50 won't stand a chance to keep sharp against hard traditional armor or wedge materials such as AR400, with HB' = 60. You'll need something harder than that, preferably with HB' > 75. These hardness and toughness requirements are then similar to the ones used for sharp one-piece spinning bars, resulting in the same optimal materials: AerMet 100 is the best, followed by 18Ni(300), AerMet 310, S7 steel at 54HRc, 18Ni(350) and AerMet 340, coincidently the same materials selected for sharp plate-like inserts.

Inserts usually have complex geometries, such as the puzzle-like fitting between the aluminum spinning bar from The Mortician and its hardened steel inserts, pictured to the right. These fittings are essential to guarantee a strong connection during high energy impacts, helping to avoid sheared bolts. Note, however, that sharp notches should be avoided in the insert, because the high hardness steel in general does not have a very high fracture toughness, typically K_{Ic}** < 33. So, if intricate geometries are necessary, use large notch radii (typically of a few millimeters) to avoid high stress concentration factors (denoted by K_t), which might lead to the fracture of the insert.

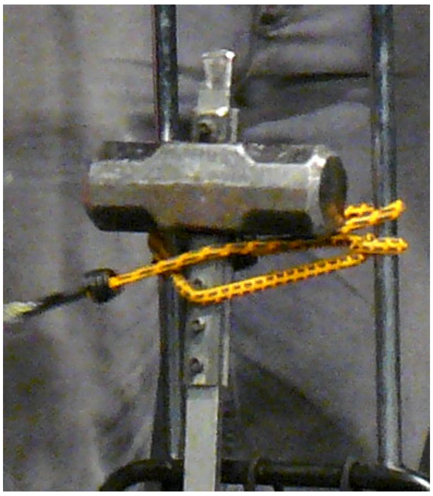
For instance, the K_t of an 8mm deep notch with a sharp 0.5mm radius can be roughly estimated by $K_t = 1 + 2 \cdot (8\text{mm} / 0.5\text{mm})^{0.5} = 9$, meaning that any stresses near this notch will be locally multiplied by 9. For very ductile and low hardness metals (such a 304 stainless steel) this may not be a problem, because these 9 times higher stresses will probably cause the notch to plastically deform and get blunt. This would increase the notch radius and thus decrease the K_t from 9 to much lower values, even lower than 2. But high hardness metals usually don't have enough ductility to blunt the sharp notch, keeping in this example the K_t in its original high value equal to 9. This is why we have to worry much more with sharp notches in high hardness metal components than in soft metals.

Even though the bar is usually made out of a softer material than its insert, it is also a good idea to avoid sharp notches as well in the bar (or disk, drum, handle). In special if the notch is very close to a threaded hole, which can have K_t of up to 7, because both K_t would get multiplied. For instance, if the sharp notch from the previous example (with $K_t = 9$) was very close to a threaded hole, the resulting K_t could be as high as $9 \times 7 = 63$. The amazing 63 times higher notch root stress would certainly break a very hard low ductility material. Tougher materials such as the ones used in the bars would be able to lower this K_t through blunting, but maybe it would still be high enough to cause fracture. So, avoid sharp notches at all costs. And never thread any hole from high hardness inserts, always leave the threads, if necessary, to the lower hardness bars, disks, drums and handles.

Using plain through holes can be a good option to avoid the stress concentration from the threads, as seen on the bar to the right, where nuts are used to hold the two bolts from the insert. Note, however, that through holes such as the ones shown in the picture should only be drilled in a very thick bar, otherwise they'll significantly lower its cross section area, compromising strength.

If your inserts are still breaking even after removing all sharp notches from their geometry, then you'll probably need to sacrifice hardness a little bit to improve the impact and fracture toughnesses, by changing the material or the heat treatment. Earlier versions of the S7 steel drum teeth of our middleweight Touro had been tempered to hardnesses between 57 and 59 Rockwell C (HRc), to guarantee their sharpness. However, as seen to the right, this led to their premature fracture in combat. The newer teeth now have a slightly lower 54 HRc hardness, but with a much better impact toughness.

Blunt beam-like weapon inserts



Hammer heads (as pictured to the right), which may be used in hammer, thwack or overhead thwack robots, are usually made out of blunt inserts, which do not need to be sharp. Medium-high hardness is still important, but now we can lower our minimum HB' grade requirement from 75 (for sharp inserts) to, for instance, 45, allowing us to have more material options and also improve other properties such as fracture toughness.

Since the diameter (or other cross-section dimensions) of hammer heads is a design parameter that can be varied, we conclude that these blunt inserts can also be modeled as beams. It is easy to see that these blunt inserts with HB' > 45 have basically the same requirements of blunt one-piece spinning bars, resulting in the same material choices: AerMet 100 as the best, followed by HP-9-4-30, 18Ni(250), Ti-6Al-4V ELI, 18Ni(200), 18Ni(300) and AerMet 310. Other good choices are Ti-6Al-4V, 4340 (at 34HRc) and 4340 (at 39HRc). So, if sharpness is not important, then high toughness titanium alloys are also good choices for inserts, together with high toughness hardened steels.

3.9.13. Minimum Weight Clamper and Crusher Claws

Since clamper and crusher robots have relatively slow active mechanisms, acting without impacts, it is more important to have claws with high S_u and S_y than high K_{Ic}. Claws are basically beams working under bending, therefore to minimize their weight it is important to choose materials with high S_u** and S_y** grades.

If high hardness inserts are used at the tips of the claws, as pictured to the right, then the choices for the claw material can include low hardness alloys. We then select the materials with a high average grade X** = (Su** + Sy**) / 2, resulting in Elektron 675-T5 as the best, followed by 7055-T7751, 7175-T736 and 7075-T6, all of them with X** > 85. Other reasonable choices are, in that order, 18Ni(350), 7050-T7451, Ti-6Al-4V, 7055-T74, ZK60A-T5, AerMet 340 and 7075-T73, all of them with X** > 80.

Note that these material choices didn't consider the possibility of the claws receiving impacts, in special from spinners. They assume that your robot will have some shield or wedge to be able to slow down the spinner before clamping or crushing it. Otherwise, you'll need to choose claw materials with high K_{Ic}** as well. So, if the claw must withstand high impacts as well, the best material choices would be the same as for spinning bars with inserts, such as the Mg alloys ZK60A-T5 and AZ31B-H24, which have high K_{Ic}** grades for beams.

Note also that the Mg and Al alloy options may require high maintenance, due to their low hardness. If low maintenance is also desired, then the best material choices would be the same as for low maintenance spinning bars with inserts, such as Ti-6Al-4V ELI.

Finally, if you want to use one-piece claws (as pictured to the right), without tip inserts, then very high hardness is required. The best choices would then be the same as for sharp one-piece spinning bars, such as AerMet 100 or 18Ni(300).

3.9.14. Minimum Weight Trusses

The weight optimization analysis of trussed elements, which can be used in the structure of trussed robots (as pictured to the right, using welded steel tube trusses), is relatively simple. Besides composites and Be alloys, we've shown that all steels, Al, Ti and Mg alloys result in similar stiffness-to-weight ratios for trusses, which depend on E/ρ. To find the best materials, it is then a matter of looking for the ones that maximize S_y/ρ, S_u/ρ and K_{Ic}/ρ at the same time, since a trussed robot structure needs high S_y not to get bent, high S_u to bear static loads and avoid fatigue, and high K_{Ic} to withstand impacts and cracks. The previous table shows the minimum weight truss grades E***, S_y***, S_u*** and K_{Ic}*** for several materials, obtained by normalizing the E/ρ, S_y/ρ, S_u/ρ and K_{Ic}/ρ ratios using the best materials in the table.

Most trussed robot designs have their trusses exposed or only partially covered by armor plates, allowing them to take direct hits. So, we'll give more importance to K_{Ic}*** than to S_u***. We choose then the materials that have higher average grade X*** = (K_{Ic}*** + S_y***) / 2, requiring as well that K_{Ic}*** > 40 and S_y*** > 50.

The best truss material from the table is Ti-6Al-4V ELI, followed by Ti-6Al-4V, AerMet 100, 18Ni(250) and 18Ni(200), all with X*** > 60. Other good choices are HP-9-4-30 and 4340 tempered to 39HRc, both with X*** > 50. Note that 304 stainless steel wasn't chosen, despite its high toughness, due to its low S_y that will allow the frame to easily get warped. And S7 and 18Ni(350) weren't chosen either, because of their insufficient fracture toughness.

The above options (with X*** > 50) are fine if the robot trusses will be bolted together. But if you want to use welds to join them, then their material will also need to have a high weldability. The above Ti alloys are still the best choice, but you might have trouble welding the presented high strength steel options, even the 4340 steel. There's no point in having high strength trusses if they're joined by weak welds. So, a good alternative to 4340 would be 4130 steel which, despite its lower S_y and S_u, results in stronger welds due to its lower 0.3% carbon content, instead of 0.4% from 4340. But note that, after welding the 4130 steel trussed frame, it needs to be heat treated to relieve residual stresses from the welds and to achieve higher S_y and S_u through temper. This means that repaired 4130 welds at the pits during a competition will probably be weak spots in the following fights, unless they're somehow heat treated.

Ti-6Al-4V and Ti-6Al-4V ELI, on the other hand, in addition to their highest X*** grades, don't need to be hardened after welding, resulting in a much better choice for repairs if proper welding equipment is available at the pits. Their only disadvantage is the higher cost.

Note that bamboo is not represented in the table, however it has a great stiffness-to-weight ratio for trusses, comparable to the performance of metals, grading E*** = 94. Its fracture toughness grade is not too bad, K_{Ic}*** = 31, comparable to low toughness aluminum alloys. The strength grades for trusses S_u*** = 19 and S_y*** = 19 are relatively low compared to high strength metals, however they are actually higher than the grades from 1020 steel, used in civil engineering. So, it's not a surprise to see that China is using bamboo-reinforced concrete to build high-rises. Note however that bamboo has only about half the K_{Ic}*** of 1020 steel, which might mean bad news during an earthquake. For combat, bamboo is not a good option, because most high strength metals will result in much better strength and toughness grades. Also, bamboo trusses, despite being light, would end up with a very high volume, leaving a limited room inside the robot to mount its components. Not to mention the challenge in putting together the bamboo trusses with strong and light joining elements.

3.10. Minimum Volume Design

All minimum weight problems presented in the previous section can be used to choose materials that make your robot lose weight without losing stiffness, strength or toughness. But what if a component needs to have its mechanical properties improved? Well, if there's space to increase the volume of the component (such as in most structural or armor elements), then this shouldn't be a problem, it is just a matter of weight optimization, using the grades from minimum weight design. If the material has not yet been optimized, then you should first change it depending on the functionality of the component, as explained before. After that, you only need to increase the component thickness (for plate elements) or cross section area (for beam and truss elements) until the desired improved properties are obtained.

But there are other components that cannot (or should not) have their volume increased. For instance, a gear that keeps breaking cannot be replaced by a thicker one without modifying the gearbox. A shaft that keeps yielding cannot have its diameter increased without changing its bearings and collars. These examples are volume optimization problems, requiring a minimum volume design, instead of minimum weight, as described next.

Minimum volume design has the goal to find the best materials to optimize the performance of a component while minimizing its volume. It assumes that the weight of the component can be increased, if necessary, but in most cases its dimensions cannot be changed. The idea is to design a component for a desired functionality with the lowest possible volume. Alternatively, if a component is failing in combat and its dimensions should not be changed, then the idea is to improve its mechanical properties only by switching its material, without changing its dimensions, while adding as little weight as possible.

Minimum volume design is quite straightforward in the case where the dimensions must be kept constant. Since the volume is not changed, it is just a matter of directly comparing the material properties. This is more easily performed if we normalize the mechanical properties using the best materials from the presented table, resulting in a system of grade points between 0 and 100 for minimum volume. These grades are represented by the property followed by the ' symbol, namely E', S_y', S_u' and K_{Ic}', shown in the previous table.

Note that minimum volume grades are completely different than minimum weight grades. Polymers are always the worst choice, by far, for minimum volume parts, with grades lower than 4 (out of 100). Al and Mg alloys are also very bad options, none of their grades is higher than 35. Even Ti alloys are not good, their highest grades only go up to 53.

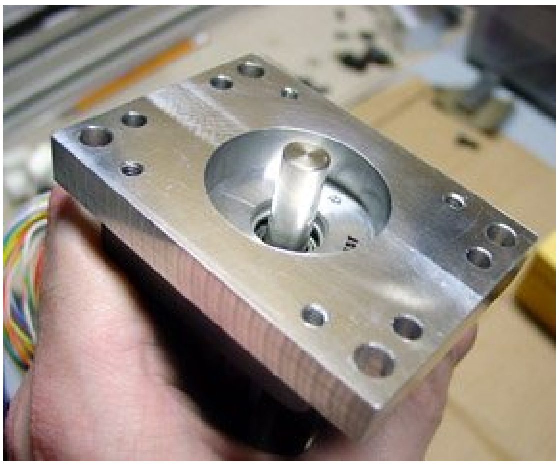
Therefore, steels are always the best choice if you need to minimize volume. Their E' grades are always between 88 and 100. The best material from the table for a minimum volume component with high yield and ultimate strengths is the 18Ni(350) maraging steel, with $S_y' = 100$ and $S_u' = 100$. The best choice to maximize fracture toughness is the 304 stainless steel, with $K_{Ic}' = 100$.

Note that, except for titanium alloys, almost all S_u' grades are only within 4 points from HB' grades. This is no surprise, because there are good correlations between S_u and hardness for different metal alloy families, as mentioned before. For instance, you can estimate $S_u \cong 3.4 \cdot HB$ for steels within a few percent. So, in most metals, high hardness and high S_u usually come together for minimum volume design. This trend is also true for titanium alloys, but the correlations are not as good.

Note also that the S_u grades are very different than HB grades for minimum weight design, because the strength of the component depends not only on its material but also on its shape and functionality, while hardness is a local property that only depends on the material.

The main minimum volume design problems in combat robots are presented next.

3.10.1. Compact-Sized Internal Mounts



Very compact robots sometimes need to minimize the volume of internal mounts so they can fit inside. For instance, an internal mount attached to the face plate of a drive system motor may have thickness limitations, in special if the motor cannot be shifted too much inside the robot or if its output shaft is not too long, as pictured to the right. If the 6061-T6 aluminum motor mount in the picture didn't have enough stiffness or strength, you'd probably have to switch its material. Minimum weight design would tell you to use magnesium alloys, but their higher thickness (despite their lower weight) would make it hard to mount any wheel or pulley in such short output shaft. This is a problem of minimum volume design.

So, to improve the properties of the internal mount, we'd need to choose materials with better minimum volume grades. Since internal mounts should have high stiffness as well as high ultimate and yield strengths, we'll select materials with highest average grade $X' = (E' + S_u' + S_y') / 3$.

The best material to minimize volume would then be 18Ni(350) maraging steel, followed by AerMet 340, AerMet 310, 18Ni(300), AerMet 100 and S7 tempered at 54HRc, all of them with average grade X' > 80. Other options would be 18Ni(250), HP-9-4-30, and 4340 tempered to 43HRc, all with X' > 70. But note that all these steels will result in heavier mounts. This is the price you pay to minimize volume.

If you're also concerned with weight, then you'll have to compromise a little the minimum volume requirement. The idea is to find the lowest density material that will satisfy your X' requirement, without significantly increasing the volume of the component.

For instance, in the above example, the 6061-T6 aluminum has X' = 19 and density $\rho = 2.7$. We won't even bother looking for polymers or Mg alloys, because mounts with same volume would have much worse mechanical properties since their X' is always below 3 and 17, respectively. For polymer or Mg alloy mounts to have similar or better mechanical properties than our 6061-T6 mount, they would need to have a much higher thickness, due to their lower density.

We'll then start looking among all aluminum alloys, which have approximately the same density ρ, between 2.66 and 2.86. The highest X' among them is 28.5, for the 7055-T7751 alloy, which would result in a better mount with about the same weight and volume as the 6061-T6 version.

If this X' is still low for your application, or if you still need to decrease the thickness (and therefore the volume) of the mount, then look into Ti alloys. Their density ρ between 4.4 and 4.6 is not too much higher, and you'll be able to achieve X' = 43.7 for the alloy Ti-6Al-4V.

Finally, if you still need a higher X' or a lower thickness, look into steels. You'll end up with a heavier mount, due to their higher density ρ between 7.7 and 8.0, but you'll be able to achieve up to X' = 98.9 for high strength alloys such as 18Ni(350). And you'll be able to get a much thinner mount, such as the steel motor mount pictured to the right.

3.10.2. Compact-Sized Drums

Spinner bars and disks naturally have a high moment of inertia. Therefore, usually the inertia and strength requirements can be met just by switching the material and changing the bar or disk thickness, which was already studied in minimum weight design. On the other hand, designing a compact drum is a little trickier, as seen next.

Compact-sized drums with inserts

If we assume that the drum thickness can be changed (changing the drum internal diameter), then we're facing a minimum weight design problem. It was already seen that Mg and Al alloys with high strength and toughness are the best options for drums with inserts, optionally using Ti-6Al-4V for low maintenance versions.

This could be fine for very fast spinning drums, such as the aluminum drum of our featherweight Touro Feather, which compensates its low moment of inertia with a high spin. Or it could be fine for drums with large outer diameter, such as the aluminum drum from the middleweight Stewie, which can reach a large moment of inertia despite its low density material.

But our low profile drumbot Touro has limited values for the drum outer diameter D (about 5", without its S7 teeth inserts), as well as for its mass m (about 11.6kg or 25.6lb) and length L (180mm, a little over 7"). These values cannot be arbitrarily increased without changing the design of the rest of the robot. A minimum weight design would select the low density Mg or Al alloys, which would result in a drum with high thickness and therefore low internal diameter d. For a drum material with density ρ, it is easy to show that $d^2 = D^2 - 4m/\rho\pi L$, which lowers as ρ decreases.

But, for a given drum mass m and outer diameter D, a very low internal diameter d would lower the moment of inertia $I_{zz} \cong m \cdot (D^2 + d^2)/8$. For Touro, we decided that the resulting lower I_{zz}, combined with a moderate 6,000RPM drum speed, would make an Al or Mg drum have low energy. To maximize I_{zz}, we had to use a material with the highest possible density. A natural choice was steel, due to its ρ between 7.7 and 8.0. Denser metals would be either too expensive (such as tungsten, tantalum, silver, gold, platinum), too brittle if unalloyed (such as molybdenum, cobalt), or too soft (such as lead).

By selecting steels, we were able to get a 1” thick drum wall, which was thick enough to mill channels to hold the teeth without compromising its strength. If the resulting thickness was too thin, we would probably need to use the lower density Ti-6Al-4V for the drum, reducing somewhat the I_{zz} but adding enough thickness to be able to mill the channels without compromising strength.

But now, which steel should we use? We once tried a hardened 410 stainless steel for the drum body, trying to achieve a low-maintenance drum. This was not a good choice, because this high strength steel has only a moderate fracture toughness, while the drum body has several stress risers such as milled channels and threaded holes. Not surprisingly, the drum not only fractured along the threaded holes, but also sheared at the notch root of its tooth channel (as seen on the right), all at the same time during its first impact test against a dead weight.

We had to change the material to improve the impact toughness. Since it is a minimum volume problem, we had to look at the E', S_y', S_u' and K_{Ic}' grades of the material candidates. We know that the drum does not lose functionality if it yields locally, so S_y’ is not that important for drums that have teeth inserts (unless there’s some major yielding that might compromise the tooth support or unbalance the drum). The grade E’ is almost the same for all steels, so it doesn't need to be considered.

Most of the loads on the drum are due to impacts, related to the grade K_{Ic}'. The static loads, related to the grade S_u', are relatively small, they're mostly due to the centrifugal forces of the drum teeth. For instance, each of the 0.63kg (1.39lb) teeth from the 2007 version of Touro's drum, which spin at 6,000RPM (628 rad/s) from a radius 0.065m (2.56"), generates a centrifugal force equal to $0.63 \cdot 628^2 \cdot 0.065 = 16{,}150$N, equivalent to 1,646 kgf or 3,629 lbf. This might seem a large static force, but it is small compared to the dynamic loads generated when hitting a stiff opponent. So, the grade S_u' is not as important as K_{Ic}'.

So, this is a volume optimization problem to maximize K_{Ic}'. The best option among the studied materials is the 304 stainless steel, with $K_{Ic}' = 100$. Other good options are, in that order, 4340 tempered at 34HRc, 18Ni(200), 1020 steel, HP-9-4-30, 18Ni(250), 4340 at 39HRc and AerMet 100, all of them have $K_{Ic}' > 50$.

Avoid using S7 steel, its K_{Ic}' at 54HRc is only 25, it could break in a similar way as shown above, near the notches. If the drum has inserts, there is no need to make the drum body out of a very hard material, lowering its impact toughness. Use hard materials only where they are needed, such as on the drum teeth, which must remain sharp. Avoid as well using other steels that might have $K_{Ic}' < 50$.

Avoid using as well polymers, magnesium, aluminum and titanium alloys, not only due to their low density, but also due to their $K_{Ic}' < 50$.

This is why Touro's drum body is made out of 304 stainless steel ($K_{Ic}' = 100$), to hold the sharp tempered S7 steel teeth. The only downside is the low yield strength of 304, but this is not much of a problem for the body of a drum. It easily yields, but it also withstands huge impacts, such as the one that broke the spinning bar of Terminal Velocity at Robogames 2007 (the resulting indentation is pictured to the right).

The drum body of our lightweight Touro Light had already been machined using 410 stainless steel, the same material from Touro's fractured drum, before that fracture happened. Instead of machining another drum out of 304 stainless steel, we've decided to save money by keeping the 410 version, but without hardening it through heat treatment. Without tempering the 410 steel, it ended up with a much higher impact toughness than the tempered version, and the much lower yield strength wouldn't be a problem for the drum body. The 304 steel would be a better choice, but the 410 steel without temper was almost as good, surviving Robogames 2007 while leading Touro Light to a gold medal.

Compact-sized sharp one-piece drums

Sharp one-piece drums have their body and teeth milled out of a single bar or block, as a single piece. They are not very popular with the heavier robots, because they're not easy to machine, and if a tooth breaks they need to be entirely replaced.

But they're a good option for lighter robots, such as insects. Teeth inserts for insect classes are very delicate to machine and temper, and they're not simple to attach to the tiny drum body. Teeth made out of hardened flat-headed allen bolts are a popular choice, but their hardness never exceeds 44 Rockwell C, even if using class 12.9 bolts. A one-piece drum can be hardened between 51 and 55 Rockwell C and still have a high toughness, if its material is wisely selected.

To maximize the one-piece drum moment of inertia, it is important to choose a dense material such as steel. So, if the drum outer diameter and width cannot be changed, then we end up facing a minimum volume problem.

We'll choose then steels that have minimum volume grades $HB' > 70$ to guarantee tooth sharpness, $K_{Ic}' > 20$ to avoid drum body or tooth fracture, and $S_y' > 60$ to avoid bent teeth. By choosing the average $X' = (K_{Ic}' + HB') / 2$ as a grading criterion, the best materials are AerMet 100, 18Ni(250), 18Ni(300), and AerMet 310, all of them with $X' > 55$. Another good choice is S7 steel tempered at 54HRc. Avoid using polymers, Mg, Al or Ti alloys, or steels with low hardness or with $X' < 45$.

3.10.3. Compact-Sized Shafts, Gears and Weapon Parts

Shafts, gears and most weapon parts are subject to impacts. If their volume cannot be increased but their mechanical properties must be improved, then we face again a minimum volume problem.

For instance, the weapon system of our middleweight spinner Titan originally used a TWM 3R2 gearbox. This nicely crafted sturdy gearbox is made out of a solid aerospace aluminum block, with tempered steel gears and a special titanium shaft adapted for spinning weapons. After very severe tests and a lot of abuse, we ended up bending the titanium shaft (pictured to the right). The shaft dimensions cannot be increased, otherwise it won't fit in the gearbox, so it's a minimum volume problem. We thought that an S7 steel shaft tempered to 54 Rockwell C (HRc) would be a good replacement, despite its higher weight. It has more than twice the ultimate and yield strengths of Ti-6Al-4V, which would certainly prevent it from getting bent. But our S7 steel shaft ended up breaking in similar tests (see picture above). Experiments don’t lie. So why did it happen?

S7 steel already has lower toughness than Ti-6Al-4V in specimens without notches, as seen from their minimum volume grades K_{Ic}' equal to 25 and 33, respectively. It is not much of a difference, but this difference is exacerbated if sharp notches are present. By notch we mean any change in the geometry of the part, such as holes, grooves, fillets. Sharp notches should always be avoided because they are stress risers. But sometimes they are inevitable, such as in keyways.

Our titanium shaft was so ductile (with $\varepsilon_f = 45\%$) that it was able to blunt its sharp notches during the impact and avoid the effects of stress concentration. It’s true that it got bent, but at least it withstood the impact without breaking (a broken shaft in your bot will award your opponent many more damage points from a judge than a bent one). But the lower ductility of the S7 steel wasn’t able to blunt the sharp notches from its keyway, concentrating the impact energy on that point and making it break. In summary, S7 is notch-sensitive, it exhibits relatively high impact strength in the unnotched condition or if it has notches with generous radii, but it has a very severe degradation in its impact absorbing ability if it has sharp notches. So, S7 steel was a poor choice.

One alternative would be to change the keyway geometry to increase the notch radius, switching the square key to a round one. Another option would be to change the material to 4340 steel tempered to 43 Rockwell C, which would result in about the same ductility as Ti-6Al-4V ($\varepsilon_f = 45\%$) and a much higher S_u = 1450MPa. This combination would result in a much better impact strength than both S7 and Ti-6Al-4V, even in the presence of notches, due to 4340's relatively high ductility, preventing it from breaking. And its higher ultimate and yield strengths would prevent it from getting permanently bent as it happened with the Ti-6Al-4V shaft.

But there are even better options than 4340 steel. Let's look for materials with minimum volume grades $K_{Ic}' > 30$ to avoid fracturing, and $S_y' > 50$ to avoid getting bent, ordering them by their average grade $X' = (K_{Ic}' + S_y') / 2$. Hardness and stiffness are also important in shafts, as discussed before, so let's look as well for HB' > 45 and E' > 85.

So, the best materials for compact-sized shafts are, in that order, 18Ni(250), AerMet 100, and 18Ni(200), all of them having X' > 60. Other good options are 18Ni(300), AerMet 310, HP-9-4-30, 4340 (tempered to 40-43HRc), and 5160 (tempered to 44-46HRc), all of them with X' > 45. Avoid using polymers, Mg, Al or Ti alloys, medium-low strength steels (such as 1020, 1045 and 304), and medium-low toughness steels (such as S7, 18Ni(350) and AerMet 340)

The above material choices are also applicable to compact-sized gears, which must also have high K_{Ic}' and S_y', together with high HB' to prevent tooth wear, and high E' to prevent excessive deflections.

Compact-sized weapon parts that do not get in touch with the opponent can also be included in this category.

But if the weapon part touches the opponent, then its material choice should be the same one used for compact-sized one-piece drums, to retain sharpness due to HB' > 70 instead of only requiring HB' > 45, resulting in AerMet 100, 18Ni(250), 18Ni(300), AerMet 310 and S7 steel tempered at 54HRc, and excluding lower hardness options such as 4340 and 5160.

3.11. Conclusions on Materials Selection

The main conclusions from the material optimization analyses presented in this chapter are:

- aluminum and magnesium alloys in general, especially the high strength ones, are a very good choice for protected structural walls, integrated structure-armor, structural top covers, bottom covers, ablative armor and internal mounts. They're also a good choice for the body of weapons that have inserts, such as spinning disks, shells, drums, bars and eggbeaters with inserts, hammer, thwack or overhead thwack handles, spears with inserts, lifter and launcher arms with inserts, and clamper and crusher claws with inserts. In all the above applications, avoid using steels, even high performance steel alloys.

- Ti-6Al-4V titanium, in special the ELI version, is the best material for wedges and for minimum weight shafts, gears and trusses. It is a very good option for the body of low maintenance weapons that have inserts, such as low maintenance spinning disks, shells, drums, bars and eggbeaters with inserts, and low maintenance hammer, thwack or overhead thwack handles. It is very good as well for blunt weapons such as blunt one-piece spinner disks, shells, bars and eggbeaters, blunt hammer heads, and blunt thwack or overhead thwack tips. It is also a good option for traditional armor, rammer shields and non-structural top covers.

- steels that combine high toughness, high strength and high hardness are the best materials for traditional armor, rammer shields, non-structural top covers, as well as compact-sized shafts, gears and weapon parts. They are also the best option for sharp weapon parts such as one-piece spinning disks, shells, drums, bars and eggbeaters, one-piece spears, and sharp weapon inserts (such as teeth, spear tips, clamper, lifter or launcher scoops). Together with Ti-6Al-4V, they're also a good option for blunt one-piece spinner disks, shells, bars and eggbeaters, blunt hammer heads, blunt thwack or overhead thwack tips, and minimum weight trusses.

- because shafts are basically beams under bending (and torsion), theoretically aluminum and magnesium alloys would be better candidates than steels for minimum weight shafts. However, an aluminum shaft would need to have a much larger diameter than an equivalent one made out of steel, which would imply in larger bearings, larger gears and pulleys, and larger gearboxes, increasing the robot weight. Therefore, hardened steel shafts are better than aerospace aluminum ones. Ti-6Al-4V titanium is the best option for minimum weight shafts, as long as the weight saved by the shaft is not gained by the slightly larger bearings, gearboxes, etc, when compared to the ones from a steel shaft. As a reference, steel shafts that drive the wheels of robust middleweights usually have diameters between 15 and 20mm (0.59" and 0.79", but it depends on the robot type and number of wheels it uses), and the main steel shafts for spinning weapons may vary from 25 to 40mm in diameter (0.98" to 1.57", but it depends, of course, on the weapon type).

- avoid using plastics such as Lexan in the robot structure, even as armor plate. Even relatively tough polymers such as Lexan and UHMW are not recommended to be used as structural parts. Structural plates made out of the best polymers can achieve higher stiffness-to-weight, strength-to-weight and toughness-to-weight ratios than most steels, however high strength aluminum and magnesium alloys are much better in all those cases. In addition, polymer plates need to be very thick to outperform steels, which will significantly increase the volume of the robot. Lexan used to be an attractive armor material due to its transparency to radio signals, because an all-metal robot used to suffer from the Faraday cage effect. However, the high frequency radios used nowadays, such as the 2.4GHz ones, do not have much problem with all-metal robots. So, plastics should be avoided in structural parts. Plastics are a good option, however, for internal mounts that do not have volume restrictions (such as UHMW motor mounts), or for other specific applications described in section 3.7.

The table in the next page summarizes all the weight and volume optimization analyses performed in this chapter.

	Applications	Grading criteria	Best material choices (in order of preference)	Good material choices (in order of preference)	Avoid using
minimum weight plates	Internal mounts; **or** Protected structural walls; **or** Bottom covers	E* > 70 order by X* = (E*+S_u^*+S_y^*)/3	Mg alloys (E*>90, X*>85): Elektron 675-T5, ZK60A-T5, AZ31B-H24, Elektron WE43-T5	7000 series Al alloys (E*>70, X*>77): 7055-T7751, 7175-T736, 7075-T6, 7050-T7451, 7055-T74	Ti-6Al-4V (E*=54, X*<67), steels (E*<40, 28<X*<55), polymers (48<E*<56)
	Integrated structure-armor; **or** Structural top covers; **or** Spinning disks, shells or drums with inserts	K_{Ic}^* > 50, E* > 70, S_y^* > 70, order by X* = (K_{Ic}^*+E*+S_y^*)/3	ZK60A-T5, AZ31B-H24, Elektron 675-T5, Elektron WE43-T5, 2324-T39 Type II, 7475-T7351, 7175-T736, 7055-T7751 or T74, 7050-T7451 (all of them with X*>73)	7075-T73 or T6, 2024-T3, Mg and Al alloys with high strength and toughness (X*>63)	Ti-6Al-4V (E*=54, S_y^*<70), steels (E*<40, S_y^*<70), polymers (K_{Ic}^*<45)
	Wedges; **or** Low maintenance spinning disks, shells or drums with inserts	HB' > 45, K_{Ic}^* > 25, Sy* > 40, E* > 35, order by X* = (K_{Ic}^*+E*+S_y^*)/3	Ti-6Al-4V ELI (X*=64), Ti-6Al-4V (X*=63)	AerMet 100, 18Ni(250), HP-9-4-30, 18Ni(200), 18Ni(300), tempered 4340, AR400, tempered 5160 (all with X*>42)	Mg, Al, polymers, low strength steels, low strength Ti alloys
	Traditional armor; **or** Rammer shields; **or** Non-structural top covers; **or** Blunt one-piece spinner disks or shells	HB' > 45, K_{Ic}^* > 30, order by X* = (K_{Ic}^*+HB')/2	K12 Dual Hardness (except for disks), AerMet 100, HP-9-4-30, AerMet 310, 18Ni(250), 18Ni(300), Ti-6Al-4V ELI, 18Ni(200), Ti-6Al-4V (all of them with X*>50)	Ti and steels with both high toughness and high hardness (such as X*>37); possibly use tempered 4340 or 5160 steel	Mg, Al, polymers, low hardness steel and Ti alloys (1020 steel, Ti grade 2), medium-low toughness steels (S7, 18Ni(350), AerMet 340)
	Ablative armor	HB' < 30, K_{Ic}^* > 55, order by K_{Ic}^*	ZK60A-T5, AZ31B-H24, 5086-H32, 2324-T39 Type II, 7475-T7351, 7055-T74 (all of them with K_{Ic}^*>69)	most Mg alloys, high toughness Al alloys (K_{Ic}^*>55)	polymers (K_{Ic}^*<45), Ti alloys and steels (not ablative because of high melting point and HB' >> 30)
	Sharp one-piece spinning disks, shells or drums; **or** Sharp plate-like weapon inserts (sharp clamper, lifter or launcher scoops)	HB' > 75, K_{Ic}^* > 20, S_y^* > 50, E* > 30, order by K_{Ic}^*	AerMet 100, 18Ni(300), AerMet 310 (all of them with K_{Ic}^*>33)	S7 steel at 54HRc, 18Ni(350), AerMet 340; possibly use 5160 at 46HRc (but this leads to only HB' = 65)	Mg, Al, Ti, polymers, steels with hardness lower than 45HRc
minimum weight beams	Sharp one-piece spinning bars or eggbeaters; **or** Sharp one-piece spears; **or** Sharp beam-like weapon inserts (teeth; spear or other sharp tips)	HB' > 75, K_{Ic}^{**} > 20, S_y^{**} > 50, E** > 30, order by K_{Ic}^{**}	AerMet 100, 18Ni(300), AerMet 310 (all of them with K_{Ic}^{**}>38)	S7 steel at 54HRc, 18Ni(350), AerMet 340; possibly use 5160 at 46HRc (but this leads to only HB' = 65)	Mg, Al, Ti, polymers, steels with hardness lower than 45HRc
	Blunt one-piece spinning bars and eggbeaters; **or** Blunt beam-like weapon inserts (hammer heads; blunt thwack or overhead thwack tips)	HB' > 45, K_{Ic}^{**} > 30, order by X** = (K_{Ic}^{**}+HB')/2	AerMet 100, HP-9-4-30, 18Ni(250), Ti-6Al-4V ELI, 18Ni(200), 18Ni(300), AerMet 310 (all X**>60)	Ti-6Al-4V, 4340 (at 34HRc), 4340 (at 39HRc), Ti and steels with both high toughness and high hardness (X**>37)	Mg, Al, polymers, low hardness steel and Ti alloys (1020 steel, Ti grade 2), medium-low toughness steels (S7, 18Ni(350), AerMet 340)
	Spinning bars and eggbeaters with inserts; **or** Hammer, thwack or overhead thwack handles; **or** Spears with inserts; **or** Lifter and launcher arms with inserts	K_{Ic}^{**} > 50, E** > 60, S_y^{**} > 60, order by X** = (K_{Ic}^{**}+E**+S_y^{**})/3	ZK60A-T5, AZ31B-H24, Elektron 675-T5, 2324-T39 Type II, 7475-T7351, 7055-T7751 or T74, 7175-T736, 7050-T7451 (X**>75)	Elektron WE43-T5, 7075-T73 or T6, Ti-6Al-4V ELI, Ti-6Al-4V, 2024-T3 (X**>70), high strength Mg, Al and Ti alloys with X**>60	polymers (X**<40), steels (X**<58)
	Minimum weight shafts and gears; **or** Low maintenance spears, lifter and launcher arms, or spinning bars or eggbeaters with inserts; **or** Low maintenance hammer, thwack or overhead thwack handles	HB' > 45, K_{Ic}^{**} > 25, S_y^{**} > 40, E** > 40, order by X** = (K_{Ic}^{**}+E**+S_y^{**})/3	Ti-6Al-4V ELI (X**=73), Ti-6Al-4V (X**=72)	AerMet 100, 18Ni(250), 18Ni(200), HP-9-4-30, 18Ni(300), tempered 4340, AR400, tempered 5160 (all of them with X**>50)	Mg, Al, polymers, low strength steel and Ti alloys
	Clamper and crusher claws with inserts	high S_u^{**} and S_y^{**}, order by X** = (S_u^{**}+S_y^{**})/2	Elektron 675-T5, 7055-T7751, 7175-T736, 7075-T6 (all of them with X**>85)	18Ni(350), 7050-T7451, Ti-6Al-4V, 7055-T74, ZK60A-T5, AerMet 340, 7075-T73 (all of them with X**>80)	Al and Mg alloys with low Sy, most steels, polymers
trusses	Minimum weight trusses	K_{Ic}^{***}>40, S_y^{***}>50, order by X*** = (K_{Ic}^{***}+S_y^{***})/2	Ti-6Al-4V ELI, Ti-6Al-4V, AerMet 100, 18Ni(250), 18Ni(200) (X***>60)	HP-9-4-30, 4340 tempered at 39HRc (all with X***>50); possibly use tempered 4130	Mg, Al, polymers, low strength steel and Ti alloys
minimum volume design	Compact-sized internal mounts	E' > 85 order by X' = (E'+S_u'+S_y')/3	18Ni(350), AerMet 340, AerMet 310, 18Ni(300), AerMet 100, S7 tempered at 54HRc (all of them with X'>80)	18Ni(250), HP-9-4-30, 4340 tempered at 43HRc (all of them with X'>70)	polymers, Mg, Al, Ti alloys, steels with X' < 50
	Compact-sized drums with inserts	ρ > 7.5, K_{Ic}' > 50, order by K_{Ic}'	304 stainless (K_{Ic}' = 100)	4340 tempered at 34HRc, 18Ni(200), 1020 steel, HP-9-4-30, 18Ni(250), 4340 at 39HRc, AerMet 100	polymers, Mg, Al, Ti alloys; steels with K_{Ic}' < 50
	Compact-sized sharp one-piece drums	ρ > 7.5, HB' > 70, K_{Ic}' > 20, S_y' > 60, order by X' = (K_{Ic}'+HB')/2	AerMet 100, 18Ni(250), 18Ni(300), AerMet 310 (all of them with X' > 55)	S7 tempered at 54HRc	polymers, Mg, Al, Ti alloys; steels with low hardness or with X' < 45
	Compact-sized shafts, gears and weapon parts	HB' > 45, K_{Ic}' > 30, S_y' > 50, E' > 85, order by X' = (K_{Ic}'+S_y')/2	18Ni(250), AerMet 100, 18Ni(200), all of them with X' > 60	18Ni(300), AerMet 310, HP-9-4-30, 4340 (tempered to 40-43HRc), 5160 (tempered to 44-46HRc), all of them with X' > 45	Mg, Al, Ti, polymers, steels with medium-low strength (1020, 1045, 304) or toughness (S7, 18Ni(350), AerMet 340)

It is interesting to note that the know-how of experienced builders, coupled with the "survival of the fittest" principle from the theory of evolution, has made several combots converge to very good if not the best material choices studied in this chapter, for instance:

- AR400 (or 4340 steel) for very hard wedges, or Ti-6Al-4V for not-so-hard wedges, both used by Devil's Plunger;
- spinner bars made out of aerospace aluminum and lightly notched S7 steel inserts, used by Last Rites and The Mortician;
- shock mounted Ti-6Al-4V top covers against vertical spinners, used by Pipe Wench;
- Ti-6Al-4V for very light shafts, such as the ones used in the TWM 3M gearboxes;
- aluminum alloys as integrated structure-armor elements, such as Team Plumb Crazy's 6061-T6 extrusions for the unprotected walls (which in theory are unprotected, as long as we do not define red wheels as armor elements!); and
- trussed robots made out of welded and tempered 4130 steel tubes, as in Last Rites and The Mortician (noting that 4130 steel is not the best truss option, but it is the cheapest and most easily weldable among the good ones).

On the other hand, this chapter has shown that there's still a lot to evolve, such as:

- making more use of high strength magnesium alloys for structural parts;
- using high toughness magnesium and aluminum alloys as ablative armor plates;
- using AerMet and maraging alloys in weapon inserts, replacing S7 steel, as well as in compact-sized shafts, replacing 4340 steel, and even in traditional armor plates, replacing Ti-6Al-4V; and
- replacing Ti-6Al-4V with Ti-6Al-4V ELI to improve impact toughness.

Finally, one might think that several high performance materials discussed in this chapter aren't used in combat because of high cost, but this is not entirely true. Most of them are not used because they're not very well known or understood. Magnesium alloys are the third most used structural metal in the world, it is not difficult to find high strength Mg alloys in surplus dealers at a low cost. The ELI version of Ti-6Al-4V, with improved impact properties, is not too difficult to find either. Maraging steels are expensive, but they can be bought in small quantities, they're worth using in critical compact shafts. AerMet alloys such as AerMet 100, on the other hand, are not only expensive, they're difficult to buy in small quantities, they're difficult to machine, and their heat treatment is very complicated, but it is worth the trouble if you want a steel as hard as S7 with 2.15 times higher impact toughness.

I hope that this chapter will, among other things, help making these high end materials more popular in combat robot design.

In the following chapter, the joining elements are studied, necessary to join the presented materials with enough stiffness and strength.

Chapter

4

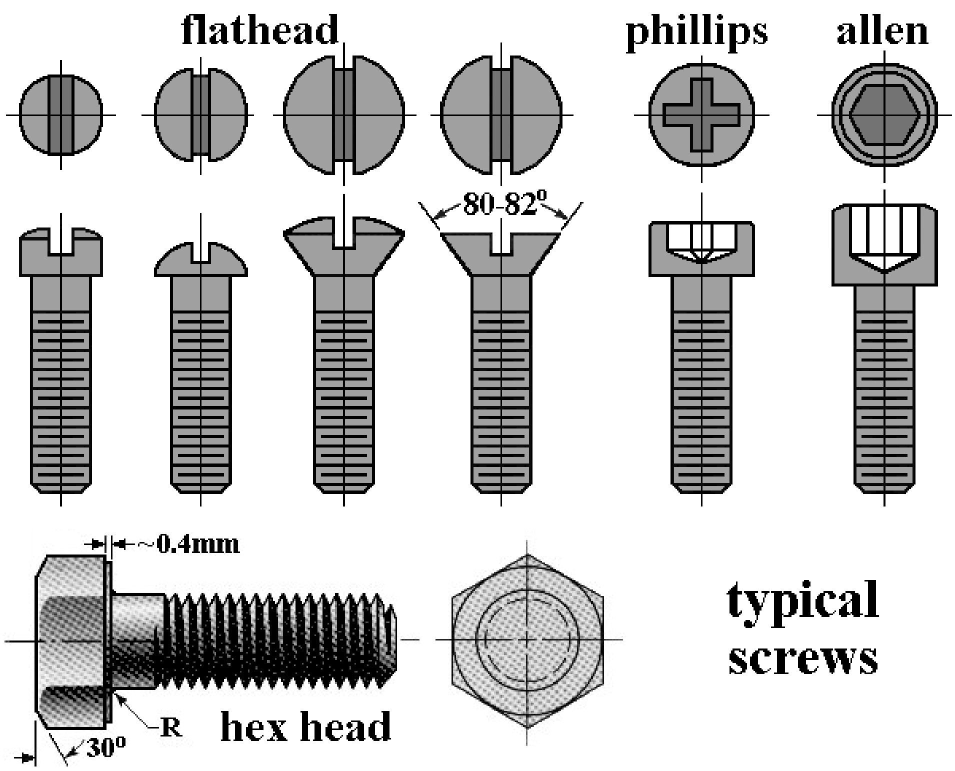
Joining Elements

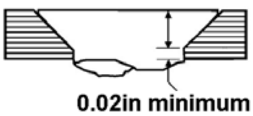
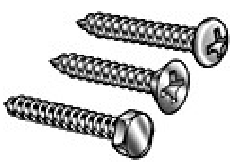
Joining elements are used to keep the robot parts held together in a rigid and strong bond. The main types are described below.

4.1. Screws

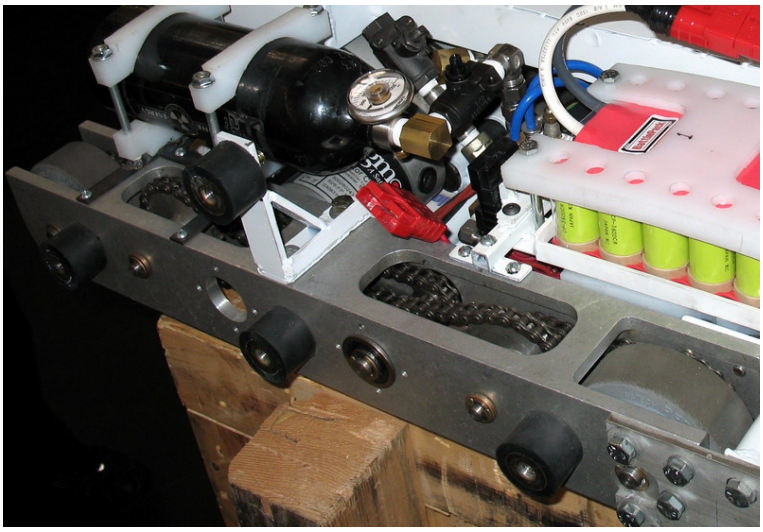
Screws are joining elements, almost always cylindrical, which have helical threads around their perimeter with one or more entries. Screws are used in countless applications to apply forces, to fasten joints, to transmit power (in worm gears) or to generate linear motion. The helical threads, in general wrapped around according to the right hand rule, are inclined planes that convert the applied torques in the screws into axial forces. The main types of screws are presented to the right.

The screws used in the robot structure should have hex (hexagonal) or Allen head, because they are the ones that allow the highest tightening torques. Screws used in the electronics can be of the flathead or Phillips types.

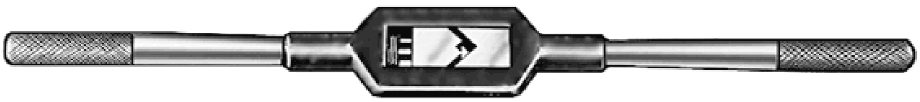


	Hex head – easily tightened with open-ended wrenches. Always use the 8.8 or 10.9 class types (made out of hardened steel), they have twice the strength of regular (mild steel) screws. Except for the few extra cents they'll cost, high class screws mean a free gain in strength, since their weight is the same as low class ones. Stainless steel screws have higher strength than mild steel ones, but much lower than hardened steel screws, so they should not be used in structural parts (besides, they are much more expensive).
 	Allen – the highest strength screws, use the 12.9 or 10.9 class types (made out of hardened alloy steel), they have 3 times the strength of regular screws. Despite their higher impact toughness, don't use stainless steel screws: their low yield strength will let them easily bend during combat, making it difficult to disassemble the robot. Stainless steel Allen bolt heads are also easier to strip than hardened steel ones. The figure shows, from left to right, the button, standard and flat head (flush head) types. The flat head types are good for thick plates used in the robot's exterior, because they are embedded flush to the plate surface, with less chance of being knocked off by spinners. Avoid using flathead screws to fasten thin sheets, in this case the button head ones should be used, they also work well against spinners. Flat head screws require that the plates are countersunk, which reduces joint strength. To avoid this, do not countersink too deep to create a knife-edge condition in the countersunk member. A knife-edge creates a significant stress riser, as well as it allows the fastener to tilt and rise up on the countersunk surface. As a general rule, at least 0.5mm (0.02in) of the plate thickness should not be countersunk, as pictured to the left.
	Self-drilling – these screws don't require tapped holes since they cut their own thread as they're fastened, being very practical. They're good for wood and sheet metal, but they're a bad option to fasten thicker sheets and plates in the robot structure: they're made out of low strength steel, and they're easily knocked off due to the lack of nuts or properly threaded holes.
	Sandwich mounts – they are basically 2 screws held together by a piece of rubber or neoprene. Besides the male-male version from the figure, there are also threaded ones such as the female-female and male-female. They are excellent dampers to mount the electronics into the robot, leaving it mechanically and electrically isolated from the structure. Note that velcro is also a good choice for light parts, such as the receiver.

A few robots have the outer armor separated from the inner structure, held together using several sandwich mounts to absorb impacts (usually from spinners). The launcher Sub-Zero uses this damping technique: in the picture to the right, 4 of its sandwich mounts can be seen mounted to the robot structure. However, half of its armor was pulled out by the spinner The Mortician during Robogames 2006 – rubber and neoprene are not very resistant, in special to traction, so use several of these mounts.



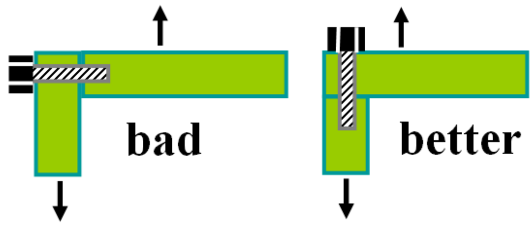
To hold the screws, nuts and washers are used in general. Washers are important to evenly distribute the force of the screws onto the part. Nuts have the inconvenience of needing 2 wrenches to be tightened, one open-ended to hold the nut, and another open-ended or Allen for the screw head. To avoid that, several robots make use of threaded holes. A hole is drilled in the piece with diameter a little smaller than the one of the screw (there are specific tables for that), and a tap (figure to the right) is used to generate threads, guided by a tap wrench (figure below). Such threaded holes make the robot assembly much easier, without having to deal with nuts, which can be hard to reach and secure during a quick pitstop, or might fall inside the robot. The mechanical structure of our middleweight Touro has more than 400 screws but no nuts.



The thickness to be tapped in the piece should be at least equal to the thickness of the nut that would be used with the screw, to avoid stripped threads. In addition, avoid tapping low strength aluminum (such as 6063-T5) and Lexan, their threads will have relatively low resistance. Also, avoid tapping deep holes in titanium by hand: besides being tough to tap, there’s a good chance that the tap will break inside the piece.

A rule of thumb for a good screw diameter is to make it a little smaller than the sum of the thicknesses of the parts being joined. For instance, to fasten a 5mm thick plate to a 4mm one (totaling 5 + 4 = 9mm), an M8 screw (with 8mm diameter) is a reasonable choice.

And what about the number of screws? In robot combat, the word “overkill” doesn't exist, it is just a matter of your opponent super sizing his/her weapon for your armor to suddenly become undersized. Therefore, the most critical parts should have the largest possible number of screws, using common sense. If you drill too many holes to use more screws, your plates will look like Swiss cheese and they will be weakened. A rule of thumb is to leave the distance of at least one washer diameter between the washers of 2 consecutive screws, in other words, the distance between the centers of the holes should be at least twice the diameter of the washer.



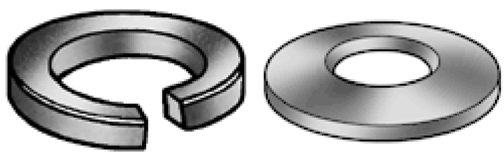
Screws shear much more easily than they break due to traction forces. Therefore, pay attention to the forces that would most likely act on each part of your robot. For instance, in the figure to the right, two parts are joined using a screw to transmit a vertical force. The configuration with the horizontally mounted screw is a bad idea, since it will be loaded in shear. Change the design so that the screw will be under traction, as in the right figure. In this way, the screw will be able to take up to twice the load.

Another important thing is the tightening torque of the screw. Impact forces are transmitted entirely to a screw that is loosely tightened, which will end up breaking. A well tightened screw, on the other hand, distributes the received impact loads evenly through the surrounding material, receiving just a smaller portion of the impact force, resulting in a structure with greater stiffness and strength. Always check for loose screws during a pitstop. Usually, open-ended and Allen wrenches have an appropriate length (lever arm) for a single person to be able to manually generate appropriate tightening torques without leaving it loose or breaking the screw. A torquemeter can be used to deliver a higher precision when tightening bolts.

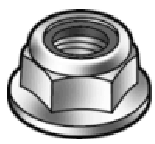
A great investment is to buy a power drill/screw driver. It makes all the difference during a pitstop, removing or tightening screws quickly. An 18V version is a good choice, avoid the cheaper versions with 12V or under (at least for use in a lightweight or heavier robot). We have been using an 18V DeWalt for 5 years, and it still works very well even after all the abuse. They are so reliable that we use 18V DeWalt motors to power the drum of our hobbyweight *Tourinho*, as well as to drive our retired middleweight *Ciclone*, with great results.

Now, how do we guarantee that a screw won't get loose during a match? The tightening torque by itself is not enough to hold the screws in robot combat. Vibration and impacts are very high and they end up making them become loose. A well tightened screw from the top cover of our spinner Titan ended up getting unscrewed after 4 full turns, until it was knocked off by our own weapon bar. To avoid this, there are 5 methods:

- spring lock or Belleville washers: they guarantee that the screw remains tightened, working as a spring to load them in the axial direction. Most of the times you can tighten the screw until these washers become flat.



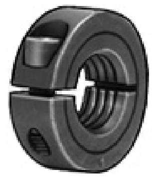
- locknuts: they have a nylon insert that holds well onto the threads of the screws, resisting vibration and holding in place anywhere along the threads of the mating part. The locking element also limits fluid leakage and it won't damage or distort threads.



- counter nuts: if in the middle of a frantic pitstop you don't find any spring lock washers or locknuts, simply add a second nut to the screw (the counter nut), and tighten it well on top of the other one. The pressure between the 2 nuts will help preventing the screw from becoming unfastened.

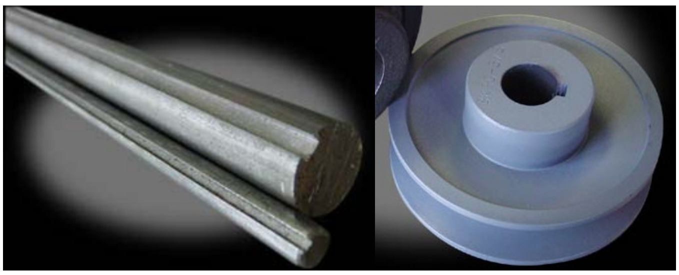
- threadlockers: they literally glue the screw onto the nuts or tapped holes. We use Loctite 242 (blue), it has medium strength and it holds very well. It is enough to use a single drop on the screw thread before tightening it. There are also the Loctite 222 (purple), which is relatively weak for combat, and Loctite 262 (red), with high strength for a permanent bond. But high strength threadlockers could be a problem if you need to disassemble the robot: you might need to heat up the part and deliver a great blow with a hammer to break the Loctite 262 bond. It is a good idea to clean up the screw and the nut or threaded hole with alcohol or acetone before using the threadlocker, to improve bonding. But in practice we always end up forgetting to do that, especially in the rush of a pitstop. Don't use threadlockers in Lexan, because they react with it and weaken the material.

- threaded shaft collars: they work as nuts with a small screw to lock them in place, as pictured to the right. They are the safest way to tighten a screw or threaded shaft. The spinning bars of our middleweights *Ciclone* and Titan are attached to their weapon shaft using threaded collars. Plain shaft collars, used in plain shafts, are also very useful, as discussed below.



4.2. Shaft Mounting

To attach pulleys, gears, sprockets and wheels to the robot shafts, keys and keyways are the best option. Keys are usually square steel bars that are inserted between the shaft and another component inside channels called keyways. They are an efficient way to deliver high torques. They also work as a mechanical fuse, breaking as a result of overloads and saving the shaft and the other component. The keyway channels can be tricky to machine, especially the ones from the shaft (left figure). The internal keyways (right figure) are easier to make using a keyway broach and a collared bushing.



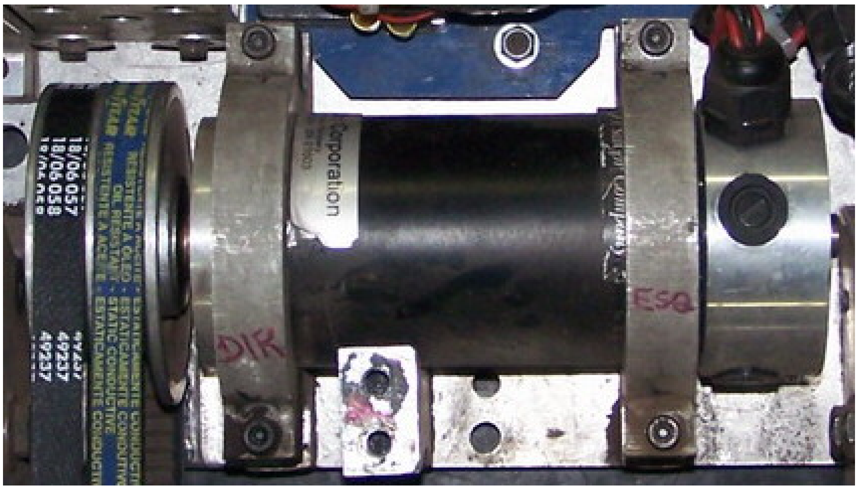
Avoid attaching components to shafts using pins or set screws. Set screws are tightened in the radial direction through the component (such as in the sprocket pictured to the right). Avoid pins and set screws, they are not a good option in the presence of impacts, they usually get loose or break. If a set screw must be used, then at least make sure you apply some threadlocker in it.

Another solution for shaft mounting is to use of a keyless bushing (pictured to the right), such as Trantorque or Shaftloc. You only need to tighten the collar nut to torque up these bushings in a few seconds, without keys or cap screws. As you tighten the collar nut, the inner sleeve contracts onto the shaft while the outer sleeve expands to hold your component. Just match the bushing internal diameter to your shaft diameter, and the bushing outer diameter to the bore of your sprocket, pulley, or gear.

To guarantee that the attached components won't slide along the axial direction of the shaft, you can use retaining rings or plain shaft collars. Retaining rings (left figure below) are mounted in such a way to wrap a groove lathed in the shaft with an external diameter A equal to their internal diameter. You must be careful with the shaft groove, it is a stress riser that could make the shaft break under severe bending stresses. Shaft collars are more resistant than rings, however they are much heavier. They are easy to install, it is enough to insert the shaft in the collar and tighten the locking screw(s), generating a holding force of the order of several tons in some cases. The two main types are the one-piece collars (middle figure above), more difficult to install, and the two-piece collar (right figure), which can be separated into two parts for easier installation.

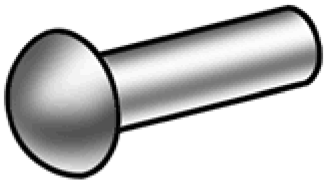
As discussed before, threaded shaft collars are also a great option. The threads guarantee that the collar won't move axially even during huge impacts. This is important to maintain, for instance, a constant pressure against other components without letting them get loose. The spinner Hazard uses threaded collars to hold the weapon bar onto the shaft, as pictured to the right. The motor torque is transmitted to the bar through the friction forces caused by a large washer. This washer is pressed against the bar using a spring element (in green in the figure), held by the threaded collars. Note that two collars are used in this case, to improve strength and to act together as counter nuts. Note also that flat surfaces were machined on the collars to make it easier to get tightened, with an open-end wrench.

Another joining element is the worm-drive clamp (pictured to the right). It is practical, easy to assemble, and it works well to clamp cylindrical objects, such as motors and air tanks, or even components with different shapes such as batteries. In the case of batteries, it is advisable to wrap electrical tape all over the clamp to avoid shorts. Use several clamps to distribute well the load and to avoid breakage. Always perform several tests to guarantee that the clamps will resist to impacts during combats.



Notice however that collars are much more resistant and reliable than clamps to hold cylindrical objects, especially motors. The weapon motor of our drumbot *Touro*, for instance, is held by two aluminum collars, with two locking screws each (as pictured to the right). These specific motor mounts for use with the S28-series Magmotors can be found at www.robotmarketplace.com. This method, besides much more resistant, is as practical as using clamps, because to switch the motor it is enough to deal with only 4 screws.

4.3. Rivets



Never use rivets! They are easy to install and they are used in aircrafts, but they are not suitable for the direct hits found in combat.

Spinners love riveted robots. Rivets are only applicable to join metal sheets, in special aluminum ones, not plates. They're a bad choice even for steel sheets, which would be better off if they were welded together. Remember that the small flange that holds the rivets is made out of a material that you were able to deform by hand, using a manual tool, as pointed out in Grant Imahara's book [10]. Besides, to disassemble the robot, you would need to drill the rivet to remove it, which consumes as much or more time than unfastening a screw.

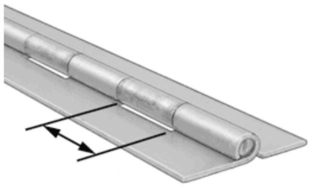
4.4. Hinges

Hinges are an excellent solution to attach wedges. Articulated wedges have the advantage of always being in contact with the arena floor, with zero clearance. This avoids other wedges from getting underneath them. They're also a great solution to make an invertible wedge: if the robot is flipped over, the wedge's own weight will make it rotate and keep touching the arena floor from its other surface.

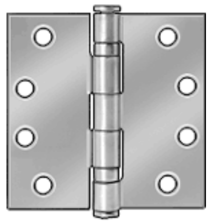
Two important types are the hinges with lay flat leaves and the ones with tight-clearance leaves. The tight-clearance type can be seen in the figure to the right, in its open and closed configurations. Their disadvantage is that the hinged part cannot be laid flat on a surface, which might be a problem to mount them to the robot's walls.

The hinge with lay flat leaves, pictured to the right in its open and closed configurations, is usually a better choice.

Piano hinges are a very popular and inexpensive choice to hold articulated wedges. Because they are continuous, they have the advantage of distributing the loads evenly along the entire wedge. Avoid using versions with brass leaves or pins, which have low strength. Steel and stainless steel versions are better, even though most of them still have low yield strength S_y. A yielded hinge will get stuck and it won't work efficiently. It is not easy to find a piano hinge that is both light weight and suitable for combat.



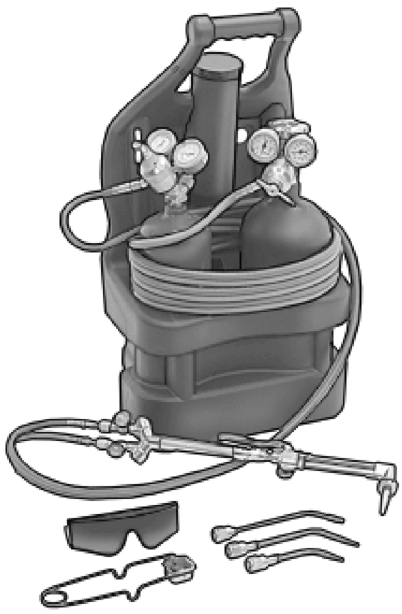
Another option is the use of door hinges (pictured to the right). In this case, it is a good idea to use only two of them for each wedge. Any misalignment when using 3 or more of those hinges might make the wedge articulation become stuck in certain positions. In this case, the wedge's own weight won't be enough to guarantee that it will touch the floor. The highest strength door hinges found in the market are made out of stainless steel (SS) type 304, which still has low S_y. Make sure that the pins are also made out of SS, not brass. Use oversized door hinges, remembering that the loads will be taken by only two of them.



Another option is to machine your own hinges out of titanium or hardened steel, integrated with the robot's structure and wedge plates. This is the solution adopted by the lifter Biohazard, pictured to the right. These integrated hinges are not easy to get knocked off in battle.

4.5. Welds

Many robots are made out of welded structures. Their main advantage is the short building time, without worrying about the high precision required to align holes in bolted components. The pitstop repairs are also faster, the weld filler works as a glue-all to hold parts together, even in the presence of misalignment, and to fill out holes and voids resulting from battle. Welds can be very resistant if well made, and they are a good option for mild and stainless steels. The figure to the right shows an oxy-acetylene system.



However, welded structures present a few problems. The welds or the surrounding heat affected zone tend to be the weakest point of the structure. To compensate for that, a lot of filler material is needed, increasing the robot weight. Note also that in several competitions the access to welding equipment during the pitstops may be limited.

Also, the welds are deposited at a much higher temperature than the one of the base material. As they cool down, thermal effects make the welds contract and compress the base material. As the base material resists this compression, the weld ends up with residual stresses in tension. These tension stresses are so high that the welds usually end up yielding, beyond S_y. These residual tensile stresses decrease a lot the fatigue strength of the material. A few ways to reduce these stresses are to pre-heat the base material before depositing the filler weld material, so that the temperature difference between them is not too high, or to perform heat treatment after welding to decrease the residual stresses. Grinding and polishing the weld surface is a good idea, it generates a good surface finish that increases a lot the fatigue life of the component, because cracks usually initiate at the badly finished asperities of the welds, which locally concentrate stresses.

Another problem is that several high strength materials are either non-weldable, or they present problems if welded during a pitstop. For instance, most high strength aerospace aluminum alloys cannot be welded, and welded 4130 steel structures only acquire high strength after heat treatment (HT) – therefore, if some weld breaks and it needs to be repaired during a pitstop, the strength of the surrounding material will be compromised because there won't be time to perform another HT.

The welds in aluminum alloys need to be made using MIG equipment (Metal Inert Gas, seen in the left figure), and in titanium preferably using TIG (Tungsten Inert Gas, right figure). The use of such equipment requires some skill and experience in order not to compromise strength. These equipments rely on an inert gas that is released during the welding process, shielding the heated part from the surrounding atmospheric gases, which would react to and weaken the weld.

Finally, it is important to clean the parts before welding, and to chamfer thicker plates to guarantee a through-the-thickness weld, increasing strength. The choice of filler material is also important. As mentioned before, grade 2 (commercially pure) titanium makes a great filler for grade 5 titanium (Ti-6Al-4V) – although grade 2 has lower strength, its higher ductility prevents cracking from the thermal effects during the welding process, resulting in better impact toughness during battle.

Chapter

5

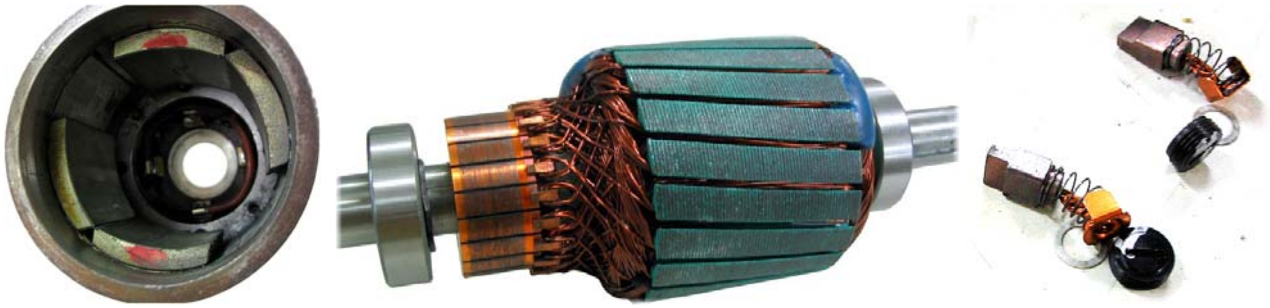
Motors and Transmissions

Motors are probably the combat robot's most important components. They can be powered either electrically, pneumatically, hydraulically, or using fuels such as gasoline. One of the most used types is the brushed direct current (DC) electrical motor, because it can reach high torques, it is easily powered by batteries, its speed control is relatively simple, and its spinning direction is easily reversed. Brushless DC motors are also a good choice, in special because they're not as expensive as they used to be. However, most brushless motor speed controls don't allow them to be reversed during combat, limiting their use to weapon systems, not as drivetrain motors. There are also other types of electrical motors, but not all of them are used in combat. For instance, step motors have in general a relatively low torque compared to their own weight. And the speed of AC motors is more difficult to control when powered by batteries, which can only provide direct current. In the next sections, we'll focus on both brushed and brushless speed motors, as well as on their transmission systems.

5.1. Brushed DC Motors

The three main types of brushed DC motors are the permanent magnet (PM), shunt (parallel), and series. The series type motors are the ones used as starter motors, they have high initial torque and high maximum speed. If there is no load on their shaft, starter motors would accelerate more and more until they would self-destruct, this is why they're dangerous. In a few competitions they can be forbidden for that reason. They are rarely used in the robot's drivetrain because it is not easy to reverse their movement, however they are a good choice for powerful weapons that spin in only one direction.

The PM DC motors and the shunt type have similar behavior, quite different from the starter motors. The PM ones are the most used, not only in the drive system but also to power weapons. They have fixed permanent magnets attached to their body (as pictured in the next page, to the left), which forms the stator (the part that does not rotate), and a rotor that has several windings (center figure in the next page). These windings generate a magnetic field that, together with the field of the PM, generates torque in the rotor. To obtain an approximately constant torque output, the winding contacts should be continually commutated, which is done through the commuter on the rotor and the stator brushes (pictured in the next page, to the right). Electrically, a DC motor can be modeled as a resistance, an inductance, and a power source, connected in series. The behavior as a power source is due to the counter electromotive force, which is directly proportional to the motor speed. The choice of the best brushed DC motor depends on several parameters, modeled next.



To discover the behavior of a brushed DC motor (permanent magnet or shunt types), it is necessary to know 4 parameters:

- V_{input} – the applied voltage to the terminals (measured in volts, V);
- K_t – the torque constant of the motor, which is the ratio between the torque generated by the motor and the applied electric current (usually measured in N·m/A, ozf·in/A or lbf·ft/A);
- R_{motor} – electric resistance between the motor contacts (measured in Ω); a low resistance allows the motor to draw a higher current, increasing their maximum torque;
- I_{no_load} – electric current (measured in ampères, A) drawn by the motor to spin without any load on its shaft; small values mean small losses due to bearing friction.

The equations for a brushed PM DC motor are:

$$\tau = K_t \times (I_{input} - I_{no\_load})$$
$$\omega = K_v \times (V_{input} - R_{motor} \times I_{input})$$

where:

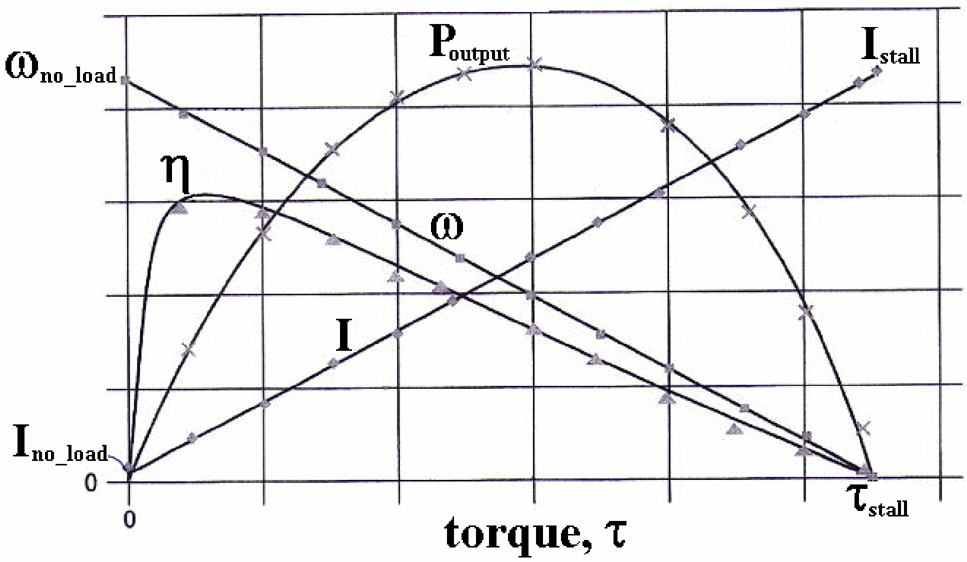
- τ – applied torque at a given moment (typically in N·m, ozf·in or lbf·ft);
- ω – angular speed of the rotor (in rad/s, multiply by 9.55 to get it in RPM);
- I_{input} – electric current that the motor is drawing (in A);
- K_v – the speed constant of the motor, which is the ratio between the motor speed and the applied voltage, measured in (rad/s)/V; it can also be calculated by $K_v = 1 / K_t$;

Although neglecting the motor inductance, the above equations are good approximations if the current doesn't vary abruptly. The consumed electric power is $P_{input} = V_{input} \times I_{input}$, and the generated mechanical power is $P_{output} = \tau \times \omega$. We want the largest possible mechanical power output while spending the minimum amount of electrical power, which can be quantified by the efficiency $\eta = P_{output}/P_{input}$, which results in a number between 0 and 1. Since $K_t \times K_v = 1$, the previous equations result in:

$$\eta = \frac{P_{output}}{P_{input}} = \frac{(I_{input} - I_{no\_load}) \cdot (V_{input} - R_{motor} \cdot I_{input})}{V_{input} \cdot I_{input}}$$

In an ideal motor (which doesn't exist in practice), there would be no mechanical friction losses, resulting in $I_{no\_load} = 0$, and the electrical resistance would be zero, resulting in $R_{motor} = 0$, and in that case $\eta = 1$ (100% efficiency). Real motors have $0 \le \eta < 1$ (efficiency between 0 and 100%).

The curves showing drawn current I (I_{input}), angular speed ω, output power P_{output}, and efficiency η as a function of the torque τ applied to the motor at a certain moment are illustrated below.



The above plots show that the maximum speed ω_{no_load} happens when the motor shaft is free of external loads, with $\tau = 0$, resulting in $I_{input} = I_{no\_load}$, and therefore

$$\omega_{no\_load} = K_v \times (V_{input} - R_{motor} \times I_{no\_load})$$

The maximum current I_{stall} happens when the motor is stalled, with speed $\omega = 0$, therefore $I_{stall} = V_{input} / R_{motor}$, generating the maximum possible torque for that motor $\tau_{stall} = K_t \times (I_{stall} - I_{no\_load})$. In practice, your motor won't see that much current, because in addition to the winding resistance from the motor, there will be the resistances from the battery and electronic system. The actual maximum current must be calculated from the system resistance R_{system}

$$I_{stall} = V_{input} / R_{system} = V_{input} / (R_{motor} + R_{battery} + R_{electronics})$$

The previous equations should also have their R_{motor} value switched to the actual R_{system}. Several manufacturers publish their motor datasheets based on values calculated using R_{motor}. This can be deceiving, because the actual (lower) performance the motor will have is obtained from R_{system}.

As seen in the plot, the maximum value of the mechanical power P_{output} happens when ω is approximately equal to half of ω_{no_load}. More precisely, differentiating the previous equations, it can be shown that the maximum P_{output} happens when

$$I_{input} = V_{input}/(2 \times R_{system}) + I_{no\_load}$$

On the other hand, the highest efficiency happens in general between 80% and 90% of ω_{no_load}, more precisely when $I_{input} = \sqrt{V_{input} \cdot I_{no\_load} / R_{system}}$.

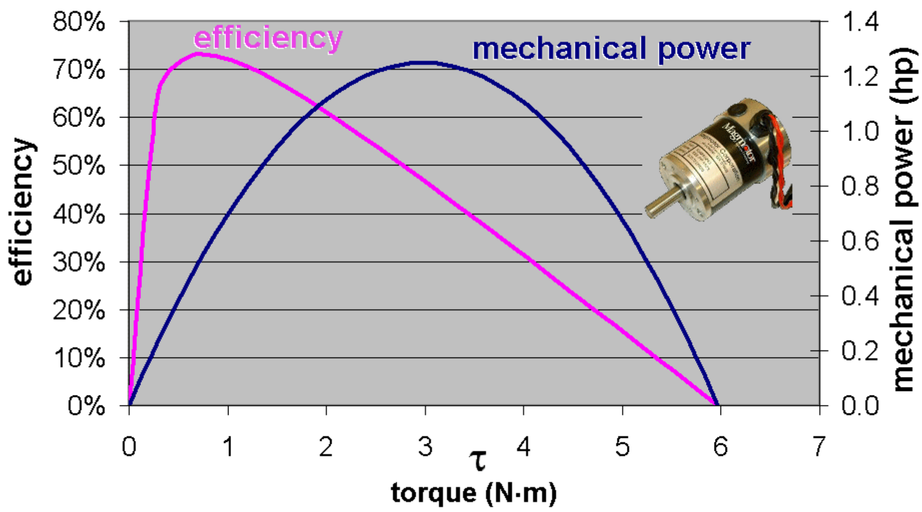
5.1.1. Example: Magmotor S28-150

We will now work out an example using the presented equations. Consider the motor Magmotor S28-150 (pictured to the right) connected to one NiCd 24V battery pack. Therefore V_{input} = 24V, while the motor has K_t = 0.03757N·m/A, R_{motor} = 0.064Ω, and I_{no_load} = 3.4A. Also, $K_v = 1/K_t$ = 26.62 (rad/s)/V = 254 RPM/V. The motor resistance, in fact, needs to be added to the battery resistance (0.080Ω in this example) and the electronics resistance (about 0.004Ω, but it depends on the speed controller), resulting in R_{system} = 0.064 + 0.080 + 0.004 = 0.148Ω.

The top speed of the motor (without loads on the shaft) is ω_{no_load} = 254 × (24 – 0.148 × 3.4) = 5,968RPM. The maximum current (with the motor stalled) is I_{stall} = 24 / 0.148 = 162A, generating the maximum torque τ_{stall} = 0.03757 × (162 – 3.4) ≅ 6.0N·m. In this case, with the motor stalled, the mechanical power is zero and therefore the efficiency is zero, however the electric power is maximum, $P_{input\_max} = V_{input} \times I_{stall}$ = 24 × 162 = 3,888W = 5.2HP, remembering that 1HP (horsepower) is equal to 745.7 W (Watts). Note that this does not mean that you have a 5.2HP motor. All this power is wasted when the motor is stalled, converted into heat by the system resistance. Therefore, avoid leaving the motor stalled for a long time during a match, it can end up overheating.

The maximum mechanical power happens when I_{input} = 24 / (2 × 0.148) + 3.4 = 84.5A, and it is worth P_{output_max} = (84.5 – 3.4) × (24 – 0.148 × 84.5) = 932W = 1.25HP. Notice that the manufacturer says that the maximum power is 3HP for that motor, you would only get that if the battery and electronic system resistances were zero, leaving only the motor resistance 0.064Ω. Recalculating using only the motor resistance 0.064Ω instead of 0.148Ω, P_{output_max} would result in 3HP, but this value is just theoretical.

The maximum mechanical power of 1.25HP happens when ω = 254 × (24 – 0.148 × 84.5) = 2,919RPM, very close to half the ω_{no_load} of 5,968RPM, as expected. Note however that this P_{output_max} happens for P_{input} = 24 × 84.5 = 2,028W = 2.72HP, with an efficiency of only η = 1.25HP/2.72HP = 0.46 = 46%. As it can be seen in the graph for this motor, pictured to the right, the maximum mechanical power happens at speeds that are not necessarily efficient.



The maximum efficiency happens if $I_{input} = \sqrt{24 \cdot 3.4 / 0.148} = 23.5A$, associated with the speed ω = 254 × (24 – 0.148 × 23.5) = 5,213RPM (about 87% of ω_{no_load}). From the previous equations, we get a maximum efficiency of 73%. If theoretically the battery and electronics didn't have electrical resistance, the maximum efficiency would go up to 82%, the value that the manufacturer displays, which is just an upper limit of what you'd be able to get in practice.

5.1.2. Typical Brushed DC Motors

The above example can be repeated for several other motors. The next page shows a table with a few of the most used motors in combat robots, and their main parameters. Several parameters are based only on R_{motor}, their actual values would not be as good after recalculating them using R_{system}.

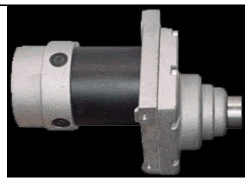
The Bosch GPA and GPB, shown in the table, have been extensively used in Brazil to drive middleweights, however they have a low ratio between maximum power and their own weight. In addition, the GPA generates a lot of noise, which can reduce the range of 75MHz radio control systems. This problem can be minimized using capacitors between the motor brushes, or switching to, for instance, 2.4GHz radio systems.

The DeWalt 18V motor with gearbox is a good choice for the drive system, we've used it in our middleweight *Ciclone*. It has an excellent power-to-weight ratio. Its main disadvantages are that it is not easy to mount to the robot structure, the gearbox casing is made out of plastic, and its resulting length including gearbox ends up very high to fit inside compact robots. Note that some older discontinued DeWalt cordless drills had other disadvantages, using Mabuchi motors instead of the higher quality DeWalt ones, and using a few plastic gears among the metal ones in their gearbox.

The NPC T64 already includes a gearbox with typically a 20:1 reduction, which is already embedded in the values of K_t (already multiplied by 20 with respect to the motor values without gearbox), in K_v (already divided by 20), and in its weight. The data in the table already include the power loss and weight increase due to the gearbox, which explains the relatively low power-to-weight ratio. But, even disregarding that, the performance of this motor is still not too high. The reason many builders use it is due to its convenience, it is easily mounted to the robot and it is one of the few high power DC motors that come with a built-in gearbox. There is also a version of that motor with almost the same weight but twice the power, the NPC T74, however this version is not so easy to find. Care should be taken with the NPC T64 and NPC T74 gears (pictured to the right, with red grease), they might break under severe impacts if used to power weapons. As recommended by the manufacturer, use them only as drive motors. Our middleweight overhead thwackbot Anubis is driven by two NPC T74, but their gears

ended up breaking after extreme impacts. This was no surprise, since we were indirectly using these drive motors to power the overhead thwackbot weapon. After replacing the gears, we've shock-mounted the motors to the robot structure, which solved the problem. Therefore, in overhead thwackbots, which have weapons that are powered by the drive system, it is a good idea to shock-mount the gearmotors.

				
Name	**Bosch GPA**	**Bosch GPB**	**D-Pack**	**DeWalt 18V**
Voltage (V)	**24**	**12**	**12 (nominal)**	**24**
P_{output_max} (W)	**1,175**	**282**	**3,561**	**946**
Weight (kg)	**3.8**	**1.5**	**3.5**	**0.5**
Power/Weight	**309**	**188**	**1,017**	**1,892**
I_{stall} / I_{no_load}	**23**	**25**	**63**	**128**
K_t (N·m/A)	**0.061**	**0.042**	**0.020**	**0.0085**
K_v (RPM/V)	**167**	**229**	**485**	**1,100**
R_{motor} (Ω)	**0.13**	**0.121**	**0.00969**	**0.072**
I_{no_load} (A)	**8.0**	**3.9**	**19.6**	**2.6**

				
Name	**Etek**	**Magmotor S28-150**	**Magmotor S28-400**	**NPC T64 (w/gearbox)**
Voltage (V)	**48**	**24**	**24**	**24**
P_{output_max} (W)	**11,185**	**2,183**	**3,367**	**834**
Weight (kg)	**9.4**	**1.7**	**3.1**	**5.9**
Power/Weight	**1,190**	**1,284**	**1,086**	**141**
I_{stall} / I_{no_load}	**526**	**110**	**127**	**27**
K_t (N·m/A)	**0.13**	**0.03757**	**0.0464**	**0.86**
K_v (RPM/V)	**72**	**254**	**206**	**10**
R_{motor} (Ω)	**0.016**	**0.064**	**0.042**	**0.16**
I_{no_load} (A)	**5.7**	**3.4**	**4.5**	**5.5**

An excellent motor for driving middleweights is the Magmotor S28-150, it is used in our robots Titan and Touro. A good weapon motor for a middleweight would be the Magmotor S28-400, with higher torque and power, which we use to power Touro’s drum. Using a single S28-150 to power the weapon of a middleweight is not a good idea, there’s a good chance that it will overheat.

Because of that, to spin the bar of our middleweight Titan, we use 2 Magmotors S28-150 mechanically connected in parallel by acting on the same gear of the weapon shaft. Note that the two S28-150 motors result together in a higher top speed (6,096RPM instead of 4,944RPM at 24V), stall torque (about 28 instead of 26.5Nm, in theory) and power (6HP instead of 4.5HP) than a single S28-400, weighing only a little more (7.6lb instead of 6.9lb). But we're considering switching to a single S28-400 for three reasons: two S28-150 motors electrically connected in parallel will draw much more current than a single S28-400 if the weapon stalls (which might damage the batteries), the S28-400 can be overvolted more than the S28-100 because it better dissipates heat (compensating for the lower resulting speed, torque and power), and the 6.7" length of the S28-400 will save space inside the robot if compared to the 8" combined length of both S28-100.

The D-Pack motor is a good candidate to replace the Magmotors, besides being much cheaper. However, its electrical resistance is so low that it almost shorts the batteries and electronics. Because of that, its current must be limited if used with speed controllers, otherwise there’s a good chance of damaging the electronics, in special since this motor is usually overvolted to 24V instead of powered by its nominal 12V. If used with solenoids to power weapons, make sure that they can take the high currents involved. This motor is difficult to find even in the US.

The Etek motor is really impressive. It may deliver up to 15HP (1HP = 745.7W), and it can deliver high torque and high speed at the same time. It is a little too heavy for a middleweight: we ended up using it in our spinner *Ciclone* but we had to power it at only 24V, because the additional battery packs that would be needed to get to 48V would make the robot go over its 120lb weight limit. The super-heavyweight shell spinner Super Megabyte only needs one of these motors, powered at 48V, to spin up its heavy shell. A few daring builders have overvolted it to 96V, but current limiting is highly recommended.

Besides the maximum power-to-weight ratio, a parameter that indicates the quality of a motor is the ratio I_{stall} / I_{no_load} between the maximum and no-load currents. The higher the ratio, the higher the current and therefore the torque the motor can deliver, with lower friction losses associated with I_{no_load}. Excellent motors have a ratio above 50. The NPC T64 only has 27, but you must take into account that its I_{no_load} was measured including the gearbox, which contributes with significant friction losses. Without the gearbox, this I_{stall} / I_{no_load} ratio for the NPC T64 would probably reach 50. The Bosch GPA and GPB are not very efficient, their ratio is around 24. The best motors are the D-Pack (with ratio 63), Magmotors and DeWalt (around 110 to 130), and Etek, with the astonishing ratio of 526 (which is just a theoretical value, since it assumes that the batteries have zero resistance and that they can dish out an I_{stall} of 3,000A at 48V).

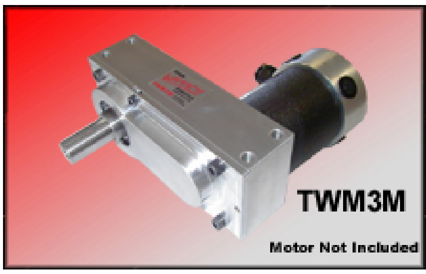
A few DC motors allow the permanent magnets fixed in their body to be mounted with an angular offset with respect to their brush housings (typically about 10 to 20 degrees, it depends on the motor), which allows you to adjust their phase timing. If the motor is used in the robot drive system, it should have neutral timing, in other words, it should spin with the same speed in both directions, helping a tank steering robot to move straight. But if it is used to power a weapon that only spins in one direction, you can advance the timing to typically get a few hundred extra RPM (on the other hand, in the other direction the motor speed would decrease). To advance the timing, loosen the motor screws that hold its body, power it without loading its shaft, and slightly rotate its body (where the permanent magnets are attached to) until the measured I_{no_load} current is maximum, and then fasten the body back in place. For neutral timing, rotate the body until I_{no_load} is identical when spinning in both directions.

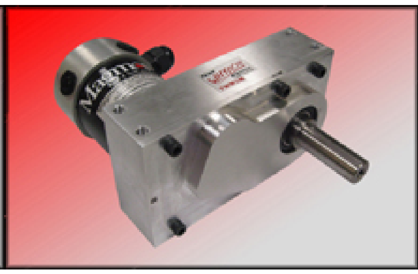
Regarding hobbyweights (12lbs, about 5.4kg), a few inexpensive gearmotor options for the drive system are the ones from the manufacturers Pittman and Buehler, which can be found in several junk yards. Our hobbyweight drumbot *Tourinho* originally used, in 2006, 2 Buehler gear motors (with 300 grams each, about 0.66lb), and our hobbyweight wedge Puminha used 4 Pittmans (with 500 grams each, about 1.10lb). We've bought used ones in Brazil for about US$10 to US$15 each (after bargaining). Most of them have nominal voltage 12V, however we've used them at 24V for 3 minute matches without overheating problems. Remember that by doubling the voltage the power is multiplied by four. The only problem is that the small gears can break due to the higher torques at 24V – we've broken quite a few 12V Pittmans after abusing them in battle at 24V. The only way to know whether they'll take the overvolting is by testing them. It's also a good idea to always have spare motors.

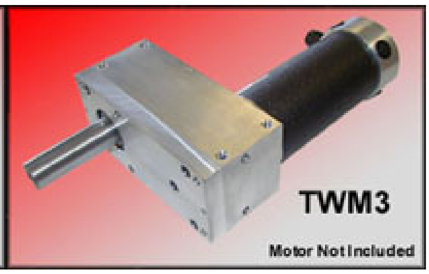
There are much better gearmotor options for hobbyweights, and even heavier robots, than the ones from Pittman and Buehler, however they usually need some modifications to get combat-ready. We've been using, for the drive system in our hobbyweights, Integy Matrix Pro Lathe motors, as pictured to the right, adapted to Banebots gearboxes that were modified following Nick Martin's recommendations, described in the March 2008 edition of Servo Magazine.

A good combination for the drive system of a featherweight is a larger Banebots gearbox connected to Mabuchi's RS-775 motor. For a lightweight, it might be a good idea to go for 18V DeWalt motors, either connected to DeWalt gearboxes or to custom-made ones.

For middleweights, S28-150 Magmotors are usually a good choice for the drive system, connected for instance to Team Whyachi's famous TWM 3M gearbox (pictured below to the left), or to the newer TWM 3M12 version (pictured below in the middle). The S28-400 Magmotors are more appropriate for the drive system of heavyweights and super heavyweights, connected for instance to the TWM3 gearbox (pictured below to the right).







A good option for the drive system of beetleweights is the Beetle B16 gearmotor (shown in the left picture), sold at The Robot Marketplace (www.robotmarketplace.com). For antweights and fairyweights, the Sanyo 50 micro geared motor (shown in the right picture) is a very popular choice.

There are several other good brushed DC motors besides the ones presented above, not only for the drive system, but also to power the weapon. Brushless motors, studied in section 5.2, have been successfully used as weapon motors in several weight classes. It is useful to do a research on which motors have been successfully used in combat. Several motors can be found at The Robot Marketplace (www.robotmarketplace.com), and much more information can be obtained, for instance, in the RFL Forum (http://forums.delphiforums.com/therfl).

5.1.3. Identifying Unknown Brushed DC Motors

If you bought your motor from a junkyard, or if you found it forgotten somewhere in your laboratory, and you don't have any clue about its characteristics, you can follow the steps below:

- Seek any identification on the motor, and look for its datasheet over the internet.
- Make sure it is a DC motor. If there are only 2 wires connecting it, there is a good chance it is DC, otherwise it could be an AC, brushless or step motor.
- Measure the electrical resistance between the terminals, obtaining R_{motor}.
- Apply increasingly higher voltages, such as 6V, 9V, 12V, 18V, 24V, waiting for a few minutes at each level, while checking if the motor warms up significantly. If it gets very hot even without loads, you're probably over the nominal voltage, so reduce its value.
- Most *high quality* motors can work without problems during a 3 minute match with twice their nominal voltage, this is a technique used in combat (such as the 48V Etek powered at 96V). The 24V Magmotors are exceptions, they are already optimized for this voltage, tolerating at most 36V, and even so the current should be limited in this case.
- Once you've chosen the working voltage V_{input}, connect the motor (without loads on its shaft) to the appropriate battery, the same that will be used in combat, and measure I_{no_load}. Note that the value of I_{no_load} does not depend much on V_{input}, however it is always a good idea to measure it at the working voltage. If you have an optical tachometer (which uses strobe lights, such as the one to the right), you can also measure the maximum no-load motor speed ω_{no_load}. A cheaper option is to attach a small spool to the motor shaft, and to count how long it takes for it to roll up, for instance, 10 meters or 30 feet of nylon thread – the angular speed in rad/s will be the length of the thread divided by the radius of the spool, all this divided by the measured time (the

thread needs to be thin, so that when it's rolled up around the spool the effective radius doesn't vary significantly).

- Attach the motor shaft to a vise grip, holding well both the motor and the vise grip, and connect the battery. Be careful, because the torques can be large. The measured current will be I_{stall}, associated with the circuit resistance $R_{system} = R_{battery} + R_{motor}$, so $I_{stall} = V_{input} / R_{system}$ and then calculate $R_{battery} = (V_{input}/ I_{stall}) - R_{motor}$. Do not leave the motor stalled for a long time, it will overheat and possibly get damaged. Also, take care not to dent the motor body while holding it, for instance, with a C-clamp, as pictured below.
- Repeat the procedure above, but supporting one end of the vise grip by a scale or spring dynamometer (with the vise grip in the horizontal position, see the picture to the right). Then, measure the difference between the weights with the motor stalled and with it turned off, and multiply this value by the lever arm of the vise grip to obtain the maximum torque of the motor, τ_{stall}. For instance, if the scale reads 0.1kg with the motor turned off (because of the vise grip weight) and 0.8kg when it is stalled, and the lever arm (distance between the axis of the motor shaft and the point in the vise grip attached to the scale) is 150mm, then $\tau_{stall} = (0.8\text{kg} - 0.1\text{kg}) \cdot 9.81\text{m/s}^2 \cdot 0.150\text{m} = 1.03\text{N}\cdot\text{m}$.

- Because $\tau_{stall} = K_t \times (I_{stall} - I_{no\_load})$, you can obtain the motor torque constant by calculating $K_t = \tau_{stall} / (I_{stall} - I_{no\_load})$.
- Alternatively, if you were able to measure ω_{no_load} with a tachometer or spool, then you can calculate the motor speed constant using $K_v = \omega_{no\_load} / (V_{input} - R_{system} \times I_{no\_load})$. Check if the product $K_t \times K_v$ is indeed equal to 1, representing K_t in N·m/A and K_v in (rad/s)/V. This is a redundancy check that reduces the measurement errors. If you weren't able to measure ω_{no_load}, there is no problem, simply calculate $K_v = 1 / K_t$, taking care with the physical units.
- Finally, once you have the values of V_{input}, K_t (and/or K_v), R_{system} and I_{no_load}, you can obtain all other parameters associated with your motor + battery system using the previously presented equations (don't forget to later add the resistance of the electronics as well).

5.2. Brushless DC Motors

A brushless DC motor is a synchronous electric motor powered by DC current, with an electronically controlled commutation system instead of a mechanical one based on brushes. Similarly to brushed DC motors, current and torque are linearly related, as well as voltage and speed.

In a brushless DC motor, the permanent magnets rotate, while the armature windings remain static. With a static armature, there is no need for brushes. The commutation is similar to the one in brushed DC motors, but it is performed by an electronic controller using a solid-state circuit rather than a commutator/brush system.

Compared with brushed DC motors, brushless motors have higher efficiency and reliability, reduced noise, longer lifetime due to the absence of brushes, elimination of ionizing sparks from the commutator, and reduction of electromagnetic interference. The stationary windings do not suffer with centrifugal forces. The maximum power that can be applied to a brushless DC motor is very high, limited almost exclusively by heat, which can damage the permanent magnets. Their main disadvantage is higher cost, which has been decreasing due to their mass production, as the number of applications involving them increases.

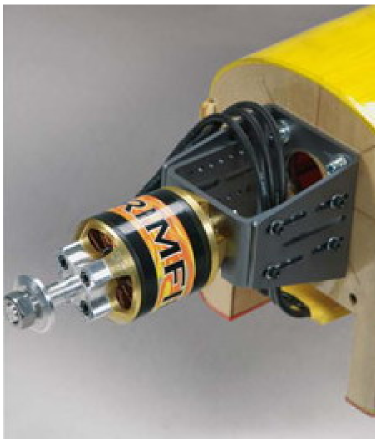
The better efficiency of brushless motors over brushed ones is mainly due to the absence of electrical and friction losses due to brushes. This enhanced efficiency of brushless motors is greatest under low mechanical loads and high speeds. But high-quality brushed motors are comparable in efficiency with brushless motors under high mechanical loads, where such losses are relatively small compared to the output torques.

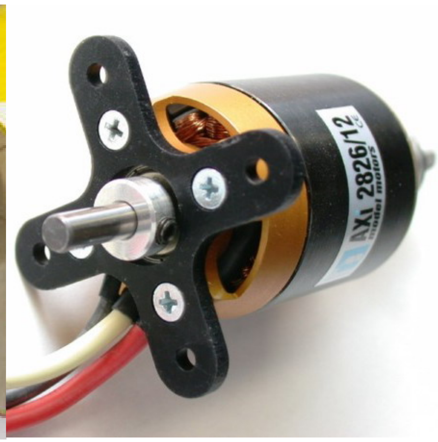
Their kV rating is the constant relating the motor RPM at no-load to the supply voltage. For example, a 1,000 kV brushless motor, supplied with 11.1 volts, will run at a nominal 11,100 RPM.

Most brushless motors are of the inrunner or outrunner types. In the inrunner configuration, the permanent magnets are mounted on the spinning rotor, in the motor core. Three stator windings are attached to the motor casing, surrounding the rotor and its permanent magnets. The picture to the right shows a brushless inrunner of the KB45 series, used to power the spinning drum of our featherweight Touro Feather.

In the outrunner configuration, the windings are also stationary, but they form the core of the motor (as it can be seen in the Turnigy motor in the left picture), while the permanent magnets spin on an overhanging rotor (the “spinning can”) which surrounds the core. Outrunners typically have more poles, set up in triplets to maintain the three groups of windings, resulting in a higher torque and lower kV than inrunners. Outrunners usually allow direct drive without a gearbox, because of their lower speed and higher torque. Due to their relatively large diameter, they're not a good option to be horizontally mounted inside very low profile robots. Remember to leave a generous clearance all around an outrunner, to prevent its outer spinning can from touching any structural part of the robot that could be bent during combat. Popular brushless outrunners are the ones from Turnigy and the more expensive ones from the famous Czech Republic company AXi, pictured above. We've also tested very good outrunners from E-Flite (such as E-Flite's Park 250) and Little Screamers (such as the "De Novo" model).

One important thing about outrunners is that they should be mounted "behind the firewall" for combat applications. Firewall is the flat panel, cross-shaped mount or standoff at the front of a model airplane where the motor is attached to. Supporting the motor in front of the firewall, as shown in the left picture, is a good idea in model airplanes to help the motor cool down with the aid of the propeller air flow. The motor shaft mostly sees axial loads in this case.





But pulleys used to power robot weapons put large bending forces on the motor shaft. So, for combat applications it is important to support the motor by mounting it as close to the output shaft as possible, behind the firewall, as shown in the right picture. To mount outrunner motors behind the firewall, you might need to reverse the position of the output shaft, for it to stick out from the face where the firewall is attached to, which can be done through the repositioning of the shaft retaining clips or screws.

Since most brushless speed controllers do not allow the motor to reverse its spin direction during combat, the use of brushless motors in combots is usually restricted to weapons that only spin in one direction. But reversible brushless speed controllers will soon become cheap and small enough to allow their widespread use in the robot drive system as well.

More information on brushless motors can be found, for instance, in the wikipedia link http://en.wikipedia.org/wiki/Brushless_DC_motor.

5.3. Power Transmission

To transmit power from the motors to the wheels or weapon, it is necessary to use gears, belts or chains. Each one of those elements is described next.

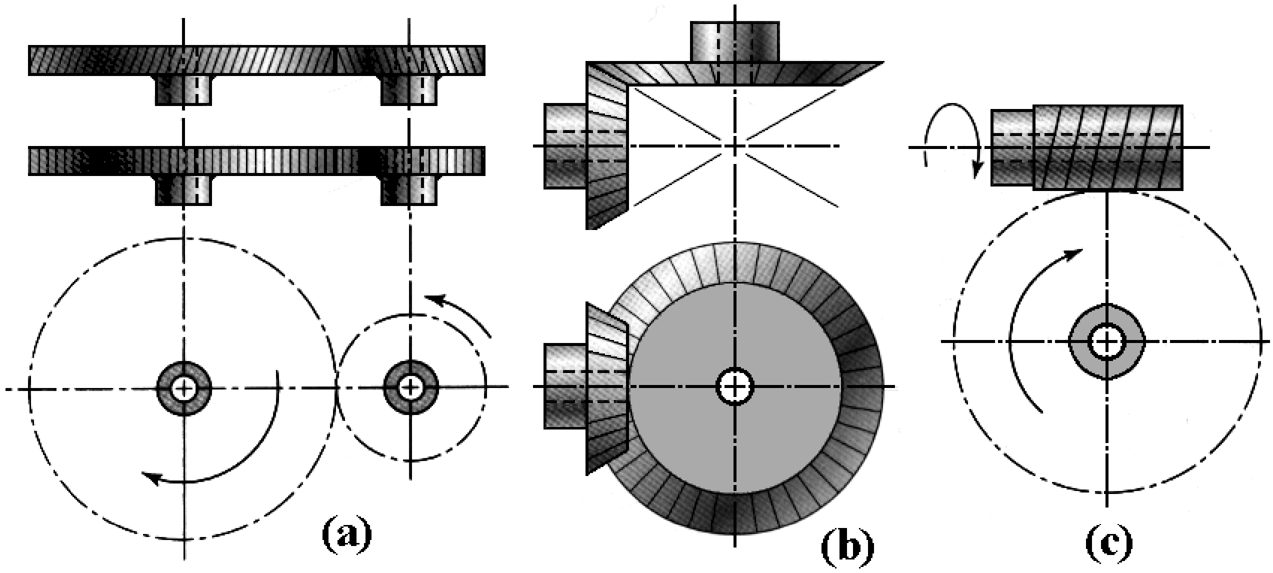
5.3.1. Gears

There are 3 main types of gears, as pictured in the next page:

(a) cylindrical gears, with straight or helical teeth;

(b) conical gears, which have perpendicular and convergent axes; and

(c) worm gears, consisting of a worm (which is a gear in the form of a screw) that meshes with a worm gear (which is similar in appearance to a spur gear, and is also called a worm wheel), where the worm and worm gear have perpendicular axes that do not converge.



Among the cylindrical gears, the straight-toothed ones don't generate axial forces, but they are noisier than the helical ones. The helical-toothed gears are more resistant, however they generate axial forces, except for the double helical ones, which cancel these loads. Grease them well before use, to increase their service life. The TWM 3M gearboxes that drive our middleweights Titan and Touro only use straight-toothed cylindrical gears, in two stages. The gears are made out of hardened steel to resist impacts. Avoid using cast iron or mild steel gears, they might not resist the rigors of combat, as seen in the figure to the right.

Conical gears are an efficient option to transmit power at 90 degrees. The gearbox of the weapon system of our spinner Titan uses a large conical gear attached to the weapon shaft, powered in parallel by two S28-150 Magmotors, each one with a smaller conical gear. In the same way as with cylindrical gears, the reduction ratio between two conical gears only depends on the ratio between the number of teeth of each of them. For instance, if the motor gear has 20 teeth and the weapon gear 30 teeth, then the reduction ratio is 30/20 = 1.5, meaning that the torque of each motor will be multiplied by 1.5, and the weapon speed will be 1.5 times slower than the motor speed.

Worm gears are used in several gearmotors, because they can have a large reduction ratio with a single stage. This ratio is equal to the number of teeth of the driven worm gear, which can be a large number. Most of them are self-locking, meaning that the driven worm gear can be designed so that it can't turn the worm. This can be dangerous in combat, because a large impact can cause the worm gear to break its teeth due to self-locking. Another disadvantage is due to the low efficiency (high power loss) caused by the functional sliding between the worm and worm gear. Because of that, avoid using electric windshield wiper motors, they have low power-to-weight ratios, and the power losses due to the worm gears are high.

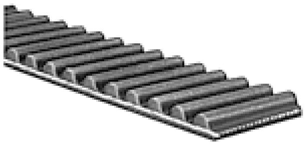
Our first combat robots, the middleweight overhead thwackbots *Lacrainha* and *Lacraia*, use worm gearboxes driven by Bosch GPB motors. Besides the low power of the GPB, their cast iron gearboxes are very heavy. A good option for the drive system is to mill a gearbox out of a solid block of aerospace aluminum, and to use straight-toothed cylindrical gears made out of hardened steel. Milling such solid block is not easy without a CNC system, because any small error (of the order of 0.1mm) may cause misalignment between the shafts and then compromise the service life of the gears, not to mention the reduction in efficiency due to the added friction losses. Besides, any error during the milling process may mean the waste of an expensive block of aerospace aluminum.

After a few tries with our manual mill, we've realized that the TWM 3M gearbox (pictured to the right), sold by Team Whyachi (www.teamwhyachi.com), is worth every penny. It is milled out of a solid block of aerospace aluminum, with hardened steel gears, and the output wheel shaft is made out of grade 5 titanium (Ti-6Al-4V). We've used the TWM 3M gearboxes together with the Magmotor S28-150 to drive the wheels of our middleweights Titan and Touro.

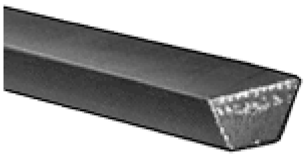
5.3.2. Belts

Belts are flexible machine elements used to transmit force and power to relatively long distances, driven by pulleys. These elements can replace gears in many cases, with several advantages: besides being relatively quiet, belts help to absorb impacts and vibrations through their flexibility, and they tolerate some misalignment between the pulleys.

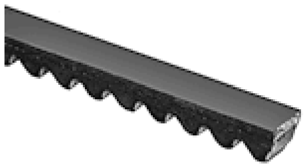
The main types of belts are the timing belts (a.k.a. synchronous or toothed belts, see the left figure) and the V-belts (right figure, showing quadruple-sheave pulleys), manufactured in standard sizes in rubber or polymeric base, in general reinforced with high resistance fibers.



Timing belts (pictured to the right) keep the relative position between the pulleys, synchronizing the movements and preventing sliding. They can be used to transmit power to the drive system. They can also be used in the robot weapon system, but in this case it is recommended to use some type of torque limiter (discussed ahead) to bear impact loads.

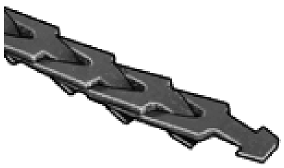


V-belts (pictured to the right), on the other hand, allow the pulleys to have some relative sliding, working as a clutch. This is very useful in combat robot weapons, allowing some sliding at the moment of impact against the opponent, which is good not to stress too much the motor or to rupture the belt. Touro uses a pair V-belts to power its drum.



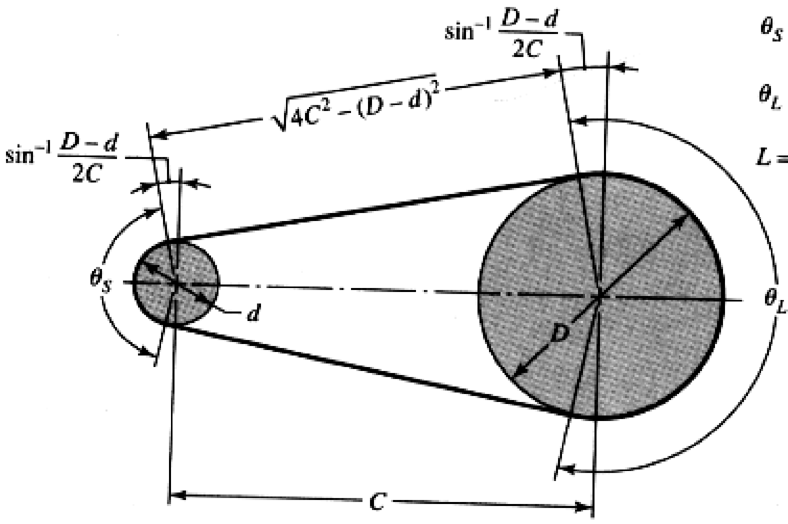
For small diameter pulleys, use cogged V-belts (pictured to the right), they are more flexible and dissipate heat better because of the cogged design. Note that they're not timing belts, the cogs are not used as teeth.

If your V-belt broke off in combat and you don't have time during a pitstop to open up your robot to install a new one, then a good alternative is to use an adjustable-length V-belt (pictured to the right). Sold by the foot, it is perfect for making replacement V-belts, easily installed by simply twisting its sections for coupling or uncoupling. Its only problem is that it tends to stretch with use, so standard or cogged V-belts are better if you have time to install them.



There are still round belts (with circular cross section), but in general they are only used in low power applications, such as in sewing machines, or in lighter combat robots such as insects.

The calculation of the nominal length L of the circumference of the belt is made starting from the distance C between the centers of the pulleys and from the primitive diameters of the smaller pulley (d) and of the larger one (D), using the equations below.



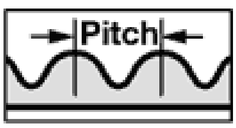
$$\theta_S = \pi - 2\sin^{-1}\frac{D-d}{2C}$$

$$\theta_L = \pi + 2\sin^{-1}\frac{D-d}{2C}$$

$$L = \sqrt{4C^2 - (D-d)^2} + \frac{1}{2}(D\theta_L + d\theta_S)$$

Note that θ_S and θ_L above need to be calculated in radians. Also, note that primitive diameters cannot be measured with a caliper, they are “imaginary” nominal values that need to be obtained from specific tables or from the manufacturer’s catalog. Since the belts are only sold in standard sizes, you’ll probably have to round up or down the calculated L. To prevent slack, you’ll need to be able to slightly adjust the pulley distance C, or to install a belt tensioner, which can be easily made out of a small ball bearing fastened along the path of the belt between both pulleys.

An important parameter in the choice of timing belts and pulleys is the pitch, which is the distance between the tips of two consecutive teeth, as pictured to the right. The larger the pitch, the larger the tooth and the torque it can handle. A few common belt denominations and pitches in the US are the MXL (2/25” pitch) and XL (1/5”) for extra light duty, L (3/8”) for light, H (1/2”) for heavy, and XH (7/8”) and XXH (1-1/4”) for extra heavy duties. The metric denominations are 3M, 5M, 8M, 14M and 20M, where each number is the pitch in mm. The metric timing belts have high strength versions that are good for combat, such as the Optibelt Omega A, B and HP, with increasing strength. To have an idea of scale, our middleweight *Ciclone* uses 8M (8mm pitch), our hobbyweight *Tourinho* uses 5M (5mm pitch), and our beetleweight *Mini-Touro* uses 3M (3mm pitch) timing belts to power their spinning bar and drums.



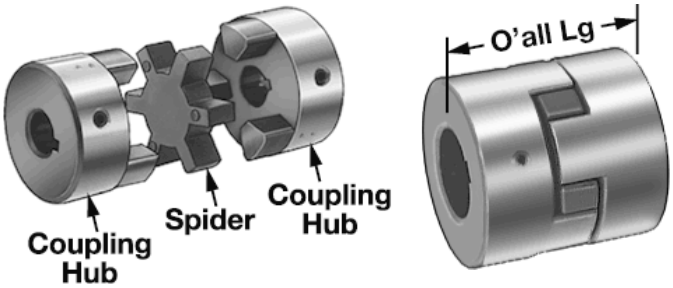
5.3.3. Chains

Chains are also flexible elements used to transmit force and power. They are a good option because they are cheap and they can have any length, you only need to custom define their size using specific tools. Their disadvantages are: they are less efficient than belts, which results in certain power loss; they are noisy; they need tensioners to keep the chains stretched; and they can come out from the sprocket due to misalignments or other deformations, or due to large impacts. Since combat robots will suffer several impacts, care should be taken with such transmission type.

To avoid these problems, it is a good idea to use short chains, eliminating the need for tensioners, and to protect them very well. This can be seen in the picture to the right, which shows a great modular drive unit sold at www.battlekits.com, designed by the famous BioHazard builder Carlo Bertocchini.

5.3.4. Flexible Couplings

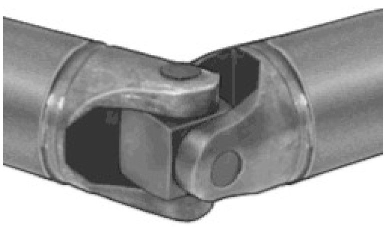
Flexible couplings allow a shaft to efficiently transmit power to another one, even in the presence of misalignments. They consist of 2 rigid coupling hubs, usually made out of cast iron, fixed to each shaft usually using keyways, and of an elastic element (rubber spider) between them, see the picture to the right. They are used in general to connect the motor shaft to the wheel shaft. Besides tolerating misalignments, they absorb impacts and vibrations, which is highly advisable if your drive system gears aren't very resistant.



Our middleweight *Ciclone* uses such couplings between its wheels and the 18V DeWalt gearmotors that drive them, which helps to prevent an infamous plastic gear inside very old versions of the DeWalt gearbox from breaking. An inconvenience of flexible couplings is their overall length (right figure above), which is relatively large, increasing the distance between the motors and the wheels, which can make your robot become too wide.

Avoid using these couplings to power impact weapons, it is likely that the rubber spider won't take the high impact torques.

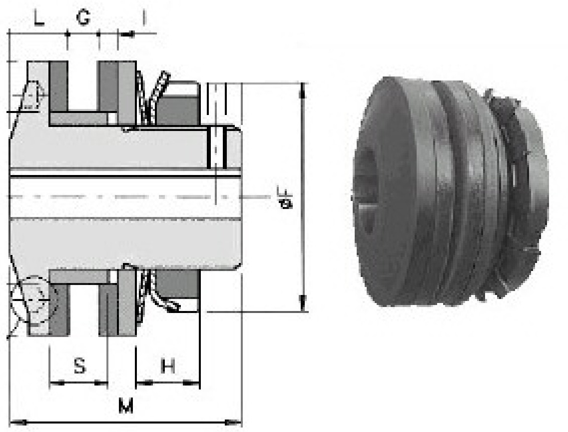
Another method to couple misaligned shafts is through universal joints (a.k.a. universal or U-joint, pictured to the right). Avoid using them: they are heavy, their strength is relatively low (their pins, which have a much smaller diameter than the joint itself, are the weakest point), and the energy efficiency is low, getting worse if the shafts have large misalignments. In combat robots, always try to replace universal joints with belt or chain transmissions.



5.3.5. Torque Limiters

Torque limiters are power transmission elements that allow relative sliding between the coupled components, acting as a clutch. They are an important component in impact weapons that do not use V-belts or some other element that acts as a clutch to limit the torques transmitted back to the robot.

The figure to the right shows the torque limiter used by our middleweight bar spinner *Ciclone*, the DSF/EX 2.90, manufactured by the Italian company *Comintec*. The spinning bar is sandwiched between 2 flanges, one fixed and the other movable. The movable flange is fastened onto the bar, applying a constant pressure with the aid of a Belleville washer (see chapter 4), in such a way to transmit friction torques to accelerate the weapon bar. The flanges allow the bar to slide in the event of an impact, acting as a clutch.



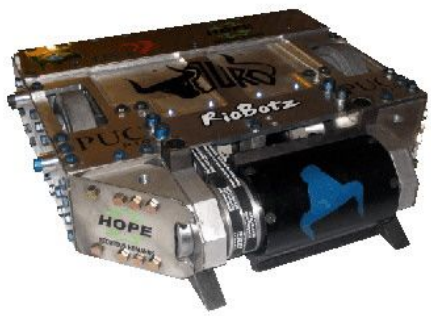
It is not necessary to buy an off-the-shelf torque limiter. It is possible to build yourself much smaller, lighter, more resistant and cheaper versions. You basically need two flanges attached to a shaft, which can be two sturdy hardened steel shaft collars – a plain one and a threaded one to be tightened with the aid of a Belleville washer against the driven element such as the weapon bar. Phenolic laminates such as garolite are a good clutch material to be inserted in between the collars and the bar. The torque limiter from our spinner Titan is much smaller than *Ciclone*'s, because the lower flange is already embedded onto the weapon shaft, saving weight and increasing strength. It is then enough to use a Belleville washer and a threaded collar to attach its weapon bar.

5.4. Weapon and Drive System Calculations

Using the above information on DC motors and power transmission elements, we can already design a typical robot weapon and drive system. We will present next a few examples.

5.4.1. Example: Design of Touro's Drive System

We will calculate the acceleration time and final speed of our middleweight Touro. It uses two Magmotors S28-150, one for each of its two wheels. The used TWM 3M gearbox has a reduction ratio of n = 7.14, in other words, the wheel spins 7.14 times slower than the motor, and with 7.14 times more torque. Touro's mass is about 55kg (120lb), however we estimated that the 2 wheels support about 50kg or less (roughly 110lb), because they are not perfectly aligned with the robot center of mass. The two skids beside the drum support the remaining 10lb. Therefore, each wheel supports static loads of about 25kg



(55lb), the equivalent to 25 × 9.81 = 245N. Note however that when the robot is accelerating, the active wheels might see a larger normal force, in special if the robot tilts back (as it happens when dragster cars accelerate) without having their rear structure touch the ground.

We will assume that the friction coefficient between the wheels and the arena floor is 0.9. This is a good number for rubber wheels with 65 Shore A hardness (see chapter 2) on a steel floor of a clean arena. This value might drop to 0.8 or even 0.6 when the arena is dirty, covered with dust and debris. The largest traction force that each wheel can generate without skidding is then 0.9 × 245N = 220.5N.

Touro's wheels have 6" diameter, therefore their radius is r = 76.2mm. The torque that makes the wheels skid is then 220.5N × 0.0762m = 16.8N·m, and the torque that the Magmotor needs to deliver to the gearbox is τ_{max} = 16.8N·m / 7.14 = 2.35N·m. As we've seen in section 5.1, this motor generates torques of up to 6.0N·m, therefore Touro should skid in the beginning of its acceleration and only later stop slipping. The maximum electric current in each motor while the robot is skidding is $I_{max} = \tau_{max} / K_t + I_{no\_load}$ = 2.35/0.03757 + 3.4 = 66A. If you are an aggressive driver and spend 50% of a match accelerating at full throttle, then in 3 minutes (0.05 hours) you would spend in both motors 2 × 66A × 0.05h × 50% = 3.3A·h (approximately, ignoring the consumption when the robot is not accelerating). Therefore, for the drive system, 1 battery pack with 24V and 3.6A·h would probably be enough (more details on batteries can be seen in chapter 8).

But be careful with the limit of validity of the calculation: we had calculated I_{stall} = 162A for each motor, but a single NiCd pack would not be able to supply 2 × 162 = 324A for both motors. But, actually, we use two 24V battery packs in parallel in Touro, so there is no problem, both are able to generate together 324A (at least with the weapon turned off). Note also that if we used two packs in parallel to power a single motor, we would have an equivalent electrical resistance of half the one of a single pack, $R_{battery}$ = 0.080Ω / 2 = 0.040Ω, which would change all the previous calculations due to the new value of R_{system}. However, because we use 2 packs to drive 2 motors, the calculations using 0.080Ω are still valid.

The maximum theoretical speed of Touro, if there were no friction losses in the gearbox, would happen with the motor spinning at ω_{no_load} = 5,968RPM = 625rad/s, generating a top speed v_{max} = $(\omega_{no\_load} / n) \times r$ = (625 / 7.14) × 0.0762m = 6.67m/s = 24km/h (almost 15 miles per hour), a relatively high speed for a middleweight.

While Touro is skidding, the current on each motor is I_{max} = 66A, which only happens for low speeds of the motor, from zero up to $\omega_1 = K_v \times (V_{input} - R_{system} \times I_{max})$ = 254 × (24 – 0.148 × 66) = 3,615RPM = 379rad/s. The robot speed when the wheels stop skidding is given by $v_1 = (\omega_1 / n) \times r$ = (379 / 7.14) × 0.0762m = 4.04m/s = 14.5km/h (9.04mph).

During this period, when the wheels are skidding, the robot's acceleration would be equal to the friction coefficient times the acceleration of gravity, worth a_1 = 0.9 × 9.81 = 8.83m/s^2. Actually, this value would be true for any all-wheel-drive robot, but Touro has two skids beside its drum that take together about 10lb of the robot weight. With all active wheels taking only 50kg (110lb), the acceleration would then be a_1 = 0.9 × 9.81 × 50kg / 55kg = 8.03m/s^2.

But because the skids are in front of Touro, when it accelerates they are almost lifted off from the ground, making almost the entire robot weight go to the active wheels, as discussed in chapter 2. Thus, the previously calculated $a_1 = 8.83m/s^2$ is a better approximation. Note that this assumption regarding the skids almost lifting off would slightly change the values of τ_{max}, I_{max} and v_1, however we will keep their previously calculated values for the sake of simplicity.

The resulting movement while the robot is skidding is a uniformly accelerated one, which happens during a time interval of $\Delta t_1 = v_1 / a_1 = 4.04 / 8.83 = 0.46s$.

After that time, the current in each motor starts to decrease, getting below 66A. The instantaneous current delivered to each motor is then $I_{input} = [V_{input} / R_{system}] - [\omega / (K_v \times R_{system})] = I_{stall} - [\omega / (K_v \times R_{system})]$, and the motor torque results in

$$\tau = K_t \cdot (I_{input} - I_{no\_load}) = K_t \cdot (I_{stall} - I_{no\_load} - \frac{\omega}{K_v \cdot R_{system}})$$

Therefore, the torque at each wheel is $\tau \times n$, which generates a traction force of $\tau \times n / r$. The 2 wheels generate together twice that force, and then from Newton's second law we obtain the equation $2 \times \tau \times n / r = 55kg \times a_2$. This robot's acceleration a_2 varies because it depends on the motor speed ω:

$$a_2 = \frac{2 \cdot n}{r \cdot 55} \cdot K_t \cdot (I_{stall} - I_{no\_load} - \frac{\omega}{K_v \cdot R_{system}}) = \frac{2 \cdot 7.14}{0.0762 \cdot 55} \cdot 0.03757 \cdot (162 - 3.4 - \frac{\omega}{26.62 \cdot 0.148})$$

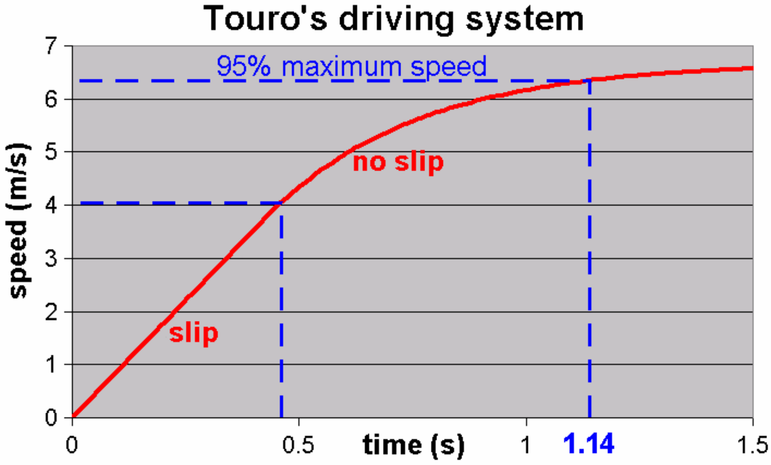
resulting in $a_2 = 20.3 - 0.0325 \cdot \omega$. Be careful with these calculations, because K_v needs to be represented in (rad/s)/V, and not in RPM/V. Because the wheels are not slipping anymore, the robot speed can be obtained directly from the motor speed, $v = (\omega / n) \times r = \omega / 93.7$, resulting in an acceleration $a_2 = 20.3 - 3.04 \cdot v$.

The robot never achieves the theoretical maximum speed, because the behavior is asymptotic. But the time interval between the moment the robot stops skidding (when v = 4.04m/s) and the moment it reaches, for instance, 95% of its maximum speed ($v = 0.95 \times 6.67m/s = 6.34m/s$) can be calculated:

$$\Delta t_2 = \int dt = \int_{4.04}^{6.34} \frac{dv}{20.3 - 3.04 \cdot v} = \frac{1}{3.04} \cdot \ln\left(\frac{20.3 - 3.04 \cdot 4.04}{20.3 - 3.04 \cdot 6.34}\right) = 0.68s$$

where ln stands for the natural logarithm function.

Thus, the total acceleration time of Touro, from its resting position up to 95% of its maximum speed, is $\Delta t = \Delta t_1 + \Delta t_2 = 0.46 + 0.68 = 1.14s$, a very close value to the measured one in our tests. The graph to the right shows the results. If your robot doesn't have enough torque to skid



(slip) during its acceleration, then it is enough to make calculations based on the integral above using the initial speed v = 0 (in other words, $\Delta t_1 = 0$, therefore $\Delta t = \Delta t_2$).

Notice that, for the robot to be agile, it is important that such acceleration time Δt is short, such as in Touro. It is not a good idea to have a very high maximum speed if the robot can't achieve it quickly enough, without the need to cross the entire arena.

It is important to emphasize that the above calculations would also be valid if the robot had 4 active wheels powered by the same 2 motors. The torque from each motor would be distributed to the 2 wheels it drives, however the combined traction force of these 2 wheels would be added up, resulting in practically the same acceleration and time intervals calculated above.

But if there were 4 motors for the 4 wheels, then the calculation results would definitely change, because we would be multiplying by 2 the system power. Probably Δt_1 would remain the same, since it is mainly determined by the tire coefficient of friction, but Δt_2 would certainly decrease. These calculations would not be difficult to perform using the above methodology.

5.4.2. Example: Design of Touro's Weapon System

We will calculate the acceleration time of Touro's drum, and the kinetic energy it stores. Touro's drum can be approximately modeled as a steel cylinder with external radius R = 65mm and internal radius r = 40mm, with length L = 180mm. The density of steel is roughly 7.8, therefore the drum mass is $m = \pi\cdot(65^2 - 40^2)\cdot 180\cdot 7.8\cdot 10^{-6}\text{kg/mm}^2 = 11.6\text{kg}$ (about 25.6lb). The rotational moment of inertia with respect to the horizontal spin axis is $I_{zz} = m\cdot(R^2 + r^2)/2 = 11.6\cdot(65^2 + 40^2)/2 = 33785\text{kg}\cdot\text{mm}^2 = 0.0338\text{kg}\cdot\text{m}^2$.

The weapon motor is one Magmotor S28-400 (pictured to the right) connected to 2 NiCd battery packs in parallel, therefore $V_{input} = 24\text{V}$, $K_t = 0.0464\text{N}\cdot\text{m/A}$, $R_{motor} = 0.042\Omega$, and $I_{no\_load} = 4.5\text{A}$. We have then $K_v = 1/K_t = 21.55$ (rad/s)/V = 206 RPM/V. The motor resistance needs to be added to the resistance of the electronics and solenoid (about 0.004Ω) and of the batteries, which for being in parallel have an equivalent resistance of half of a single pack (0.080Ω / 2 = 0.040Ω in this case), resulting in $R_{system} = 0.042 + 0.004 + 0.040 = 0.086\Omega$. Note that those 2 packs are the same as the ones used in the drive system of Touro, therefore we will assume in the following calculations that the robot is not being driven around during the weapon acceleration.

The 2006 version of Touro had V-belt pulleys used in the weapon system with same diameter, therefore there was no speed reduction (n = 1). The theoretical top speed of the drum is then $\omega_{no\_load} = 206 \times (24 - 0.086 \times 4.5) = 4{,}864\text{RPM} = 509\text{rad/s}$ (in 2007, this speed was increased to about 6,000RPM by reducing the diameter of the drum pulley). In practice, because of the friction losses, the drum (from the 2006 version of Touro) spins at a little more than 4,750RPM, which was measured using a strobe tachometer.

The peak current at the beginning of the acceleration is I_{stall} = 24 / 0.086 = 279A. Note that, ideally, the V-belts should not slide during the drum acceleration, they should only slip at the moment of impact against the opponent. This is why they need to be well tensioned. Assuming that they don't slide during the acceleration, the only other thing we need to know is whether the batteries are able to supply the required 279A.

If this weren't true, we would need to split the calculations into 2 parts: an initial acceleration period when the batteries would be supplying their maximum current (which would be a certain value smaller than I_{stall}), and another period when the batteries would be able to supply the motor needs. The solution of this problem would not be difficult, the calculations would be similar to those made for the design of the drive system, adding up the time intervals from both parts.

In the case of Touro, the batteries are able to supply together the required 279A, which simplifies the calculations. As studied before, the motor torque is a function of its angular speed ω:

$$\tau = K_t \cdot (I_{input} - I_{no\_load}) = K_t \cdot (I_{stall} - I_{no\_load} - \frac{\omega}{K_v \cdot R_{system}}) = 12.74 - 0.025 \cdot \omega$$

Because the gear ratio is n = 1 (same diameter pulleys), this torque is applied directly to the drum to accelerate it:

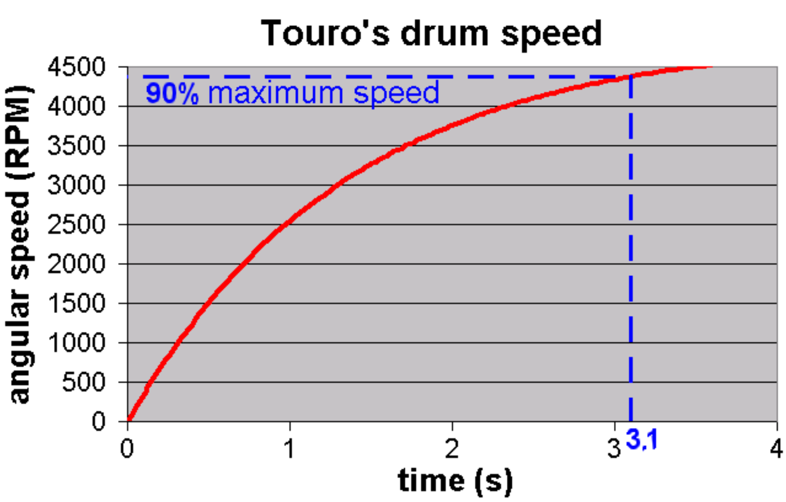
$$\tau = I_{zz} \cdot \frac{d\omega}{dt} \quad \Rightarrow \quad 12.74 - 0.025 \cdot \omega = 0.0338 \cdot \frac{d\omega}{dt}$$

It would not be difficult to include the effect of a gear ratio n different than one, the procedure would be similar to the one used in the drive system calculations.

The acceleration (spin up) time of the drum from zero speed up to, for instance, 90% of its maximum speed (0.90 × 509 = 458rad/s), is then

$$\Delta t = \int dt = \int_0^{458} \frac{0.0338 \cdot d\omega}{12.74 - 0.025 \cdot \omega} = \frac{0.0338}{0.025} \cdot \ln\left(\frac{12.74 - 0.025 \cdot 0.0}{12.74 - 0.025 \cdot 458}\right) = 3.1\text{s}$$

The graph to the right summarizes the drum spin up results. Considering the friction losses, it would be expected in practice that the actual value would be slightly above 3.1s. On the other hand, fully charged 24V NiCd batteries are able to deliver up to 28V, which would more than compensate for these friction losses.



As a result, the above approximation ends up quite reasonable: the experimentally measured spin up time until 90% of the maximum speed was about 3s. In general, it is a good idea that the spin up time of a weapon is shorter than 4 seconds (see chapter 2), therefore 3s is a good value.

Note that those calculations assumed that the robot was not moving around, and therefore the 2 battery packs were used exclusively to accelerate the weapon. If the robot was driving around during the weapon acceleration, then naturally the actual spin up time would be longer than 3s.

The accumulated kinetic energy by the drum after these 3.1s would be $E = I_{zz} \cdot \omega^2 / 2 = 0.0338 \cdot 458^2 / 2 = 3,545J$ (for 90% of its maximum speed), the equivalent to about 10 caliber 38 shots, or 1 rifle shot. The actual maximum kinetic energy, from the measured speed 4,750RPM (497rad/s), is $E = I_{zz} \cdot \omega^2 / 2 = 0.0338 \cdot 497^2 / 2 = 4,174J$.

Theoretically, this energy would be able to fling a middleweight opponent to a height of $h = E / (m \cdot g) = 4174 / (55 \cdot 9.81) \cong 7.7$ meters (more than 25 feet into the air). In practice, the height is much lower because the impact is not entirely transmitted to the opponent, and a lot of the energy is dissipated in the form of heat and deformation. The equations to estimate the actual height will be presented in chapter 6.

Finally, note that the above calculations can be applied to horizontal and vertical spinners as well, not only to drumbots, as long as the weapon inertia I_{zz} is known. For instance, a flat bar with mass m, length 2·a and width 2·b, spinning around its center of mass, has $I_{zz} \cong m \cdot (a^2+b^2)^2/3$. And a solid disc, with mass m and radius a, would have $I_{zz} \cong m \cdot a^2/2$. More details can be seen in chapter 6.

5.4.3. Energy and Capacity Consumption of Spinning Weapons

It is very important to calculate the energy consumption of an electrical motor from a spinning weapon, in order to evaluate battery requirements. The weapon consumption can be divided into a portion needed to spin up the weapon after each impact, and another one from friction losses.

It is possible to estimate the energy and capacity consumption of the battery during the spin up of a weapon with moment of inertia I_{zz} in the spinning direction, assuming that I_{no_load} is much smaller than I_{stall} (which is true for all good quality DC motors). In this case, if we approximate $I_{no\_load} = 0$, the motor torque is simply $\tau = K_t \times I_{input}$. The torque transmitted to the weapon after a reduction ratio of n:1 is $\tau_{weapon} = \tau \times n$, and the weapon angular speed is reduced to $\omega_{weapon} = \omega / n$.

In the equation $\omega = K_v \times (V_{input} - R_{system} \times I_{input})$, the only variable terms are ω and I_{input}, all others are constant, therefore the angular acceleration is $d\omega/dt = -K_v \times R_{system} \times dI_{input}/dt$. The dynamic equation of the system is then:

$$\tau_{weapon} = I_{zz} \cdot \frac{d\omega_{weapon}}{dt} \quad \Rightarrow \quad \tau \cdot n = \frac{I_{zz}}{n} \cdot \frac{d\omega}{dt} \quad \Rightarrow \quad K_t \cdot I_{input} \cdot n = -\frac{I_{zz} \cdot K_v \cdot R_{system}}{n} \cdot \frac{dI_{input}}{dt}$$

and therefore

$$I_{input} dt = -\frac{I_{zz} \cdot K_v \cdot R_{system}}{K_t \cdot n^2} \cdot dI_{input}$$

The *capacity consumption* of a battery, which is its *energy consumption* divided by its voltage, is then obtained by integrating the current with respect to time, from its initial value I_{stall} (in the start of the weapon acceleration) until its final zero value (because it approaches $I_{no\_load} = 0$), therefore

$$\text{Capacity Consumption} = \int I_{input} dt = -\frac{I_{zz} \cdot K_v \cdot R_{system}}{K_t \cdot n^2} \cdot \int_{I_{stall}}^{0} dI_{input} = \frac{I_{zz} \cdot K_v \cdot R_{system}}{K_t \cdot n^2} \cdot I_{stall}$$

The above equation is valid for any spinning weapon powered by PM DC motors. But be careful with the units, K_v should be in (rad/s)/A and the resulting capacity consumption is in A·s. In the 2006 version of Touro, the capacity consumption during each spin up of its drum was

$$\text{Capacity Consumption} = \frac{0.0338 \cdot 21.55 \cdot 0.086}{0.0464 \cdot 1^2} \cdot 279 = 377 A \cdot s = 0.104 A \cdot h$$

However, we still need to consider the capacity consumption due to the friction losses of the weapon. This is very hard to model theoretically, but it can be easily measured experimentally. To do that, we've powered Touro's drum and, at its maximum speed, we've measured the electrical current going through the motor, which was about 40A. Be careful when testing weapons, safety always comes first! This average 40A value is continuously consumed while the drum is powered, to compensate for friction losses from the motor, drum bearings and V-belts, as well as the aerodynamic losses due to the high tangential speed of the drum teeth.

We will consider that the drum is powered during an entire 3 minute match, and that it delivers about 10 large blows against the opponent (therefore needing to fully accelerate 10 times). The total capacity consumption of the weapon motor in 3 minutes (180 seconds) is then approximately:

$$\text{Weapon Capacity Consumption} = 40A \times 180s + 10 \times 377 A \cdot s = 7200 A \cdot s + 3770 A \cdot s = 10970 A \cdot s \cong 3.1 A \cdot h$$

Note that most of the weapon consumption (almost 66% in this case) is used up to compensate for friction and aerodynamic losses. Therefore, you should always use well lubricated ball, roller or tapered bearings. Shielded and sealed bearings are a good option to avoid debris, but the sealed type usually results in higher friction. Plain bronze bearings can also be used, but the friction losses are usually higher, and they can heat up a lot at high speeds unless they are of the plugged type.

The total energy consumption of Touro in 3 minutes, adding the contributions of the drive system (with an aggressive driver accelerating half of the match, as previously considered) and the weapon system (with the drum turned on during the whole time and delivering 10 great blows) is

$$\text{Total Capacity Consumption} = 3.3A\cdot h + 3.1A\cdot h = 6.4A\cdot h$$

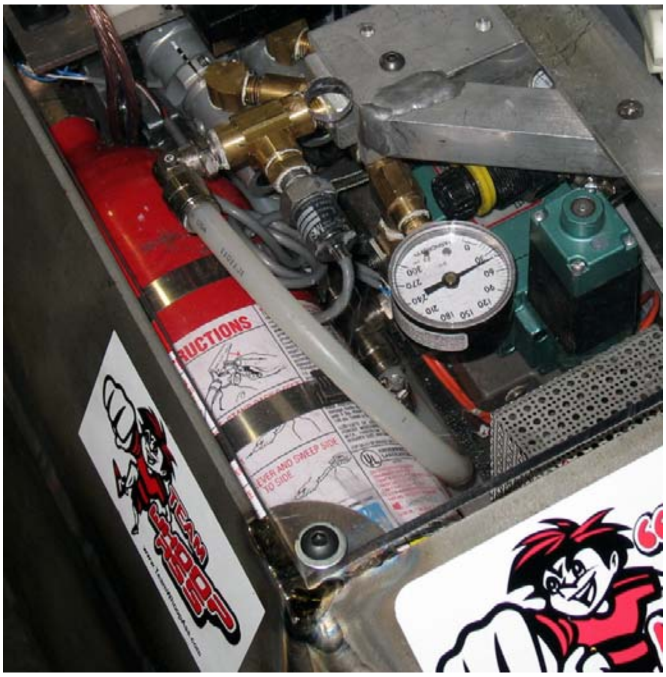
therefore two 24V battery packs with 3.6A·h each (totaling 7.2 A·h) would be enough.

These calculations can also help to define the driver's strategy in case of contingency. For instance, if you have available two packs with only 2.4A·h each (totaling 4.8A·h), the driver could accelerate the robot (drive system) 25% of the time, turn off the weapon during 30% of the match (attacking as a rammer during this time), and still be able to deliver 10 great blows, because after recalculating the capacity consumption we would get

$$\text{Total Capacity Consumption} = 1.65A\cdot h \text{ (drive)} + 2.45A\cdot h \text{ (weapon)} = 4.1A\cdot h$$

which would be enough if both batteries can actually deliver 4.8A·h.

5.5. Pneumatic Systems



Up to now we've basically focused on DC motors, because they're the most used actuators in combat. However, there are other actuation elements that are as good as or even better than electric systems. Their only disadvantage is the higher complexity and, in some cases, reduced reliability.

Pneumatic systems are capable of generating a great amount of energy in a short period, which is fundamental for robots with intermittent weapons such as hammerbots or launchers (such as the lightweight Hexy Jr, from Team WhoopAss, pictured to the right). They are usually powered by high pressure air or nitrogen (N_2), or liquid CO_2.

CO_2 can be stored in reservoirs in the liquid form. This allows tanks to store a great amount of CO_2 in a small space. The storage pressure is about 850 to 1000psi (about 60 to 70 atmospheres). Because it is used in paintball weapons, many components for CO_2 are easily found. The problem with CO_2 is that the phase change from liquid to gas is an endothermic process, which can make the reservoirs freeze during a match.

Air and N_2 can be compressed in gas form to higher pressures, such as 3000psi (about 200 atmospheres). Their advantages over CO_2 are that they do not have the freezing problem and they are lighter (saving about 0.5kg in typical middleweights with a full tank). The disadvantage is in the need for high pressure components, which are more expensive. Besides, a few competitions limit the pressure that can be stored in the robots.

In a simplified way, the pneumatic systems consist of one or more storage tanks, connected to a pressure regulator, accumulator, solenoid valve, and pneumatic cylinder, not to mention the safety valves.

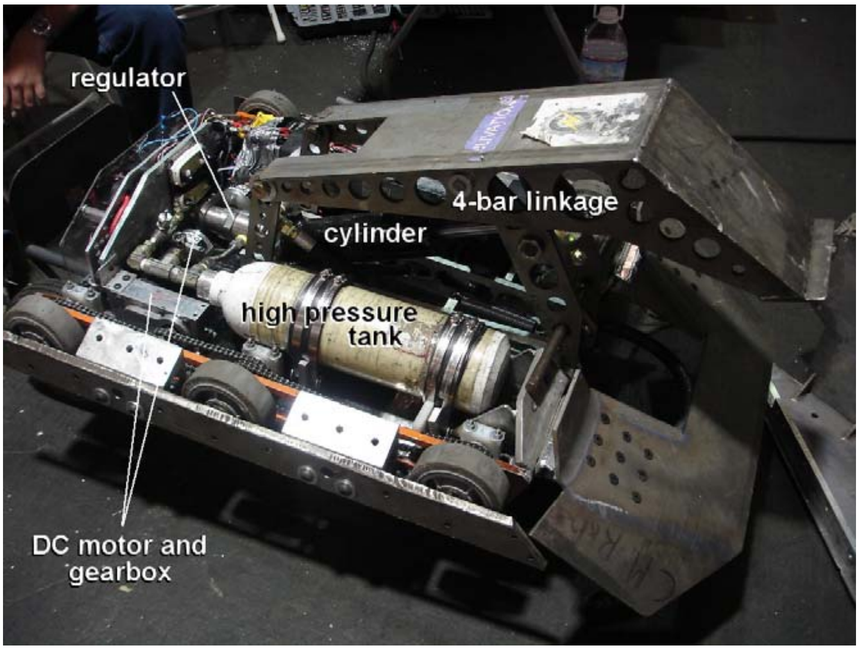
Storage tanks are necessary because it is not practical to use air (or N_2) compressors. Besides being heavy, air compressors would not have enough power to supply the robot's needs in time during an attack, even if some accumulator was present to act as a buffer.

Regulators are components that transform the high pressures of the pneumatic tanks (about 1000psi for CO_2 and 2000 to 3000psi for air or N_2) into lower pressures that can be used in conventional pneumatic systems, typically between 150 to 250psi.

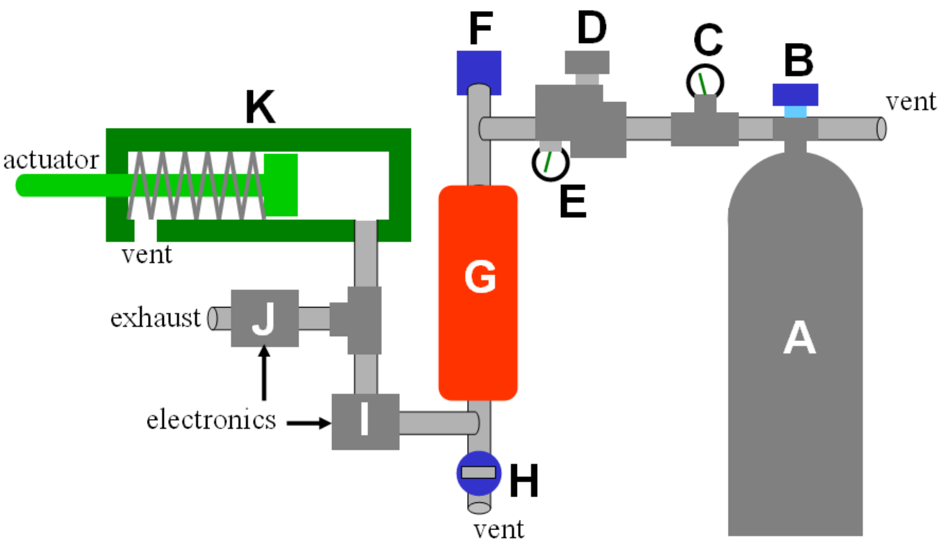
Accumulators are buffers, small reservoirs that store the gas already in the operating pressure of the robot's weapon. They are necessary only if your regulator doesn't generate enough flow for an efficient attack. They usually store enough gas for one attack, guaranteeing the required flow during the entire stroke of the cylinder, without suffering the bottleneck effects of the regulator or safety valves.

The cylinders are actuated through solenoid valves, which usually are of two types: two-way two-port, to power single-acting cylinders (which are only powered in one direction, they usually need a spring return), or four-way five-port, for double-acting cylinders (which are pneumatically powered in both directions). Naturally, the larger the piston area, the larger the generated forces by the cylinder.

The picture below shows the super-heavyweight launcher Ziggy, with its high pressure tank, high pressure regulator (a “GO regulator” PR-59 Series), and its cylinder, which powers a 4-bar linkage. The solenoid valves cannot be seen in the picture, because they’re on the opposite side. No accumulator is used in this case, therefore the regulator is the system bottleneck, even though it is of a high flow type. The picture shows as well the Magmotor S28-400 motors and TWM 3M gearboxes used in the chained drive system.

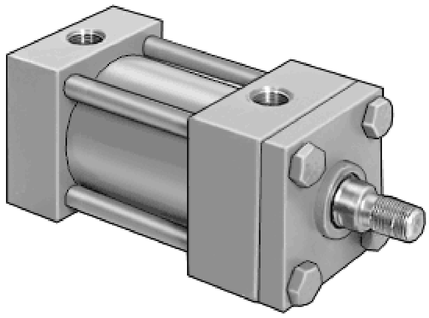


The figure below displays the schematics of a single-acting cylinder. The items A, B, C and D of the diagram represent the high pressure line, and the remaining elements are the operating pressure line.



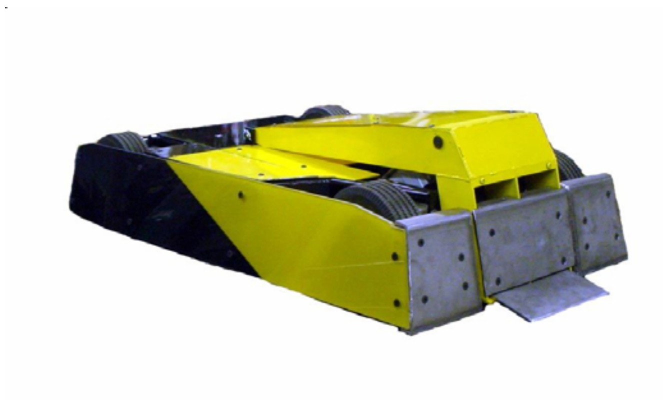
A. high pressure tank;
B. high pressure purge valve;
C. high pressure gauge;
D. regulator;
E. low pressure gauge;
F. safety valve;
G. accumulator;
H. low pressure purge valve;
I. normally closed two-way valve;
J. normally open two-way valve;
K. single-acting cylinder, with spring return.

Several daring builders use CO_2 tanks without regulators, sending high pressure directly to the cylinders. For that it is necessary to eliminate any bottlenecks in the pressure line, removing any needle valves and avoiding turns and sharp corners in the pipeline. If the entire flow is free of bottlenecks, it is not necessary to use an accumulator. The schematics would be similar to the one above, except that the items D, E, F, G and H would be eliminated. But be careful: instead of working with 150 to 250psi, the items I, J and K would be submitted directly to about 1000psi. They might not tolerate such pressure level.



To tolerate such unregulated pressure, you would need hydraulic components, especially hydraulic cylinders, as pictured to the right. A few of them are rated to up to 2500psi. However, they would be pneumatically powered. Be careful with these systems, because they are potentially self-destructive! Hydraulic cylinders are not designed for the high-speeds of the pneumatic systems, thus there is a chance that the piston will break due to the impact at the end of its stroke. Use certified systems for 2500psi hydraulic if you plan to power them at 1000psi pneumatic.

Even so, as pointed out by Mark Demers, builder of Ziggy, an unmodified 2500psi cylinder which is not designed for impact loading at stroke end doesn’t guarantee it will hold up at 1000psi pneumatic: “Impact loads are dramatically higher than static loads. I recommend some sort of external constraint to eliminate the impact load which occurs at the end of the stroke. The higher the launching force, the more sense it makes to add a limiting constraint. Back in the days of BattleBots, the Inertia Labs launcher robots (T-Minus, Toro, Matador) used nylon strap restraints to limit the extension of the arm and relieve the cylinder from the shock loading. Nylon straps are also used in Monster trucks to prevent over-extension in the suspension. Ziggy’s 4-bar system limits the stroke of the cylinder by design – the cylinder has an 8” stroke but the linkage does not allow extension of more than 7.75.”

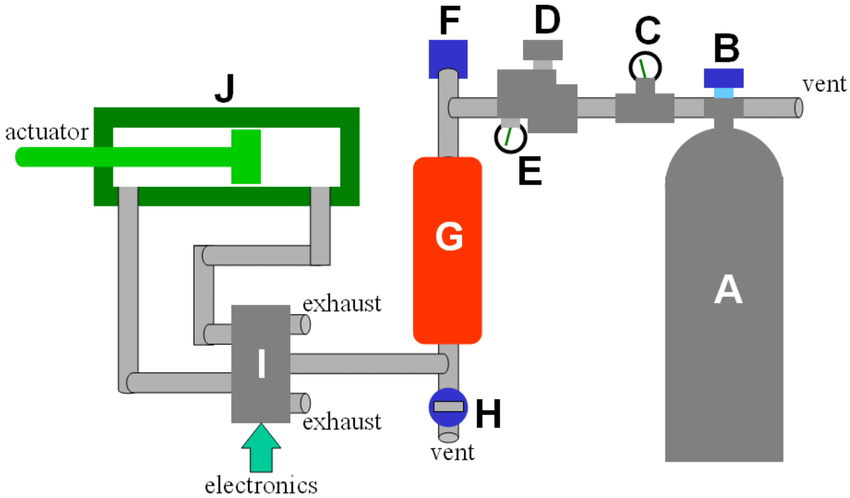


In addition to end-of-stroke restraints, most cylinders used in launchers need modifications to take the impact loads. Team Hammertime’s famous launchers, such as Bounty Hunter (pictured to the right) and Sub-Zero, use cylinders powered by high-pressure CO_2. Their builder, BattleBots veteran Jerry Clarkin, has modified his cylinders for the additional load. As pointed out by Mark Demers, “the cylinders Jerry is using have an air cushion at the end of their stroke. Additionally, Jerry has added high strength steel tie rods and steel containment plates to dramatically increase the axial strength of the cylinder.”

But be careful, do not try using unregulated systems unless you already have a lot of experience with conventional regulated pneumatics. Also, don't forget to check the competition rules to see whether the use of such unregulated pressures is allowed.

Back to regulated systems, to power a double-acting cylinder, it is necessary to use a slightly different schematics, shown below.

A. high pressure tank;
B. high pressure purge valve;
C. high pressure gauge;
D. regulator;
E. low pressure gauge;
F. safety valve;
G. accumulator;
H. low pressure purge valve;
I. four-way valve;
J. double-acting cylinder.

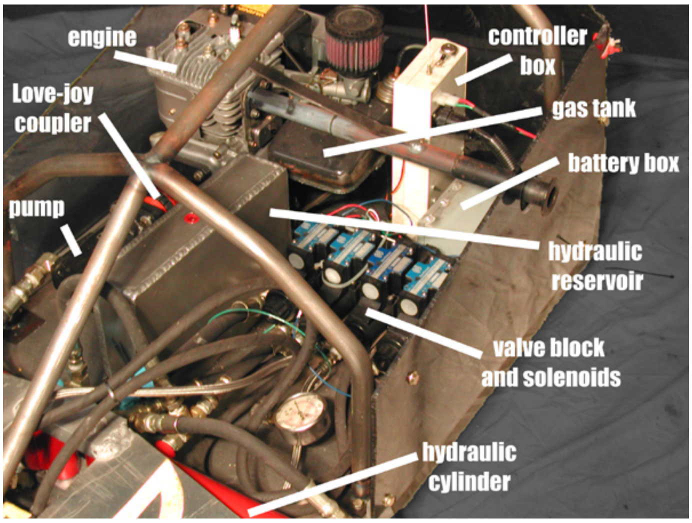


A few tips to increase the speed of your cylinder are: use a larger accumulator; use hoses and connections with the largest possible diameter; avoid sharp corners in the path of the hoses and pipes; leave the gas exhaust path as free as possible, directed towards outside the robot. More information can be found at www.teamdavinci.com/understanding_pneumatics.htm, and in the references [4] and [10].

5.6. Hydraulic Systems

Among weapon system actuators, hydraulic cylinders are the ones capable of generating the largest forces. Their inconvenience is in the low speed of the weapon, which is a big issue in combat. A two-stage hydraulic system would solve this issue, however its implementation is very complex. The hydraulic cylinder is powered by hydraulic servo-valves through solenoids. These systems also require a compressor (hydraulic pump), which needs to be powered either electrically or using an internal combustion engine (ICE). Hydraulic fluid leakage is also a common problem.

Hydraulic weapon systems were only successfully used in crusher bots. The picture below, from www.boilerbots.com, shows the weapon system from the famous super heavyweight Jaws of Death. Note the need for an electric system (for the servo-valves and drivetrain), hydraulic system (weapon), as well as an ICE to power the hydraulic pump. There are so many heavy components required in the weapon system, that usually only a super heavyweight is able to use them without compromising drivetrain speed or armor. Few hydraulic robots are still active, mainly due to their complexity.



5.7. Internal Combustion Engines

Internal combustion engines (ICEs) are capable of storing a great amount of energy. The energy density of gasoline, for instance, is about 100 times larger than that of NiCd batteries. They deliver more power to weapon systems than an electric motor would. Another advantage is that their torque increases (up to a certain point) with speed, unlike PM DC motors, which tend to zero torque at high speeds. Internal combustion engines also do not lose power when the tank is almost empty, as opposed to DC motors, which start to run slow as the batteries drain. In addition, the loud noises can impress well the judges during a match.

The ICE system design is relatively simple, you just need a good quality servo-motor and a centrifugal clutch (such as the ones used in go-karts). These clutches guarantee that the weapon will not spin until the beginning of the match, as required by the competition rules, even with the ICE turned on.

A great challenge is to guarantee that the ICE works upside down, in case the robot is invertible, guaranteeing that the fuel flow remains constant and without leakage. Chainsaw motors are good candidates, because their carburetor can operate in any orientation. ICEs used in airplanes also work upside down. Jet engines have also been used to power spinners, however they would usually be too heavy for a middleweight, sometimes even for a heavyweight.

The ICEs only spin in one direction, therefore they are only used to power combot weapons. To power a drive system, the ICE would need a complex gear system to reverse the wheel spin.

A serious problem with an ICE is the large radio interference that the spark plugs can cause. Therefore, place the receiver and electronics as far away as possible from the motor. To eliminate this problem, you can also use resistor spark plugs, which cause ignition through electric resistance, not causing any radio interference. Or you can use, for instance, 2.4GHz radio systems, which do not suffer from such ICE noise problems.

The greatest disadvantage of an ICE robot is its low reliability. The technique to turn it on in the beginning of a match is known as “pull and pray”: you pull-start it, and pray for it to keep running. If the ICE dies during a match, it will be impossible to start it again, unless it has its own onboard starter, controlled by an additional channel of the radio. This system adds weight to the robot and it also suffers reliability problems. Besides, you will end up needing to use 4 radio channels to power a single ICE.

In summary, ICE robots are extremely powerful and dangerous, but due to their low reliability they depend a lot on luck to win a competition without technical problems.

A curiosity: the robot Blendo (pictured to the right) was the first ICE spinner, using a lawnmower motor. It was built by Jamie Hyneman, and its electronic system was wired by Adam Savage. Jamie and Adam’s appearances in BattleBots called the attention of producer Peter Rees, leading to their debut hosting the famous Discovery Channel TV show MythBusters.

Chapter

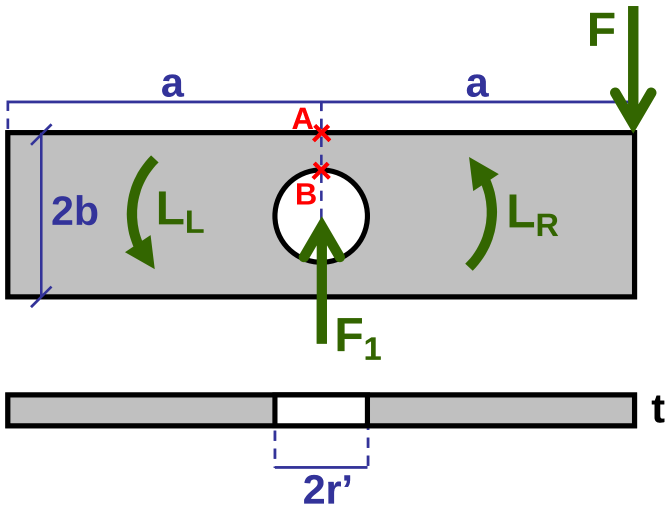
6

Weapon Design

In this chapter, we'll address several specific issues concerning weapon design. The idea is to show that mechanics calculations based on basic physics concepts and common sense can help a lot in the design of powerful and robust weapon systems.

6.1. Spinning Bar Design

It is not difficult to specify the dimensions of the bar of a spinner robot using basic stress analysis and a very simplified impact model. Consider the bar on the right, made out of hardened steel with length 2·a, width 2·b and thickness t, with a central hole of radius r'. During the impact, the angular momentum of the left and right hand sides of the spinning bar, L_L and L_R, will cause an average reaction force F from hitting the opponent, as seen in the figure. Since the bar is symmetric, it is easy to see that $L_L = L_R$.



If we assume that the chassis of the spinner robot is much heavier than its bar, we can say that the average reaction force F_1 from the weapon shaft is approximately equal to F, therefore $F_1 \cong F$ (we'll see later a better model that will allow different values for F_1 and F). We will also assume that the opponent is much heavier than the bar, and that the impact is inelastic, making the bar stop spinning after the brief time interval Δt of the impact. Therefore, the average torque F·a with respect to the weapon shaft, caused by the force F, must be able to bring the initial value of the angular momentum $(L_L + L_R)$ of the bar to zero during this Δt, resulting in $F \cdot a = (L_L + L_R) / \Delta t$, which gives $L_L / \Delta t = L_R / \Delta t = F \cdot a/2$. The average bending moment M_{max} in the middle of the bar, the region where bending is maximum, can then be calculated, $M_{max} = L_L / \Delta t = F \cdot a - L_R / \Delta t = F \cdot a/2$.

The stress at point A (see figure) due to bending is $\sigma_A = 3 \cdot M_{max} \cdot b/[2 \cdot (b^3 - r'^3) \cdot t]$. The stress at point B, theoretically, would be smaller than in A, however the hole acts as a stress raiser. It amplifies the stresses close to its border. In the geometry and loading of this example, it multiplies the stress by a factor of approximately 2, in other words, the stress concentration factor is 2 (this value is obtained from specific stress concentration factor tables [8]). Therefore, the stress acting at B is $\sigma_B = 2 \times 3 \cdot M_{max} \cdot r' / [2 \cdot (b^3 - r'^3) \cdot t]$.

If $\sigma_A > \sigma_B$, then if the bar breaks it will be from the outside in, beginning to fracture in A (where the stress is higher) and propagating a crack abruptly until point B. The bar will then break in two because the residual ligament on the other side of the hole (region below the hole in the figure) will be overloaded and break. All this happens in a split second – in metals, the fracture propagates at a speed of about 2 to 3km/s (1.24 to 1.86 miles per second), therefore a typical middleweight spinner bar would take about 0.01ms to fracture.

On the other hand, if $\sigma_B > \sigma_A$, the bar will break from the inside out, beginning fracturing from point B to point A. This was how the 5160 steel bar from our middleweight spinner *Ciclone* broke during the Winter Challenge 2005 competition, from B to A. That was because the diameter 2·r' of the hole of *Ciclone*'s bar was large with respect to its width 2·b, penalizing point B.

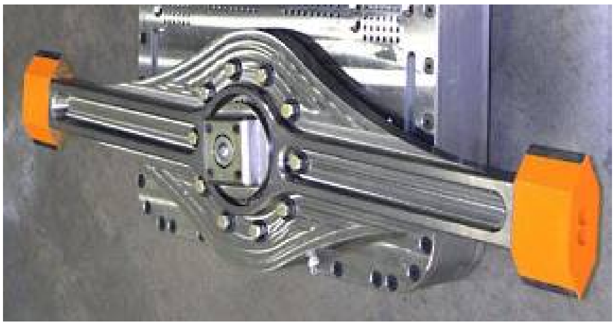
A good design choice would be to try to make point A at least as resistant as point B. For that, it is enough to equate $\sigma_A = \sigma_B$. After a little algebra with the previous expressions, we get $b = 2 \cdot r'$. Therefore, design your spinning bar (and the weapon shaft that will hold it) so that its width 2·b is at least twice the diameter 2·r' of its center hole. The bar from our middleweight spinner Titan was designed having this in mind.

And how much force would the bar support? Consider, for instance, 2·a = 1000mm, 2·b = 80mm, 2·r' = 2·b/2 = 40mm, and the thickness t = 12mm. The steel bar, with average density ρ = 7800kg/m^3, would have a mass of, approximately (without considering the hole), $\rho \cdot (2 \cdot a) \cdot (2 \cdot b) \cdot t$ = 7800kg/m^3 · 1m · 0.080m · 0.012m = 7.5kg (16.5lbs), which is a reasonable value for a middleweight – from the 30-30-25-15 rule, a middleweight would have 16.3kg (36lbs) for the weapon system, leaving in that example 16.3 – 7.5 = 8.8kg (more than 19lbs) for the weapon shaft, bearings, transmission and motor, an also reasonable value. A hardened steel with 45 Rockwell C (unit that measures how hard the material is, see chapter 3) tolerates a maximum stress of about 34 × 45 = 1530N/mm^2 before breaking (this 34 factor is only valid for steels, estimating well the ultimate strength from the Rockwell C hardness).

Making both stresses at A and B equal to 1530N/mm^2, then $\sigma_A = \sigma_B = 3 \cdot M_{max} \cdot b / [2 \cdot (b^3 - r'^3) \cdot t]$ = 1530N/mm^2, where the bending moment $M_{max} = F \cdot a/2$, resulting in F = 68,544N, equivalent to almost 7 metric tons! Now it is necessary to guarantee that the weapon shaft and the rest of the robot can tolerate such average 7 tons, which can be made using the same philosophy presented above, from basic stress analyses. Approximate calculations can be very efficient if there is common sense and some familiarity with the subject.

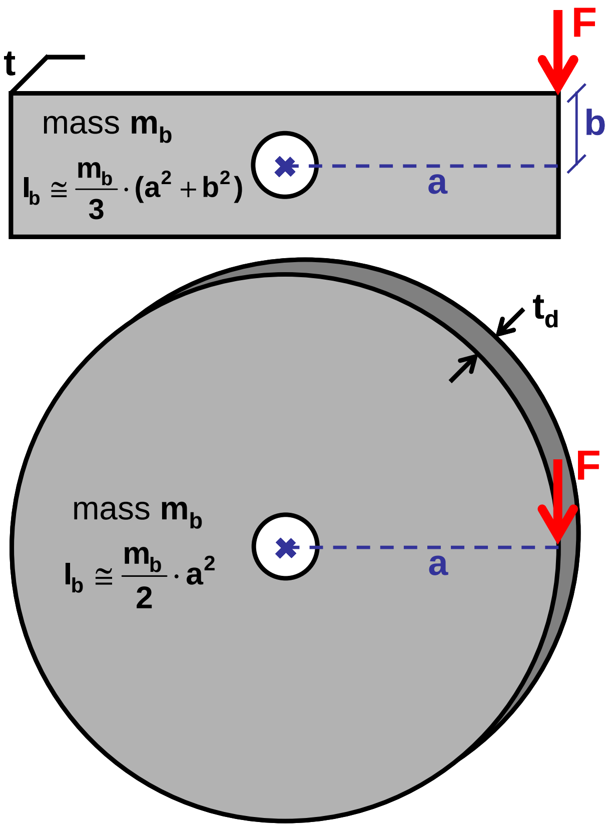
Clearly, bars with $b > 2 \cdot r'$ will result in even more strength, because a higher width 2·b will decrease both σ_A and σ_B values. But don't exaggerate, otherwise you'll have to decrease too much its thickness t not to go over the weight limit, compromising the strength in the out-of-plane bending direction.

Another solution would be to have a variable width bar, with a wider middle section, as pictured to the right. Note how the bar shape is optimized, with an increasingly wider middle section to withstand high bending moments, and sharp and heavy inserts at its tips to guarantee a high moment of inertia in the spin direction. Note also the ribs milled in the bar to increase its bending strength without adding too much weight.



6.2. Spinning Disk Design

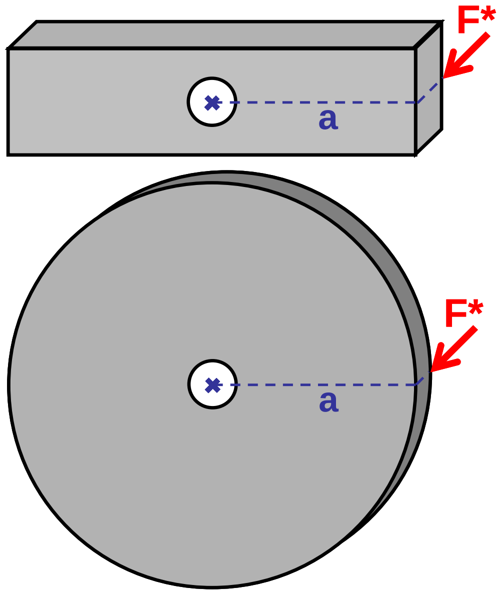
There has always been a great debate whether bars or disks make the best spinning weapons. Consider that the robot design allows a spinning weapon with mass m_b, and its reach from the weapon shaft must have a length a. Then let's compare a bar with length $2 \cdot a$ to a disk with radius a, pictured to the right. Both weapons, with same mass m_b, would be originally spinning until suffering an impact force F from hitting the opponent. If made out of the same material with a mass density ρ, then the thicknesses t and t_d of the bar and disk would be approximately $t \cong m_b/(\rho \cdot 4 \cdot a \cdot b)$ and $t_d \cong m_b/(\rho \cdot \pi \cdot a^2)$.



Concerning moment of inertia (I_b), it is easy to see from the values in the figure that the disk is a better choice, unless the half-width b of the bar is very large, above $0.707 \cdot a$. The moment of inertia of a narrow bar (with b much smaller than a) would be roughly 66.7% of the value of a disk with same mass m_b and length a.

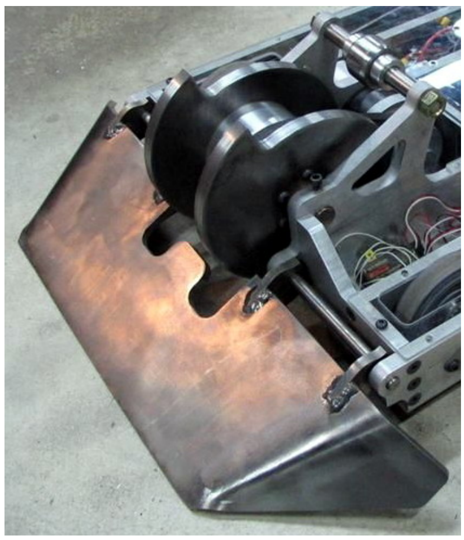
Let's take a look now at the stresses. If the width $2 \cdot b$ of the bar is much higher than twice the diameter of the center hole, then the maximum stress due to the force F is approximately $\sigma_{bar} \cong 3 \cdot F \cdot a/(4 \cdot t \cdot b^2)$. And assuming the disk diameter is much larger than its hole diameter, then the maximum stress would be $\sigma_{disk} \cong 3 \cdot F/(4 \cdot t_d \cdot a)$. It is easy to show from these equations and the expressions for t and t_d that, assuming b smaller than a, any bar would see higher maximum stresses than the disk.

So, disks are a better choice concerning both stresses (while delivering an impact) and moment inertia. But they have a major drawback. If a vertical disk is hit by a horizontal spinner, or a horizontal disk is hit by a drum or vertical spinner, it will see a force F* perpendicular to its plane, as pictured to the right, which will cause a maximum out-of-plane bending stress of approximately $\sigma_{disk}^* \cong 3 \cdot F^*/t_d^2$. The same perpendicular force would cause on the bar a maximum out-of-plane bending stress of $\sigma_{bar}^* \cong 3 \cdot F^* \cdot a/[(b-r') \cdot t^2]$, where r' is the radius of the hole. It is easy to show that any disk would result in higher maximum out-of-the-plane stresses than a bar.

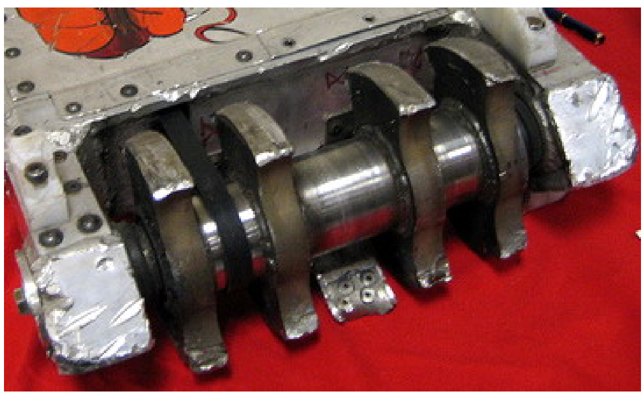


For instance, a bar with $b = 2 \cdot r'$ would only see $\pi^2/32 \cong 31\%$ of the stresses found on an equivalent disk. The above equations, together with estimates for F and F*, are very useful to find out values for the bar width 2·b that will meet requirements for maximum allowable stresses σ_{bar} and σ_{bar}^*, as well as to decide whether a disk would be an acceptable option despite its high resulting σ_{disk}^*.

Therefore, we conclude that horizontal bars are a better choice than horizontal disks against drums, vertical spinners, and wedges (which can deflect a hit and also cause high out-of-plane bending stresses). Horizontal disks would be better against all other types of opponents, due to their higher in-plane bending strength and also higher moment of inertia. And vertical disks would be a better choice than vertical bars against most robots, except against horizontal spinners, which will most likely warp or break the disk with a powerful out-of-plane hit. You can get away with a vertical disk against a horizontal spinner, but you should either limit the disk radius (having a lower radius a to decrease σ_{bar}^*), or protect it against out-of-plane hits having it recessed into the chassis or using a wedge, as seen in the lightweight K2 on the right.



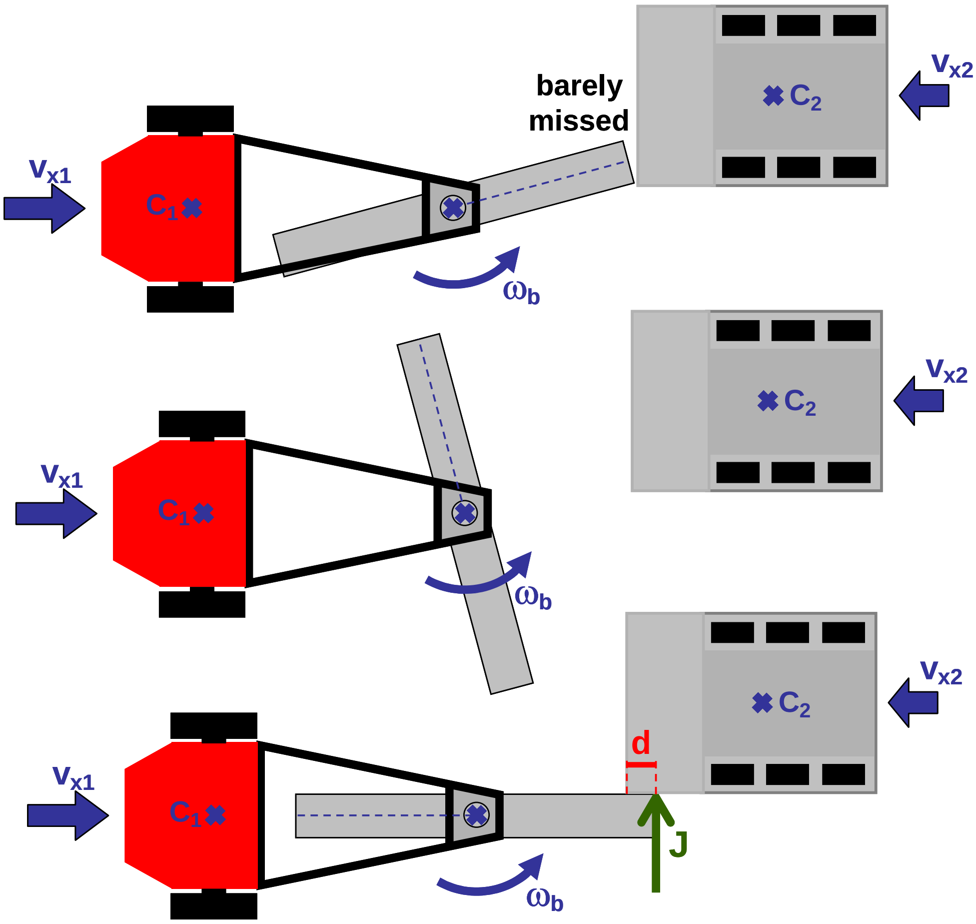
Note that the calculations above assumed solid bars and disks, without considering any shape optimization. But the conclusions would still hold if comparing an optimized bar to an optimized disk. Shape optimization can also generate hybrids between disks and bars, trying to get the best of both worlds. The drum teeth from the middleweight Angry Asp (pictured to the right) are a good example of that, with their wide disk-like mid-section and elongated bar-like overall shape.



6.3. Tooth Design

One important issue when designing spinning weapons such as disks, bars, drums and shells is regarding the number of teeth and their height. Too many teeth on a spinning disk, for instance, will make the spinner chew out the opponent instead of grabbing it to deliver a full blow. Everyone who's used a circular saw knows that fewer teeth means a higher chance of the saw binding to the piece being cut, which is exactly what we want in combat.

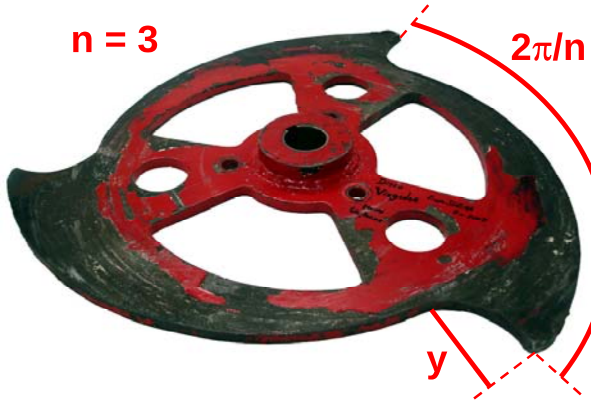
6.3.1. Tooth Height and Bite



Before we continue this analysis, we need to define the tooth bite d. The tooth bite is a distance that measures how much the tips/teeth of the spinner weapon will get into the opponent before hitting it. For instance, if two robots are moving towards each other with speeds v_{x1} and v_{x2}, one of them having a bar spinning with an angular speed ω_b (in radians per second), as pictured to the right, then the highest bite $d = d_{max}$ would happen if the bar barely missed the opponent before turning 180 degrees to finally hit it. The time interval the bar takes to travel 180° (equal to π radians) is $\Delta t = \pi/\omega_b$, during which both robots would approach each other by $d_{max} = (v_{x1}+v_{x2})\cdot\Delta t = (v_{x1}+v_{x2})\cdot\pi/\omega_b$. So, the tooth bite d could reach values up to d_{max}.

Small values for d mean that the spinner will have a very small contact area with the opponent, most probably chewing its armor instead of binding and grabbing it. So, a spinner needs to maximize d to deliver a more effective blow. This is why an attack with the drive system at full speed is more effective, since a higher speed v_{x1} will result in a higher d. And this is why very fast spinning weapons have a tough time grabbing an opponent, their very high ω_b ends up decreasing the tooth bite d.

The maximum obtainable tooth bite $d = d_{max}$ can also be generalized for a weapon with n teeth. In this case, the teeth are separated by $2 \cdot \pi / n$ radians, as pictured to the right, resulting in $\Delta t = 2 \cdot \pi / (n \cdot \omega_b)$, and therefore $d_{max} = (v_{x1}+v_{x2}) \cdot \Delta t = (v_{x1}+v_{x2}) \cdot 2 \cdot \pi / (n \cdot \omega_b)$. Since the tooth bite cannot be higher than d_{max}, there is no reason to make the tooth height $y > d_{max}$ (see picture), which would decrease its strength due to higher bending moments. Therefore, the optimal value for the tooth height y is some value $y < (v_{x1}+v_{x2}) \cdot 2 \cdot \pi / (n \cdot \omega_b)$.



Using the maximum values of both v_{x1} and v_{x2} speeds will probably result in large values for y, so it is a reasonable idea to assume $v_{x2} = 0$. Most attacks will happen at full speed v_{x1} but without the opponent moving towards you. Besides, a spinner doesn't know beforehand the value of v_{x2} of all of its possible opponents. So, a tooth height $y = v_{x1,max} \cdot 2 \cdot \pi / (n \cdot \omega_{b,max})$ is usually more than enough. Note that this height assumes the weapon at full speed, if you want to deal with lower ω_b speeds before it fully accelerates then the value of y should be increased accordingly.

The tooth height calculated above can still be reduced if necessary without compromising much the tooth bite d. This is because the above estimates assumed that one tooth barely misses the opponent, until the next tooth is able to grab it at a distance d. But, if instead of barely missing the opponent, the previous tooth had barely hit it, it would have hit it with a distance much smaller than d. It is a matter of probability, the tooth bite can be any value between 0 and d, with equal chance (constant probability density). So, in 50% of the attacks at full speed the travel distance d will unluckily be between 0 and $d_{max}/2$, and in the other 50% it will luckily be between $d_{max}/2$ and d_{max}. An (unlucky) hit with d very close to zero probably won't grab the opponent, and it will significantly reduce the attacker speed v_{x1} until the next tooth is able to turn $2 \cdot \pi / n$ radians, decreasing the distance d of subsequent hits. If v_{x1} gets down to zero without grabbing the opponent, you'll probably end up grinding it. If this happens, the best option is to back up, and then charge again trying to reach $v_{x1,max}$ and hoping for a high d.

The chance of d being exactly d_{max} is zero, because it is always smaller than that, so if you want you can make the tooth height $y < d_{max}$. If you choose, for instance, $y = d_{max}/2 = v_{x1,max} \cdot \pi / (n \cdot \omega_{b,max})$, your robot won't notice any difference with this lower height in 50% of the hits, when $d < d_{max}/2$, while on the other 50% (where d would be higher than $d_{max}/2$) the opponent will touch the body of the drum/disk before being hit by a tooth, resulting in $d = y = d_{max}/2$. As long as this $d_{max}/2$ value is high enough to grab the opponent instead of grind it, it is a good choice.

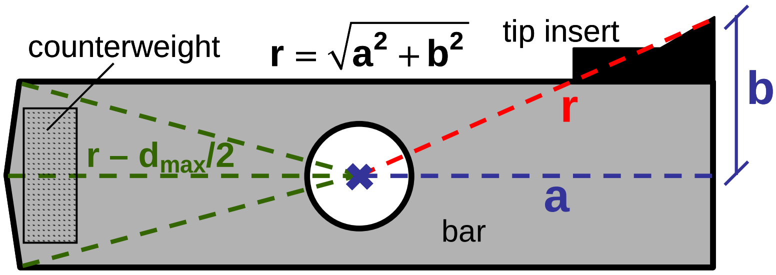
For instance, the 2008 version of our featherweight Touro Feather had a drum with n = 2 teeth (pictured to the right) spinning up to $\omega_{b,max}$ = 13,500 RPM (1413.7 rad/s). Since the robot top speed is $v_{x1,max}$ = 14.5mph (equal to 23.3km/h or

6.48m/s), then $d_{max} = 6.48 \cdot 2 \cdot \pi/(2 \cdot 1413.7) \cong 0.014m = 14mm$. Since the overall height of the drum needed to be smaller than 4" by design, a tooth height y = 14mm would result in a drum body with low diameter. We then chose y = 10mm for the tooth to stick out of the drum body. This 10mm height is usually enough to grab an opponent. Also, in 10mm/14mm = 71% of the hits at full speed, the tooth height y will be higher than the tooth bite d. The opponent will only touch the drum body in the remaining 29% of the hits, when the next tooth will be able to hit the opponent with its full 10mm height (unless the opponent had bounced off immediately after hitting the drum body).

But beware with a frontal collision between two vertical spinning weapons, because the opponent may be able to grab your drum or disk body with its teeth before you can grab it. In this case, it is a game of chance. The robot with higher teeth will have a better chance of grabbing the opponent, as long as it spins fast enough. Since a vertical spinning bar does not have a round inner body, it basically behaves as if its "tooth height" y was equal to the bar radius. So, usually a powerful vertical bar will have an edge in weapon-to-weapon hits against drums or vertical disks.

6.3.2. Number of Teeth

An important conclusion from the previous analyses is that you must aim for a minimum number of teeth, n. The lower the n, the higher the value of d. Disks with n = 3 or more teeth are not a good option. The best choice is to go for n = 2, as with bars or two-toothed disks. Even better is to try to develop a one-toothed spinning weapon, such as the disk of the vertical spinner Professor Chaos, but this requires a careful calculation to avoid unbalancing by using, for instance, a counterweight diametrically opposite to that tooth.



Note that a one-toothed weapon does not have to be too much asymmetric, nor will it need heavy counterweights, if you do your math right. For instance, the one-toothed bar pictured to the right can be made out of a symmetrical bar, as long as the short end is chamfered to reach a maximum radius $r - d_{max}/2$, where r is the effective radius of the long end including the insert, calculated from a and b as shown in the figure, and the maximum tooth bite d_{max} is calculated for n = 1 tooth. In this way, with the bar at full speed, even if the long end barely misses the opponent, the short end won't touch it because during a half turn it would approach at most half of d_{max}. After the full turn it would have approached up to d_{max}, hitting for sure with the long end. With such n = 1, it is possible to move twice as much into the opponent before hitting it, transferring more impact energy.

With this proposed one-toothed bar geometry, the counterweight wouldn't have to be much heavy, because its mass would only have to account for the mass of the tip insert plus the removed mass from the chamfers. This bar is also relatively easy to fabricate, with very little material loss. In fact, for wide bars with large inserts, which increase the value of b, it is even possible to design the bar such as $a = r - d_{max}/2$, making it almost symmetrical even after chamfering. In addition, if you perform some shape optimization removing some material from the long end, it is even possible to remove the counterweight, but be careful not to compromise the bar strength at its most stressed region.

In our experience, to bind well to the opponent, the tooth bite should not be below 1/4", no matter if the robot is a hobbyweight or a super heavyweight. We've tested different tooth heights with our drumbot hobbyweight Touro Jr and featherweight Touro Feather, and values below 1/4" made the robot grind instead of grab the used deadweights. With this in mind, it is possible to generate a small table with estimated maximum weapon speeds to avoid the grinding problem. We only need to make sure that in at least 50% of the hits at full speed the tooth will be able to travel at least 1/4" (0.00635m), thus $\omega_{b,max}$ can be found from 1/4" = $d_{max}/2 = v_{x1,max} \cdot \pi / (n \cdot \omega_{b,max})$, see the table to the right. Of course these are just rough estimates, because tooth sharpness and armor hardness also play a hole helping or avoiding dents that bind with the opponent.

number of teeth n	drivetrain speed $v_{x1,max}$	maximum $\omega_{b,max}$ to avoid grinding
3	5mph (8km/h)	3520RPM
	10mph (16km/h)	7040RPM
	15mph (24km/h)	10560RPM
2	5mph (8km/h)	5280RPM
	10mph (16km/h)	10560RPM
	15mph (24km/h)	15840RPM
1	5mph (8km/h)	10560RPM
	10mph (16km/h)	21120RPM
	15mph (24km/h)	31680RPM

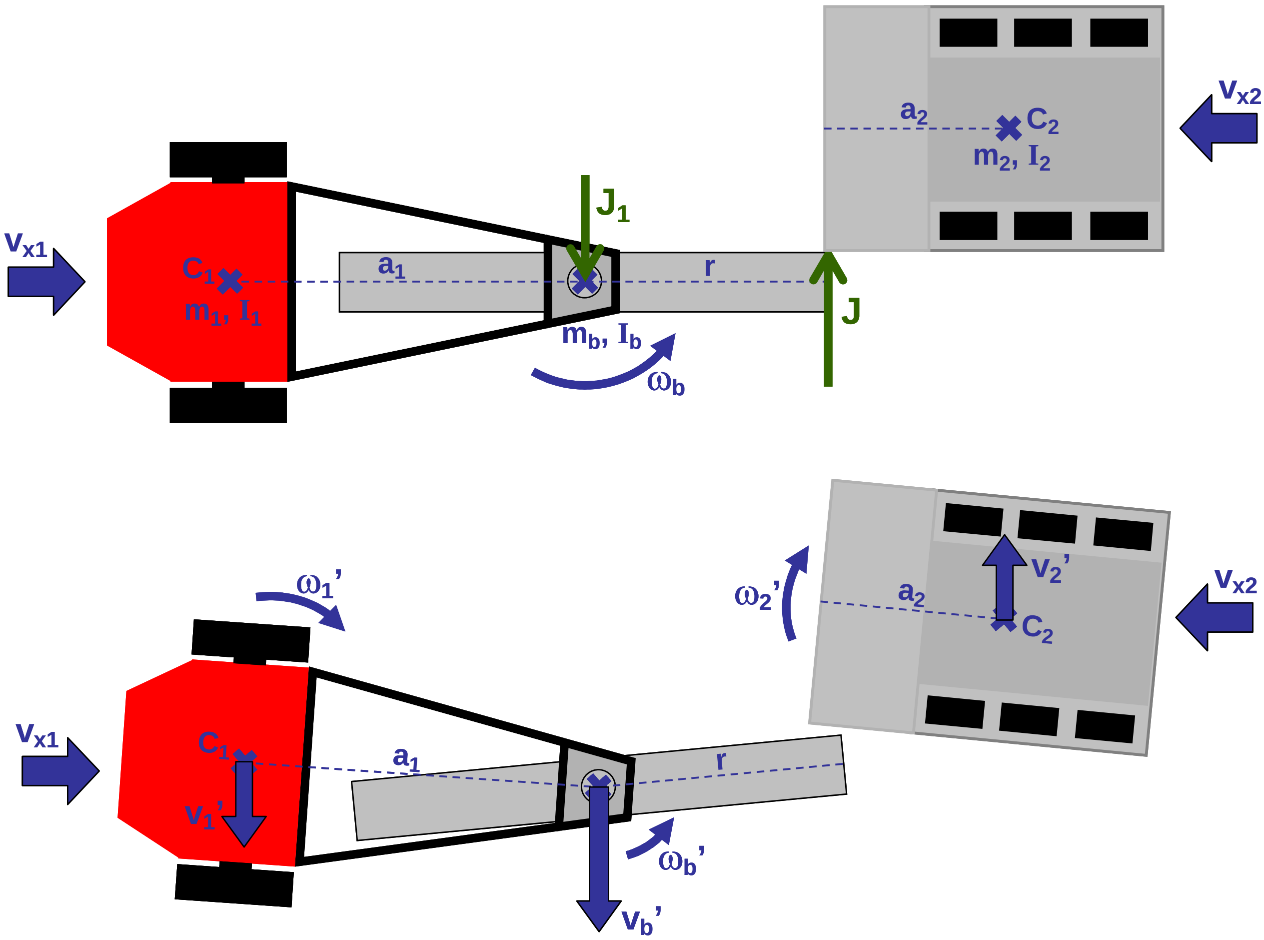
6.4. Impact Theory

In the previous sections, we've used very simplified models to describe the impact of a spinner weapon on another robot. We'll extend these models here, to get a deeper understanding of the physics behind these impacts, and hopefully design a better spinner.

6.4.1. Impact Equations

We'll consider the problem of a bar spinner hitting a generic opponent (pictured in the next page), during the impact and right after it. The spinning bar has a length $2 \cdot r$, a mass m_b and moment of inertia I_b with respect to its center in the spin direction. It is initially spinning with an angular speed ω_b. The chassis of the spinner robot, without its bar, has a mass m_1 and a moment of inertia I_1 in the spin direction with respect to the chassis center of mass C_1. The opponent has mass m_2 and moment of inertia I_2 in the spin direction with respect to its center of mass C_2. We'll assume that the opponent does not have vertical spinning weapons, which could cause gyroscopic effects.

We'll assume that the impact impulse J that the bar inflicts on the opponent is in a direction perpendicular to their approach speed ($v_{x1} + v_{x2}$), and the distance between C_2 and the vector J is a_2. If the impact force was constant during the time interval Δt of the impact, then the impulse J could be simply calculated multiplying this force times Δt, otherwise we'd have to integrate the force over time to get J. The bar will also generate a reaction impulse J_1 over the weapon shaft of the spinner. This impulse J_1 is at a distance a_1 from the chassis center of mass C_1. The distance a_1 is usually greater than r for an offset spinner when hitting as shown in the picture, or very close to zero for traditional spinners that have their weapon shaft close to C_1.



The picture also shows the moment right after the impact, where the opponent will gain a speed v_2' in the direction of J, when it will start spinning with an angular speed ω_2'. Note that both initial speeds v_{x1} and v_{x2} remain unchanged, because we assumed the impulse J perpendicular to them (we're implicitly assuming that there is no friction during the impact). The bar ends up with a slower angular speed ω_b' after the impact, while its center moves with a speed v_b' as a result of the reaction impulse J_1. The spinner robot chassis will gain a speed v_1' in the direction of J_1, and it will start spinning with an angular speed ω_1'. Note that ω_b' is measured with respect to the arena, and not with respect to the (now spinning) chassis.

If we assume that no debris is released from either robot during the impact, that the spinner bar has a perfect clutch system (which does not transmit any torque during the impact), and that the opponent does not have any spinning weapons that might cause some gyroscopic effect (studied later in this chapter), then basic physics equations of conservation of linear and angular momentum can show that

$$v_2' = \frac{J}{m_2}, \quad \omega_2' = \frac{J \cdot a_2}{I_2}, \quad v_1' = \frac{J_1}{m_1}, \quad \omega_1' = \frac{J_1 \cdot a_1}{I_1}, \quad v_b' = \frac{J - J_1}{m_b}, \text{ and } \omega_b' = \omega_b - \frac{J \cdot r}{I_b}$$

To find the values of J and J_1, we need to know the coefficient of restitution (COR) of the impact, defined by e, with $0 \le e \le 1$. The COR is the relative speed between the bar and the opponent after the impact divided by the relative speed before the impact. A purely elastic impact, where no energy is dissipated, would have e = 1. A purely inelastic impact, where a good part of the impact energy (but not all) is dissipated, would have e = 0. All other cases would have 0 < e < 1. Note that this dissipated energy is not only due to damage to the opponent in the form of plastic deformation or fracture, it also accounts for absorbed energy by the opponent's shock mounts, vibrations, sounds, and even damage to the weapon system of the spinner.

For very high speed impacts, as we see in combat, the COR e is usually close to zero, simply because no material can absorb in an elastic way all the huge impact energy. For instance, a bullet (taken from its cartridge) might have up to e = 0.9 when dropped from a 1" height against a metal surface. But the very same bullet, when fired to hit the same surface at very high speeds, will plastically deform and probably become embedded into the surface, resulting in e = 0. So, the value of e depends not only on the materials involved, but also on the impact speed.

In this problem, the approach speed before the impact is only due to the speed of the tip of the spinning bar, namely $v_{tip} = \omega_b \cdot r$. The relative speed between the bar tip and the opponent right after the impact (the departure speed) is due to several terms, such as the linear and angular speeds of the spinner and opponent robots, as well as the remaining angular speed of the bar, resulting in

$$e = \frac{v_{departure}}{v_{approach}} = \frac{v_2' + \omega_2' \cdot a_2 + v_1' + \omega_1' \cdot a_1 - \omega_b' \cdot r}{\omega_b r}$$

The speed v_b' of the center of the bar can be obtained from the linear and angular speeds of the spinner chassis, resulting in $v_b' = v_1' + \omega_1' \cdot a_1$. Solving all the previous equations, we finally obtain the values of the impulses J and J_1

$$J = M \cdot (1+e) \cdot v_{tip} \qquad \text{and} \qquad J_1 = \frac{J \cdot I_1 m_1}{I_1 m_1 + m_b \cdot (I_1 + m_1 a_1^2)}$$

where M is the effective mass of both robots, obtained from the effective masses M_1 from the spinner and M_2 from the opponent, namely

$$\frac{1}{M} = \frac{1}{M_1} + \frac{1}{M_2}, \quad \text{where} \quad \frac{1}{M_1} = \frac{1}{m_b + m_1 \cdot \dfrac{I_1}{I_1 + m_1 a_1^2}} + \frac{r^2}{I_b} \quad \text{and} \quad \frac{1}{M_2} = \frac{1}{m_2} + \frac{a_2^2}{I_2}$$

With these values of J and J_1, we can now calculate all the speeds after the impact. For instance, let's check a few limit cases to better understand the equations.

6.4.2. Limit Cases

If the spinner, instead of hitting an opponent, hits a very light debris very close to its center of mass (therefore $a_2 \cong 0$), then the debris has an effective mass $M_2 = m_2$. Since m_2 is much smaller than m_1 and m_b, we find that M_2 is much smaller than M_1, which leads to $M \cong M_2$. So, the effective mass of the entire system is only $M = m_2$, resulting in a small impulse $J = m_2 \cdot (1+e) \cdot v_{tip}$ that will accelerate the debris to a speed $v_2' = J/m_2 = (1+e) \cdot v_{tip}$.

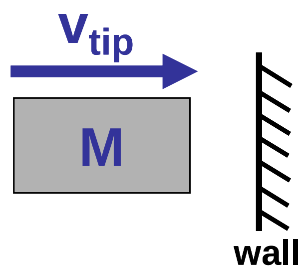
This means that if the debris is a little lump of clay (inelastic impact with $e \cong 0$), it will be thrown with basically the same speed v_{tip} of the bar tip. On the other hand, if it is a very tough rubber ball that won't burst due to the impact, its $e \cong 0.8$ will allow it to be thrown at 1.8 times the speed of the bar tip. Also, since m_2 is very small, the equations predict that the speeds of the spinner robot will almost remain unchanged, which makes sense since very little energy was transferred to the debris.

The other limit case is the spinner hitting a very heavy arena wall. The wall is so much heavier than the robot that we can assume that $m_2 \rightarrow \infty$ and $I_2 \rightarrow \infty$, resulting in $M_2 \rightarrow \infty$ and therefore the system effective mass is $M \cong M_1$, the effective mass of the spinner robot. This will result in the maximum impact that the spinner can deliver, $J = M_1 \cdot (1+e) \cdot v_{tip}$. This value is twice the impact that would be delivered to an opponent with $M_2 = M_1$. This is why it is a much tougher test to hit an arena wall than an opponent with similar mass. And, of course, the equations will tell that the speeds of the arena after the impact will be approximately zero.

6.4.3. Impact Energy

Before the impact, we'll assume that the attacking robot (such as a spinner) will have an energy E_b stored in its weapon. For the spinner impact problem presented above, $E_b = I_b \cdot \omega_b^2 / 2$. The impact usually lasts only a few milliseconds, but it can be divided into two phases: the deformation and the restitution phases.

In the deformation phase, a portion E_d of the stored energy E_b is used to deform both robots (such as bending the spinner bar or compressing the opponent's armor), while the remaining portion E_v is used to change the speeds of both robots and weapon. It is not difficult to prove using the presented equations that $E_d = M \cdot v_{tip}^2 / 2$ for the spinner impact problem. Interestingly, this would be the deformation energy E_d that a mass M with a speed v_{tip} would generate if hitting a very heavy wall, as pictured to the right. So, the higher the effective mass M, the higher the E_d. We'll see later in this chapter how an attacking robot can manage to maximize M to increase the inflicted damage to the opponent.



After the deformation reaches its peak, the restitution phase starts. A portion E_k of the deformation energy E_d was stored as elastic deformation, which is then retrieved during the restitution phase to change even more the speeds of both robots. The remaining portion E_c of E_d (where $E_d = E_k + E_c$) is the dissipated energy, transformed into permanent deformations, fractures, vibration, noise, as well as damped by the robot structure and shock mounts. We can show that, for an impact with COR equal to e, $E_k = E_d \cdot e^2$ and $E_c = E_d \cdot (1-e^2)$.

So, a perfectly elastic impact (e = 1) would have no dissipated energy ($E_c = 0$), and a perfectly inelastic impact (e = 0) would dissipate all its deformation energy ($E_c = E_d$). Note that inelastic impact does not mean that the entire energy of the system (which originally is E_b) is dissipated, it only means that the portion E_d is completely dissipated.

In summary, $E_b = E_v + E_d = E_v + E_k + E_c$, where the energy ($E_v + E_k$) will account for the changes in linear and angular speeds of the robots and weapon, and E_c will be dissipated.

6.4.4. Example: Last Rites vs. Sir Loin

Let's solve the impact equations for an example inspired on the heavyweight match between the offset spinner Last Rites (pictured to the right) and the eggbeater-drumbot Sir Loin, at RoboGames 2008. The mass of each robot is assumed as $m = m_1 + m_b = m_2 = 220$lb. We'll estimate the weight of the bar with the steel inserts as $m_b = 44$lb $= m/5$, therefore $m_1 = 220 - 44 = 176$lb $= 4\cdot m/5$. The bar is assumed to have a length $2\cdot r = 40$", spinning at $\omega_b = 2000$RPM (209.4 rad/s) before the impact, with an offset length $a_1 = 30$". If the opponent robot is assumed to have a square shape with side length $2\cdot a_2 = 30$", then the value of a_2 for the studied impact situation is about $a_2 = 15$".

The speed of the bar tip is $v_{tip} = \omega_b \cdot r = 209.4$rad/s $\cdot$ 20" $= 106.4$m/s (equal to 383km/h or 238mph). The moment of inertia of the bar is approximated as $I_b = m_b\cdot r^2/3 = 5867lb\cdot$in^2 (1.72kg$\cdot$m^2). The moment of inertia I_2 of the second robot is roughly estimated assuming it is a 30" square with uniform density, as seen from above, resulting in $I_2 = 220$lb$\cdot 2\cdot 15"^2/3 = 33{,}000lb\cdot$in^2. The value of I_1 for the bar spinner chassis is roughly estimated as $I_1 = I_2\cdot m_1/m = I_2\cdot 4/5 = 26{,}400lb\cdot$in^2. The effective mass of both robots is then

$$M_1 = \left\{\frac{1}{44 + 175\cdot\dfrac{26400}{26400+175\cdot 30^2}} + \frac{20^2}{5867}\right\}^{-1} = 12.1 \text{ lb} \quad \text{and} \quad M_2 = \left\{\frac{1}{220} + \frac{15^2}{33000}\right\}^{-1} = 88 \text{ lb}$$

and the effective mass of the system is $M = \{M_1^{-1} + M_2^{-1}\}^{-1} = 10.64$lb (4.825kg). So, even though the spinning bar had a kinetic energy of $E_b = I_b\cdot\omega_b^2 / 2 = 1.72kg\cdot$m$^2\cdot$(209.4rad/s)^2 / 2 = 37,654J, the deformation energy involved in the impact (distributed to both robots) is only $E_d = M\cdot v_{tip}^2 / 2 = 4.825kg\cdot$(106.4m/s)^2 / 2 = 27,309J (72.5% of E_b).

If the impulse vector was aligned with the center of mass C_2 of the other robot, then the distance a_2 would be equal to zero. In this case, the effective mass M_2 would be much higher, equal to the robot mass $m_2 = 220$lb. Despite this much higher M_2, the effective M would not increase too much, resulting in $M = \{M_1^{-1} + M_2^{-1}\}^{-1} = 11.47$lb (5.202kg) and $E_d = 29{,}445$J.

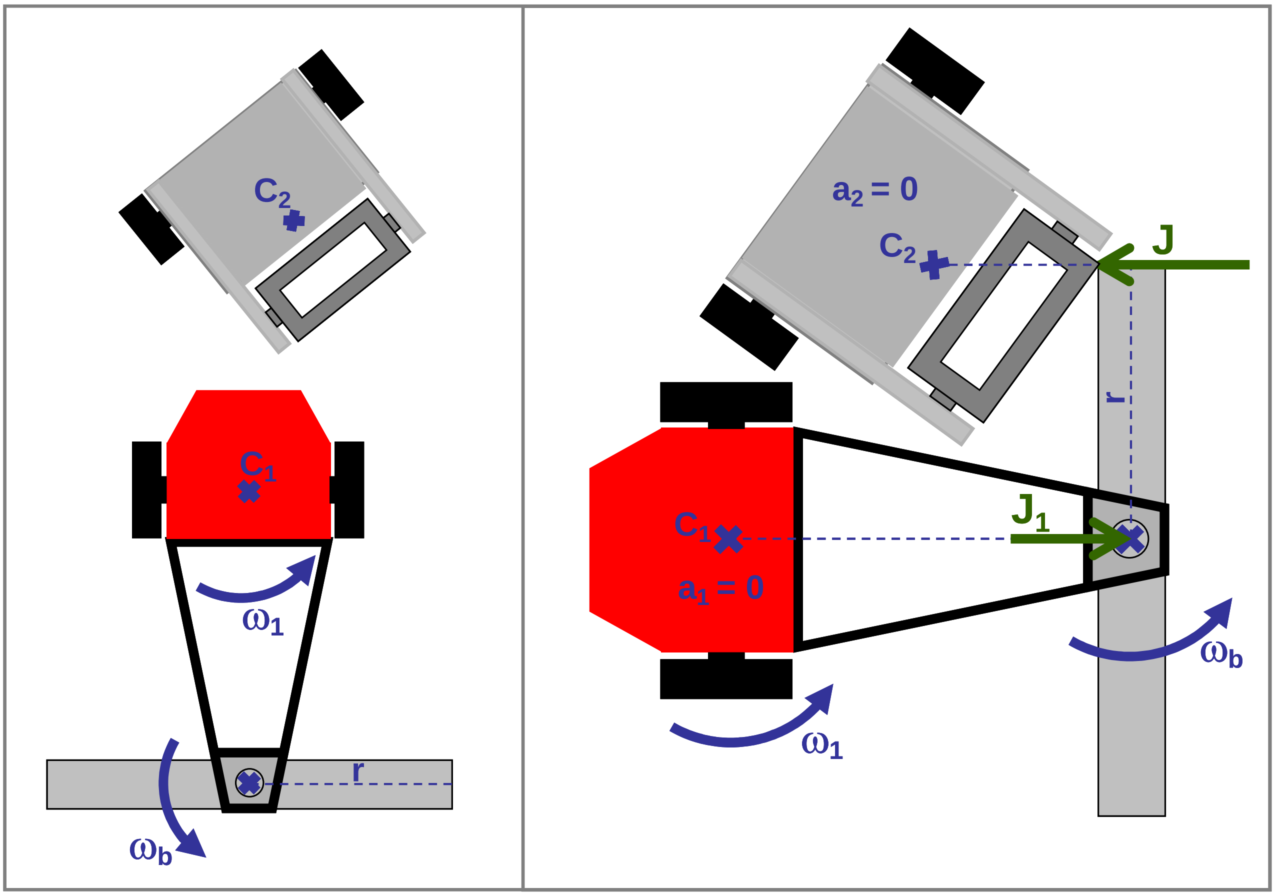
For offset spinners such as Last Rites or The Mortician, there's a way to increase even more the deformation energy caused by the impact. For frontal impacts, part of the energy of its bar is wasted making the offset spinner gain an angular speed ω_1', as shown in the next picture for The Mortician. To avoid that, the impulse J should be parallel to the line joining the chassis center of mass C_1 and the center of mass of the bar. In this case, the resulting impulse vector J_1 on the weapon shaft would be aligned with C_1, therefore its distance to C_1 would be $a_1 = 0$.

This configuration can be achieved with a special maneuver adopted by Ray Billings, the builder and driver of Last Rites. Last Rites starts facing away from the opponent, and then it turns 90 degrees to hit in the way shown below. In the best case scenario (for Last Rites), the impulse J_1 would be aligned with C_1, making $a_1 = 0$, and J would be aligned with C_2, resulting in

$$M_1 = \{\frac{1}{44+175} + \frac{20^2}{5867}\}^{-1} = 13.7 \text{ lb} \quad \text{and} \quad M_2 = \{\frac{1}{220} + \frac{0^2}{33000}\}^{-1} = 220 \text{ lb}$$

Then, $M = \{M_1^{-1} + M_2^{-1}\}^{-1} = 12.94$lb (5.868kg). Note that the angular speed ω_1 of the spinner chassis before the impact would help to slightly increase v_{tip}, but the effect is usually negligible, because ω_b is much higher than ω_1.

So, it is not ω_1 that makes a difference here, but the alignment of the impact, which significantly increases M. If we neglect the effect of ω_1 on v_{tip}, then E_d = 33,215J, so the maneuver could increase the impact deformation energy in almost 22%.



But remember that both robots have to absorb parts of the energy E_d, so you must make sure that the attacker can also withstand the higher impact from the maneuver. In the sequence shown to the right, Last Rites won the fight after performing the described maneuver against Sir Loin, dishing out enough energy to fracture the opponent's chassis, which was already damaged from previous hits, and breaking off the eggbeater.

To calculate the speeds after the impact, we would need to know the COR e. A high speed video of the fight, for instance, could provide an estimate of the angular speed ω_b' of the bar right after the impact. If we assume that $\omega_b' = 0$, and that the impact happened in the ideal way drawn above (with $a_1 = a_2 = 0$), then

$$\omega_b' = 0 = \omega_b - \frac{J \cdot r}{I_b} = \omega_b - \frac{M \cdot (1+e) \cdot (\omega_b \cdot r) \cdot r}{m_b \cdot r^2 / 3} = \omega_b - \frac{12.94 \cdot (1+e) \cdot \omega_b}{44/3} \quad \Rightarrow \quad e \cong 0.13$$

This low value for e is reasonable, considering the high energy of the impact. The impulse values are then J = 705.5Ns and J_1 = 564.4Ns, accelerating both robots to $v_1' = v_2'$ = 7.07m/s (25.5km/h or 15.8mph), while keeping ω_1 unchanged ($\omega_1' = \omega_1$). Note that this v_2' value assumed that Sir Loin didn't lose its eggbeater weapon. Since the eggbeater broke off, it is expected that it was flung with a speed above v_2', while the heavier remaining chassis acquired a speed lower than v_2'.

During the first phase of the impact, while the spinning bar was compressing the opponent's chassis, the original energy E_b = 37,654J was used in part to deform both robots, with E_d = 33,215J, and the remaining $E_v = E_b - E_d$ = 4,439J was used to change their speeds. Since the COR is small, a very small part of the deformation energy is elastically stored, namely $E_k = E_d \cdot e^2 = 33{,}215J \cdot 0.13^2 = 561J$. The remaining energy $E_c = E_d \cdot (1-e^2)$ = 32,654J is dissipated by both robots, either by their structural parts and shock mounts in the form of vibration and sound, or transformed into plastic (permanent) deformations or fractures.

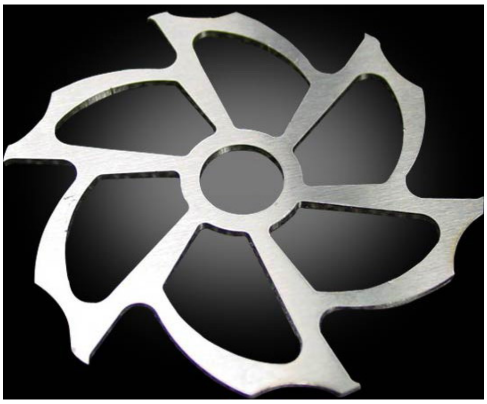
During the second part of the impact, the small stored elastic energy E_k = 561J is restituted to the system, further accelerating both robots. Therefore, from the original E_b = 37,654J, 86.7% (E_c = 32,654J) is dissipated while 13.3% ($E_v + E_k$ = 5,000J) is used to change the speeds of both robots and spinning bar.

6.5. Effective Mass

Let’s study a little bit more the concept of effective masses for an impact problem. As we’ve seen above, these masses are very important to find out how much energy is dissipated during the impact, potentially causing damages to the opponent. Therefore, an attacking robot should aim for high M_1 values. We’ll assume below that the masses of the robot chassis and weapon are m_1 and m_b, respectively. The weapon mass ratio is then defined as $x \equiv m_b/(m_1+m_b)$, it measures how much of the robot mass is spent on its weapon. We’ll also define a normalized effective mass, $M_1' \equiv M_1/(m_1+m_b)$, to make it easier to present the results.

6.5.1. Effective Mass of Horizontal Spinners

A spinning bar with length $2\cdot r$ has a moment of inertia I_b of at least $m_b\cdot r^2/3$. If it has a large width, or if its shape is optimized, as discussed before, then the value of I_b can reach significantly higher values. It is easy to show from this result that a horizontal bar spinner without an offset shaft (therefore $a_1 = 0$) has normalized effective mass $M_1' \geq x/(3+x)$. An offset bar spinner would have a lower M_1' due to its a_1, which is usually greater than zero, unless it performs the maneuver described before to make $a_1 = 0$.



A spinning disk with radius r has I_b of at least $m_b\cdot r^2/2$. Shape optimization can increase this value, concentrating most of the mass m_b on the disk perimeter (as pictured to the right), trying to reach the (unreachable) value of $I_b = m_b\cdot r^2$. A horizontal disk spinner with $a_1 = 0$ has then $M_1' \geq x/(2+x)$, while an offset disk spinner would have a lower M_1'. These values are higher than the ones for bars.

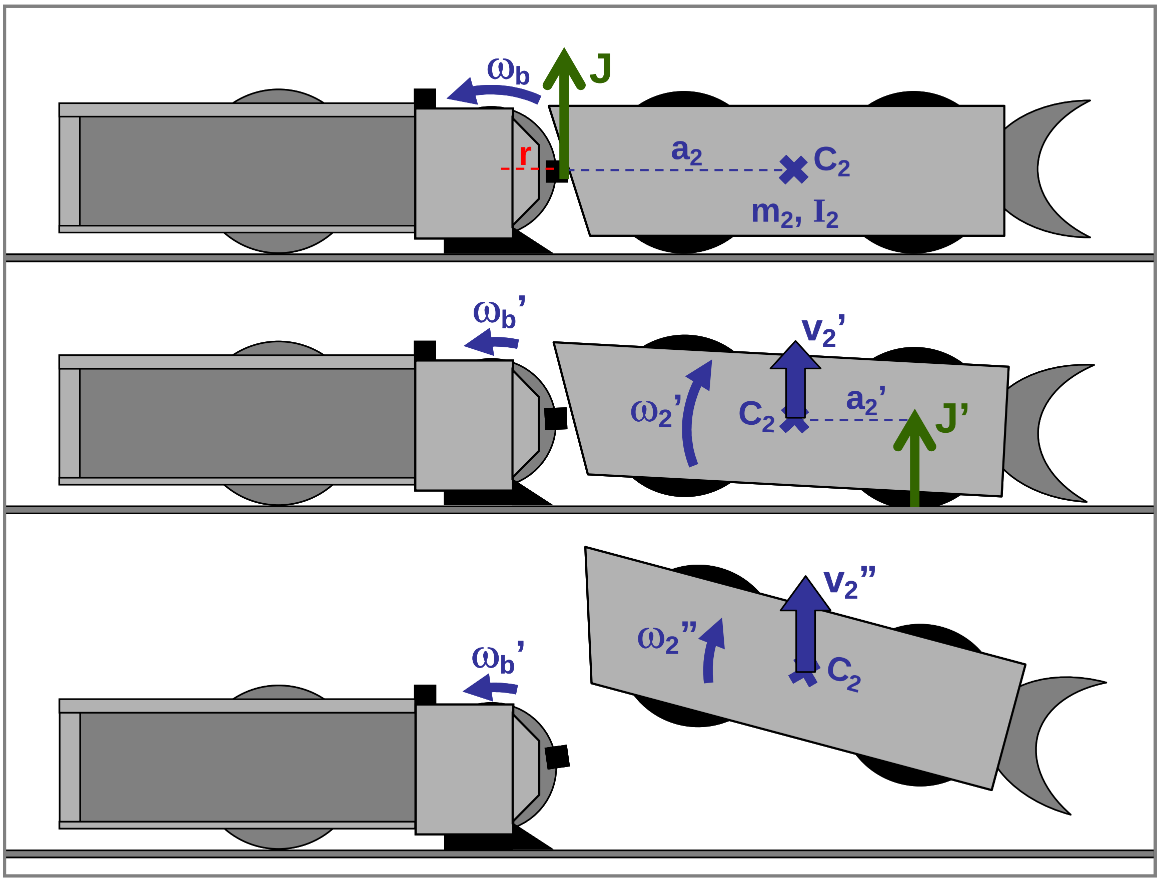
A few robots have successfully implemented a horizontal spinning ring, supported by rollers, such as the hobbyweight Ingor (pictured to the right). The advantage of a ring-shaped weapon is its high I_b, which can reach up to $m_b\cdot r^2$ for a ring with external radius r. This results in M_1' up to $x/(1+x)$, better than bars and disks.

A horizontal shell spinner, on the other hand, can have different shell shapes. If the shell is shaped like a disk, with uniformly distributed mass, then we can estimate $I_b \cong m_b\cdot r^2/2$ and then $M_1' \cong x/(2+x)$. But if its shape is optimized to concentrate most of its mass at its perimeter, then it behaves as a ring, therefore I_b can reach values up to $m_b\cdot r^2$, with M_1' up to $x/(1+x)$.

A disk-shaped thwackbot, with radius r, is basically a full-body spinner. It spins is entire mass (m_1+m_b), therefore its I_b is at least $(m_1+m_b)\cdot r^2/2$, achieving higher values if its weight is more concentrated on its perimeter. Assuming that the spin axis coincides with the robot center of gravity (otherwise it would become unbalanced), then the offset $a_1 = 0$, resulting in M_1' equal to at least 1/3 (33.3%).

6.5.2. Effective Mass of Vertical Spinners and Drumbots

All previous analyses were based on horizontal spinners, which can suffer changes in their angular speed and in the speed in the direction of the impact. But the chassis of vertical spinning robots such as drumbots or vertical spinners does not accelerate during an impact, if the impulse J is vertical in the upwards direction, as pictured below. As long as the spinning drum, disk or bar has solid ground supports that will transmit the entire impulse J without allowing the robot to tilt forward after the attack, the chassis vertical speed v_1' and angular speed ω_1' should remain equal to zero. Obviously, the arena floor won't let the attacking robot move down. Therefore, drumbots and vertical spinners that spin their weapon upwards behave as if they had a chassis with infinite inertia, with $m_1 = \infty$ and $I_1 = \infty$. Note that I_1, I_b and I_2 here are the values in the weapon spin direction, which is horizontal, not vertical. The weapon can change its angular speed, ending up with a slower ω_b' after the impact, so its moment of inertia I_b in the horizontal spin direction is still considered. But the weapon speed v_b' in the vertical direction must remain equal to zero, behaving as if $m_b = \infty$. Note that, since there is no restriction for the opponent to be launched upwards, it will gain a speed v_2' in the direction of J, and it will start spinning with an angular speed ω_2', calculated from the previously presented equations.



For m_1, m_b and I_1 tending to infinity, we have $M_1 = I_b/r^2$. So, a vertical bar spinner will have I_b of at least $m_b \cdot r^2/3$, resulting in $M_1 > m_b/3$, therefore $M_1' = M_1/(m_1+m_b) \geq x/3$. Similarly, a vertical disk spinner will have I_b of at least $m_b \cdot r^2/2$, resulting in $M_1' \geq x/2$. And a drumbot, which has I_b between $m_b \cdot r^2/2$ (for a solid homogeneous drum) and $m_b \cdot r^2$ (for a hollow drum with thin walls), ends up with a normalized effective mass M_1' between x/2 and x.

But the opponent almost always suffers a second impulse J' immediately after the impact, at the wheel (or skid, or some other ground support) that is farther away from the location of the first impact. This happens because this wheel develops, right after the first impact, a downward speed $v_{wheel}' = \omega_2' \cdot a_2' - v_2'$, where a_2' is the horizontal distance between the wheel and C_2, see the picture above. This v_{wheel}' is almost always positive, pushing the wheel down against the ground, which reacts with the vertical impulse J'. This second impulse makes v_2' increase to a value v_2'', and ω_2' decrease to ω_2'', following the linear and angular momentum equations $J' = m_2 \cdot (v_2'' - v_2')$ and $J' \cdot a_2' = I_2 \cdot (\omega_2' - \omega_2'')$, where I_2 is the moment of inertia of the opponent at C_2 in the spin direction of the weapon. These new values can be calculated if the coefficient of restitution (COR) e' between the wheel and the ground is known. The resulting equations are quite lengthy, but not difficult to obtain, as seen next.

6.5.3. Example: Drumbot Impact

Let's solve an example for a special case where $I_2 = m_2 \cdot a_2^2/3$ and $a_2 = a_2' = 0.3m$, typical of a very low profile opponent with four wheels located near its perimeter, resulting in $M_2 = m_2/4$. Remember that I_2 here is the value in the horizontal spin direction, not in the vertical one as in the horizontal spinner impact calculations. If, for instance, the opponent robot is hit by a solid drum with mass $m_b = m_2/6$ and tip speed $v_{tip} = 32m/s$ (115km/h or 71.6mph), then the drumbot's effective mass for the first impact is $M_1 = I_b/r^2 \cong m_b/2 = m_2/12$, resulting in $M = m_2/16$. Powerful weapon impacts are nearly inelastic so, if we can assume that e = 0.2, then $J = M \cdot (1+e) \cdot v_{tip} = m_2 \cdot 1.2 \cdot v_{tip}/16$, leading to $v_2' = J/m_2 = 2.4m/s$ and $\omega_2' = J \cdot a_2/I_2 = 3 \cdot 2.4/a_2 = 24rad/s$ (229RPM). Note that these values are only valid if no debris is released from either robot, and if the opponent does not have any horizontal spinning weapons that might cause some gyroscopic effect (studied later in this chapter).

Right after the first impact, there would be a downward wheel speed $v_{wheel}' = \omega_2' \cdot a_2' - v_2' = 4.8m/s$. The wheel will depart from the ground after the second impact with a speed $v_{wheel}'' = v_{wheel}' \cdot e' = 4.8 \cdot e' = v_2'' - \omega_2'' \cdot a_2'$. The other equation relating the unknowns ω_2'' and v_2'' comes from the second impulse $J' = m_2 \cdot (v_2'' - v_2') = I_2 \cdot (\omega_2' - \omega_2'')/a_2'$, resulting in an increased $v_2'' = (3.6 + 1.2 \cdot e')m/s$ and a decreased $\omega_2'' = 12 \cdot (1-e')rad/s$.

So, a purely inelastic wheel impact (e' = 0) would result in $v_2'' = 3.6m/s$ and $\omega_2'' = 12rad/s$, an angular speed more than enough to flip the opponent. And a purely elastic wheel impact (e' = 1) would lead to $v_2'' = 4.8m/s$ and $\omega_2'' = 0rad/s$, launching the opponent without flipping it at all. So, interestingly, by using rubber wheels, the opponent makes it more difficult to get flipped over because of their high COR, up to e' = 0.85 for relatively slow impacts, with low v_{wheel}'. High speed impacts, however, tend to decrease the value of e'.

If e’ = 0.75 could be used for the considered speed v_{wheel}’ = 4.8m/s, then the resulting speeds after the second impact would be v_2” = 4.5m/s and ω_2” = 3rad/s (28.6RPM). These launching speeds would make the opponent reach a height of $v_2”^2/(2g)$ = 1.03m, where g = 9.81m/s^2 is the acceleration of gravity. The flight time would be approximately $\Delta t = 2 \cdot v_2”/g$ = 0.92s, but it can be a little less than that if the opponent lands vertically on its nose, instead of flat on the ground. During this flight time, the opponent flips 3rad/s·0.92s = 2.76rad = 158^o, more than enough to get flipped over.

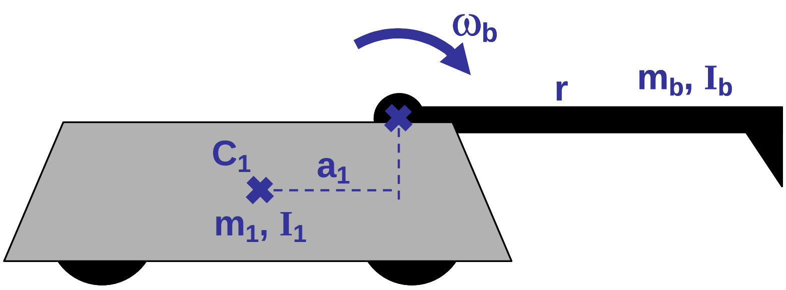
Note that it is not unusual to see an opponent being spun, for instance, by 540^o before touching the ground after a powerful hit from a horizontal spinner. But it is very difficult for a vertical spinner or drumbot to cause a 540^o flip while launching an opponent. The reason for that is the second impact, which only happens in a vertical launch. In the example above, it was able to decrease the opponent’s angular speed from ω_2’ = 229RPM to only ω_2” = 28.6RPM. If the second impact hadn’t happened, the original ω_2’ and v_2’ after the first impact would have made the opponent flip 673^o, instead of only 158^o. But, because of the second impact, the drumbot from this example would have to spin its drum with v_{tip} = 59.2m/s to launch the opponent 3.53m into the air to make it flip 540^o. Even if the drumbot had the required energy and the arena was tall enough, some part of the opponent would probably break off and prevent it from reaching such height. This is why we don’t usually see drumbots or vertical spinners flipping opponents beyond 180^o.

6.5.4. Effective Mass of Hammerbots

Technically, hammerbots are not spinners, however their impact behavior can be directly obtained from the previous equations if we consider them as bar spinners that only rotate 180 degrees before hitting the opponent.

If the hammer is a homogeneous bar with length r, without a hammer head, then its I_b is $m_b \cdot r^2/3$. If it has a hammer head, then part of its mass m_b will be concentrated at its tip, increasing I_b.

Differently from vertical spinners that spin upwards, hammerbots hit downwards, so their chassis is subject to being launched, and m_1, m_b and I_1 cannot be assumed as infinite. So, their model is similar to the one for horizontal (and not vertical) bar spinners, including the effects of m_1, m_b and I_1. If the hammer pivot coincides with the chassis center of mass, then the offset a_1 is zero, and the resulting normalized effective mass is the same as the one from the bar spinner, $M_1' \geq x/(3+x)$. Otherwise, if a_1 is different than zero, as in the picture to the right, then it must be modeled as an offset horizontal bar spinner.



Note that, similarly to a drumbot’s opponent, the hammerbot will probably receive a second impact immediately after the first impact. This second impact, which happens on its back wheels, will be discussed later in this chapter.

6.5.5. Full Body, Shell and Ring Drumbots

Curiously, shell drums are not very popular, even though they have one of the highest possible effective masses. Shell drums are the vertical equivalent of shell spinners, they spin their entire armor to try to launch the opponents. The heavyweight Barber-ous II (pictured to the right) is an example of a shell drum, it uses two drive motors for the wheels and a separate motor for the drum, which doubles as its armor. The shell drum is supported on a shaft that is aligned with the wheel axis. Alternatively, if the drum was a cylinder mounted on rollers, it should be called a ring drum, the vertical equivalent of a ring spinner.

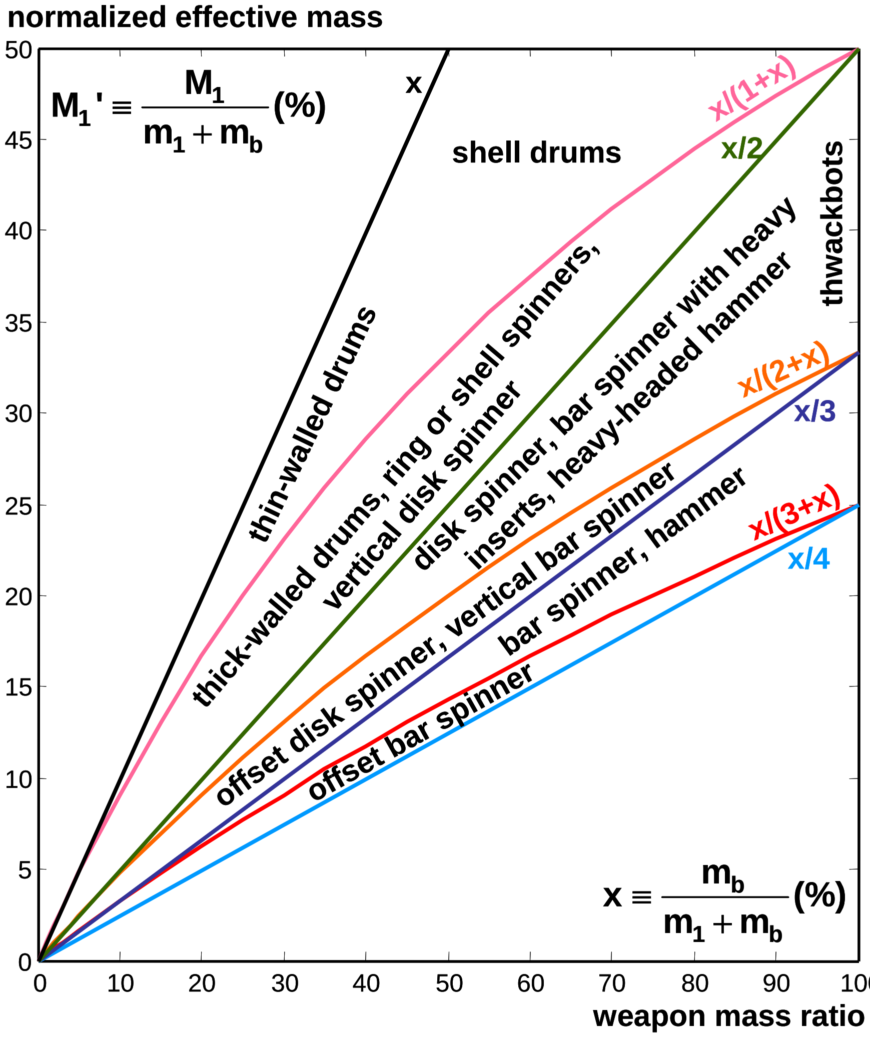
A robot type that might have never been tried is a full-body drum, which is basically an overhead thwackbot without a long rod. This robot would use the power of its two wheel motors to spin its entire chassis (and not only its armor) as if it were a big drum, maximizing its moment of inertia. It would not need a separate motor for the weapon. The challenge would be to implement at each wheel an independent braking system that would allow the chassis to spin up without moving the robot around. After reaching full speed, the braking system would be released, and the robot would be driven by slightly accelerating or braking each wheel motor. With a clever gearing system to make each wheel turn in the opposite sense of each motor, it would be possible to implement a "kamikaze attack": with the chassis/drum spinning at full speed while facing the opponent, both motors could be shorted out or reversed, directing part of the drum energy straight to the wheels to move the robot towards the opponent with very high acceleration. The combination of high robot speed, high drum angular speed and moment of inertia, and high effective mass, would result in a devastating blow to the opponent. In theory, if its wheels were very light, the weapon mass ratio $x \equiv m_b/(m_1+m_b)$ would be very close to 1 (100%), allowing the normalized effective mass M_1' of full-body drums to get very close to the absolute maximum $M_1' = 1$ (100%).

Unfortunately, all these shell, ring or full-body drumbots have a major drawback: they are easily launched by their own drum energy if attacked from behind, where the spin direction would be downwards. In addition, similarly to shell, ring and full-body horizontal spinners, their internal components need to be very well shock-mounted to avoid self-destruction.

6.5.6. Effective Mass Summary

The table in the next page summarizes the values of the weapon moment of inertia I_b and normalized effective mass M_1', as a function of weapon mass ratio x, for the robot types discussed above. The results are also presented in a graph, which shows a mapping with the ranges of the values of x and M_1' for different robot types.

robot type	weapon moment of inertia	normalized effective mass
offset bar spinner	$I_b \geq m_b \cdot r^2/3$	$x/4 \leq M_1' \leq x/(3+x)$
bar spinner	$I_b \geq m_b \cdot r^2/3$	$M_1' \geq x/(3+x)$
offset disk spinner	$I_b \geq m_b \cdot r^2/2$	$x/3 \leq M_1' \leq x/(2+x)$
disk spinner	$I_b \geq m_b \cdot r^2/2$	$M_1' \geq x/(2+x)$
shell spinner	$m_b \cdot r^2/2 \leq I_b < m_b \cdot r^2$	$x/(2+x) \leq M_1' < x/(1+x)$
ring spinner	$I_b < m_b \cdot r^2$	$M_1' < x/(1+x)$
vertical bar spinner	$I_b \geq m_b \cdot r^2/3$	$M_1' \geq x/3$
vertical disk spinner	$I_b \geq m_b \cdot r^2/2$	$M_1' \geq x/2$
drumbot	$m_b \cdot r^2/2 \leq I_b < m_b \cdot r^2$	$x/2 \leq M_1' < x$
hammerbot	$I_b \geq m_b \cdot r^2/3$	$M_1' \geq x/(3+x)$
thwackbot	$I_b \geq (m_1+m_b) \cdot r^2/2$	$M_1' \geq 1/3$



As seen on the graph, for a given weapon mass ratio x, drumbots have the highest effective mass, while horizontal and offset bar spinners have the lowest. This does not necessarily mean that drumbots are better than horizontal bar spinners, because the impact impulse and energy also depends on the weapon tip speed v_{tip}.

Drums, for instance, cannot have a very large radius r without reducing their thickness and possibly compromising their strength. They also cannot compensate their lower radius r with an arbitrarily high angular speed ω_b to achieve high v_{tip}, because they would lower their tooth bite (as explained before), ending up grinding instead of grabbing the opponent. So, despite their excellent M_1, drumbots have limitations in their achievable v_{tip}.

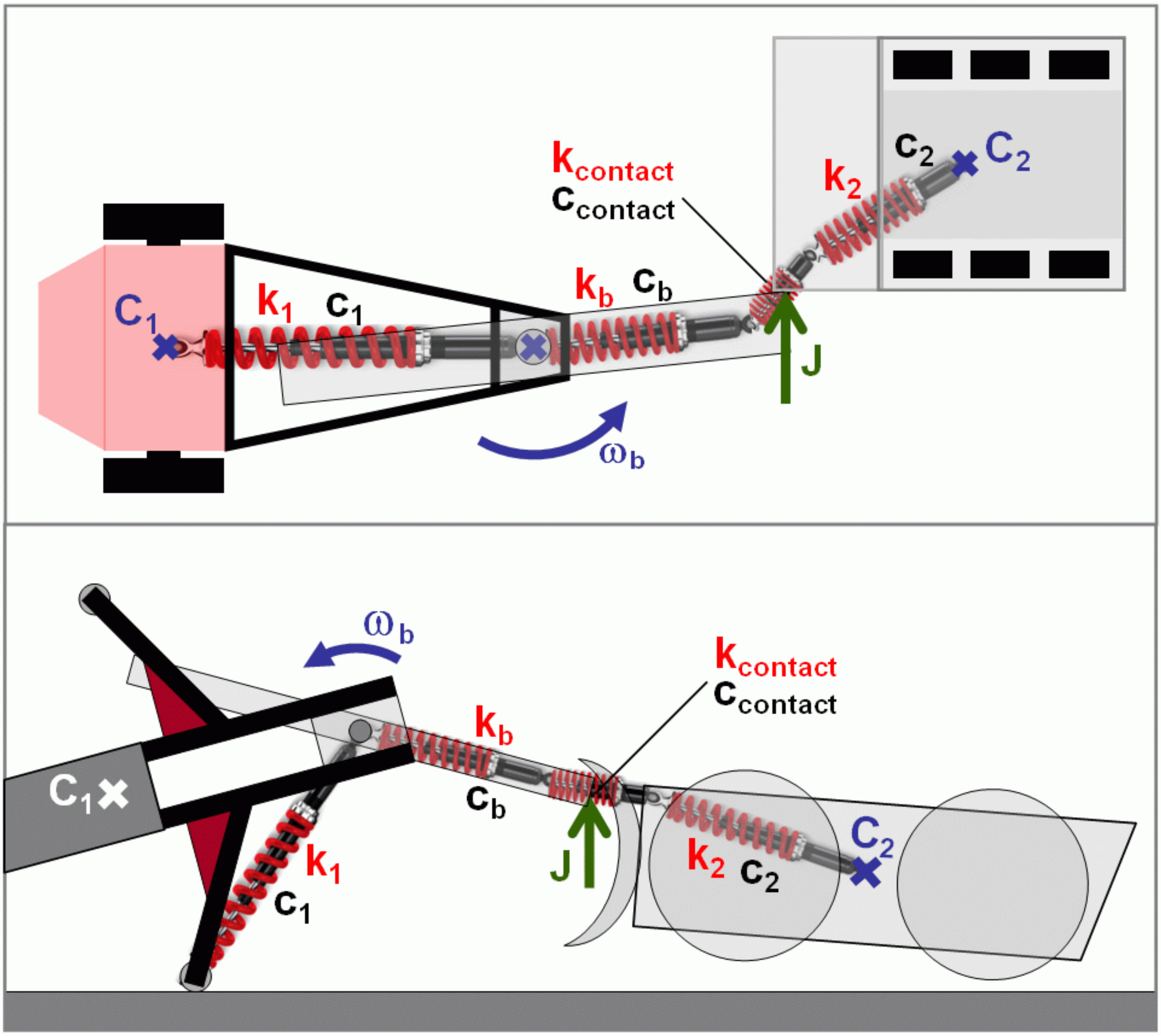
Spinning bars, on the other hand, can achieve a very large radius r without compromising strength. Their angular speed ω_b does not need to be too high to generate a very fast v_{tip}. So, they make up for their poor M_1 with their amazing v_{tip} speeds. In summary, all robot types have their advantages and disadvantages, fortunately there is no single superior design, guaranteeing diversity.

6.6. Effective Spring and Damper

We've learned that the effective mass of the impact determines how much of the weapon energy will be used to compress and deform both robots. But how is this energy distributed between the two robots? To find that out, we need to evaluate the stiffness and damping properties of the system. The stiffness is responsible for storing the elastic energy E_k, while the system damping is related to the dissipated impact energy E_c.

6.6.1. A Simple Spring-Damper Model

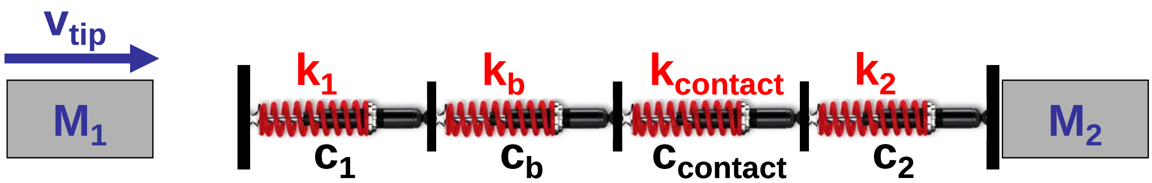
A very simple model would consider stiffness and damping coefficients for the structure of the attacking robot (k_1 and c_1), for its weapon (k_b and c_b), for the contact region between the weapon tip and the opponent's armor ($k_{contact}$ and $c_{contact}$), and for the opponent's structure (k_2 and c_2). The picture below schematically shows virtual effective spring-dampers with these stiffness and damping coefficients, for a horizontal spinner impact and for a vertical spinner impact.



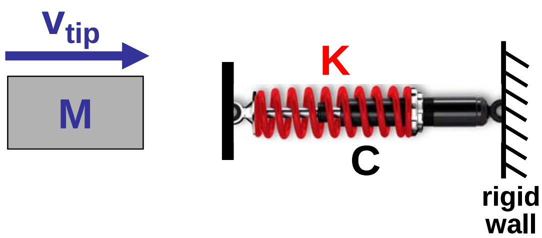
The k_2 and c_2 coefficients come from the stiffness and damping between the impact point and the center of mass C_2 of the opponent robot. The $k_{contact}$ and $c_{contact}$ coefficients are due to the localized contact (compression) between the weapon tip and the opponent's armor, achieving high values for a blunt tip and low ones for a sharp tip. The k_b and c_b coefficients represent the weapon properties, which in the figure above would be the bending stiffness and damping of the bars.

For a horizontal spinner (or hammer), the coefficients k_1 and c_1 would represent the stiffness and damping properties of the attacking robot between its center of mass C_1 and the weapon shaft (or pivot). On the other hand, for a drumbot or vertical spinner (that does not tilt forward during the impact), these k_1 and c_1 properties would reflect the stiffness and damping of the path between the weapon shaft and the ground supports, not necessarily passing through C_1, because the reaction forces from the opponent are transmitted directly to the ground.

This relatively complex impact problem, which deals with 3 different bodies (the attacker chassis, its weapon, and the opponent), involving translations and rotations, can be analyzed as a very simple impact problem, pictured below. It is equivalent to an effective mass M_1, moving at a speed v_{tip}, hitting an effective mass M_2 through a compliant interface, made out of 4 spring-damper systems in series.



The system can be simplified even more, to a single effective mass M hitting a rigid and heavy wall through an effective spring-damper system with stiffness K and damping C, see the figure to the right. The values of K and C are obtained from the equations of springs in series and dampers in series,



$$\frac{1}{K} = \frac{1}{k_1} + \frac{1}{k_b} + \frac{1}{k_{contact}} + \frac{1}{k_2} \quad \text{and} \quad \frac{1}{C} = \frac{1}{c_1} + \frac{1}{c_b} + \frac{1}{c_{contact}} + \frac{1}{c_2}$$

6.6.2. Spring and Damper Energy

When the springs are fully compressed, we define their elastically stored energies as E_{k1}, E_{kb}, $E_{kcontact}$ and E_{k2}, where $E_{k1} + E_{kb} + E_{kcontact} + E_{k2} = E_k$. Similarly, the energies dissipated by each of the dampers are called E_{c1}, E_{cb}, $E_{ccontact}$ and E_{c2}, where $E_{c1} + E_{cb} + E_{ccontact} + E_{c2} = E_c$. The individual energies are obtained from

$$\begin{cases} E_{k1} = E_k \cdot \dfrac{K}{k_1}, & E_{kb} = E_k \cdot \dfrac{K}{k_b}, \quad E_{kcontact} = E_k \cdot \dfrac{K}{k_{contact}}, \quad E_{k2} = E_k \cdot \dfrac{K}{k_2} \\ E_{c1} = E_c \cdot \dfrac{C}{c_1}, & E_{cb} = E_c \cdot \dfrac{C}{c_b}, \quad E_{ccontact} = E_c \cdot \dfrac{C}{c_{contact}}, \quad E_{c2} = E_c \cdot \dfrac{C}{c_2} \end{cases}$$

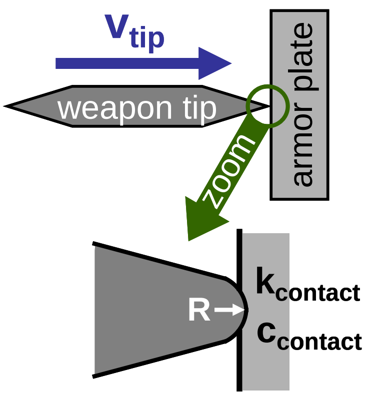
The above equations are such that K is always smaller than the smallest stiffness coefficient, and C is smaller than the smallest damping coefficient. Also, for instance, if k_2 and c_2 are much smaller than the other stiffness and damping coefficients, then $K \cong k_2$ and $C \cong c_2$, and the energies E_k and E_c are almost entirely stored into or damped by the opponent robot, because in this case we would have $E_{k2} \cong E_k$ and $E_{c2} \cong E_c$. It may seem strange, but the above equations show that the component in a series connection that has the lowest damping or stiffness coefficients is the one that will damp or elastically store the most amount of energy. This is analogous to what we see in electric circuits with resistors or capacitors connected in parallel: the resistor with lowest resistance will dissipate more energy than the others, while the capacitor with lowest elastance (the inverse of capacitance) will store more energy.

6.6.3. Offensive Strategies

From the equations above, we conclude that the strategy for the attacking robot is not only to maximize the impact energies E_c and E_k, but also to concentrate them on the opponent robot's structure (maximizing E_{c2} and E_{k2}) or contact surface (maximizing $E_{ccontact}$ and $E_{kcontact}$). To achieve that, the attacker must have c_1, k_1, c_b and k_b much higher than the opponent's c_2 and k_2 (to maximize E_{c2} and E_{k2}), or try to make the contact values $c_{contact}$ and $k_{contact}$ as low as possible (to maximize $E_{ccontact}$ and $E_{kcontact}$).

This is why the attacking robot must have a very stiff and robust weapon, with very high c_b and k_b. A very flexible weapon would end up vibrating a lot after the impact and dissipating most of its energy, instead of transferring it to the opponent. A horizontal spinner, in special an offset spinner, also needs to have a very stiff and robust connection between its weapon shaft and its center of mass, to maximize c_1 and k_1, as we can see for instance in the rigid trussed weapon support from Last Rites. And a vertical spinner or drumbot needs a very stiff and robust structure linking its weapon shaft with the ground supports, to maximize its c_1 and k_1. Here's the reason why robots with active weapons should not have their structure made out of plastic (such as UHMW): their probably low c_1 and k_1 would make the plastic structure deform and absorb most of the impact energy, instead of delivering it to the opponent.

The contact behavior between the weapon tip and the opponent's armor can be understood using a simplified model (adapted from the Hertz contact theory between two solids). The $c_{contact}$ and $k_{contact}$ of the contact between a sharp blade, with a small tip radius R, and an armor plate (pictured to the right) is proportional to the square root of R. This is why it is good to have a razor-sharp weapon, its tip radius R can reach values below one thousandth of a millimeter, lowering $c_{contact}$ and $k_{contact}$ to concentrate most of the impact energy on $E_{ccontact}$ and $E_{kcontact}$, penetrating the opponent's armor. But, to keep this sharpness, the weapon tip must be made out of a very hard material. Also, the lower the tip radius R, the more often you'll need to resharpen the weapon edge due to chipping and blunting.



6.6.4. Defensive Strategies

The values of the contact coefficients $k_{contact}$ and $c_{contact}$ are proportional to, respectively, the stiffness (measured from the Young modulus E, see chapter 3) and the hardness of the armor material. If the weapon tip has very high stiffness and hardness, then $k_{contact}$ and $c_{contact}$ will not depend much on the material properties of the weapon, they will mostly depend on the material properties of the armor.

There is a very old hardness test, using a testing instrument called a Scleroscope, where a diamond tipped hammer (which would be analogous to the weapon tip) is vertically dropped from a 10" height onto the surface of the material under test (analogous to the armor plate). A low hardness material results in a low $c_{contact}$, which causes large indentations that absorb most of the impact energy due to the high $E_{ccontact}$, lowering the height of the rebound of the hammer. So, the higher the material hardness, the higher will be the rebound height, resulting in less damping.

We can conclude then that the attacked robot has three different strategies to defend itself from a sharp blade:

1) absorb the energy at the contact – this strategy involves using an ablative armor, made out of materials with very low hardness (such as aluminum or magnesium alloys, see chapter 3), which will make sure that $c_{contact}$ will be much lower than the c_2 and k_2 coefficients of the attacked robot structure, directing most of the impact energy to $E_{ccontact}$ to be dissipated in the ablation process. With this strategy, the attacked robot structure will only need to deal with relatively small residual energies E_{c2} and E_{k2}. But make sure that your ablative armor is thick enough not to get pierced.

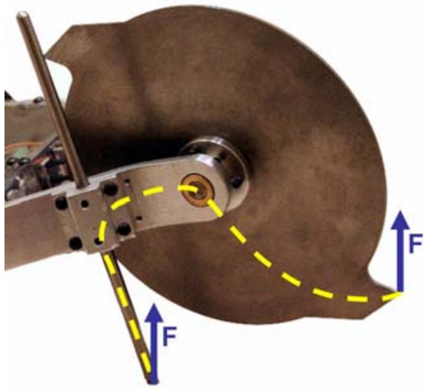
2) absorb the energy at the shock mounts – this strategy involves using a shock-mounted armor. The armor is usually of the traditional type, very hard, but an ablative armor would also work. The shock mounts make the c_2 and k_2 coefficients become very low. The high resulting energies E_{c2} and E_{k2} do not damage the attacked robot structure because they are almost entirely dissipated or stored by the shock mounts. The challenge here is to make sure that the shock mounts won't rupture while absorbing such high amounts of energy.

3) break the weapon – this is the strategy of very aggressive rammers. It involves having a very hard and stiff traditional armor mounted to a very stiff chassis, without any shock mount in between. Shock mounts should only be used for critical internal components. The goal here is to reach high $c_{contact}$ and $k_{contact}$ (due to the traditional armor) as well as high c_2 and k_2 (from the stiff chassis without shock mounts). If these coefficients end up much higher than c_b, k_b, c_1 and k_1, then most of the impact energy will be diverted back to the attacker robot, either breaking its weapon (if E_{cb} and E_{kb} become high) or its structure (if E_{c1} and E_{k1} become high).

In summary, stiffness and damping are key properties for both attacking and attacked robots, so always design your robot keeping this in mind.

6.6.5. Case Study: Vertical Spinner Stiffness and Damping

The following robots exemplify the application of several of the presented concepts. The middleweight vertical spinner Docinho (pictured to the right) is a high power vertical disk spinner driven by 2 pairs of wheels in an ingenious invertible design. Despite its high power, it seemed to have some trouble launching the opponents. Its disk usually grinds the opponent instead of launching it, mainly because it has 3 teeth spinning at high speeds (n = 3, instead of better values such as 1 or 2), and also because the teeth are not hard enough to keep their sharpness. Another reason for not living up to its potential is the use of compliant wheels supporting the robot under its disk. These compliant wheels act as dampers. They significantly lower the k_1 and c_1 coefficients, ultimately making $K \cong k_1$ and $C \cong c_1$. This makes most of the deformation energy E_d go to E_{k1} and E_{c1}, permanently deforming the wheels, instead of transferring the energy to the opponent. Also, the relatively thin disk (due to its large diameter) and the Lexan armor makes it vulnerable to powerful horizontal bar spinners.

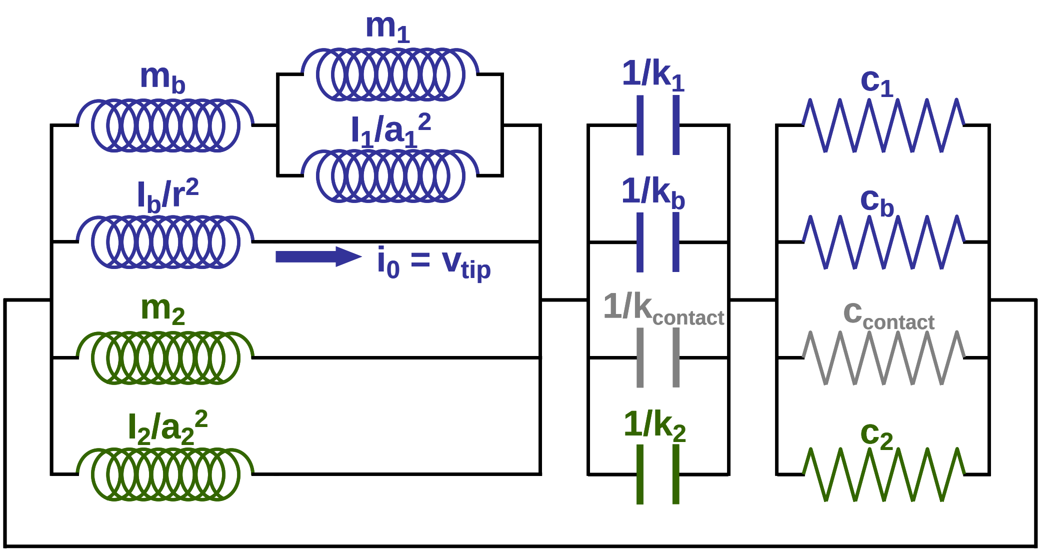


The beetleweight Altitude (pictured on the right) has addressed most of these issues. Its single-piece disk has only 2 teeth, with high hardness to prevent them from getting blunt. It is supported under the disk by skids made out of solid steel bars, which are much stiffer than rubber wheels, resulting in high k_1 and c_1 to deliver much more impact energy and peak forces. It is very important to keep in mind the force path in the robot, as seen in the picture as a dashed line. This path must only have components with high strength and stiffness to be able to guarantee high c_1, k_1, c_b and k_b and thus deliver high energy blows. Also, you must avoid any sharp notches (which are stress raisers), especially along this critical force path. The middleweight Terminal Velocity (pictured below) is another example of a vertical spinner with a stiff force path. It also has rigid skids to support its vertical spinning bar, using roller bearings to minimize sliding friction, as pictured to the right, without compromising stiffness.

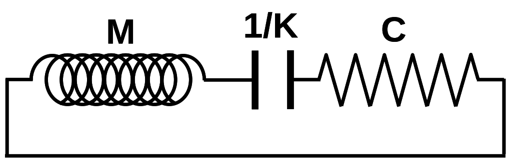
Finally, avoid installing any sensitive components, such as receivers or other electronic parts, close to the force path between the weapon tip and the ground (for drumbots or vertical spinners) or between the weapon tip and the chassis center of mass (for horizontal spinners). The impact vibrations along this path are very high, causing the sensitive components to malfunction if not shock mounted. In most drumbot and vertical spinner designs, the weapon motor ends up very close to this force path. To avoid a broken weapon motor due to impact vibrations, you can either shock mount it to the robot structure or, if possible, move it a little further towards the back of the robot.

6.6.6. Equivalent Electric Circuit

For those of you more electrically inclined, the entire impact problem has exactly the same dynamic equations as the resonator circuit below, if we consider all masses and inertial terms as if they were inductors, the elastic terms as capacitors, the damping terms as resistances, and the electric current as speeds. All blue components would come from the attacking robot, the green ones from the opponent, and the grey ones from the mechanical contact between them. The inductances would have the same numerical values (but with different physical units, of course) as the masses m_b, m_1, m_2, and inertial terms I_b/r^2, I_1/a_1^2 and I_2/a_2^2. The stiffnesses k_1, k_b, $k_{contact}$ and k_2 would be numerically equal to the elastance (the inverse of capacitance) of each capacitor, while the damping coefficients c_1, c_b, $c_{contact}$ and c_2 would be the resistances.



It is easy to see that the equivalent inductance of all blue inductors (attacker inertia) has exactly the same equation as the effective mass M_1, while the equivalent inductance of all green inductors (from the opponent) is M_2. The equivalent inductance of the entire circuit, as expected, would be M. Similarly, the equivalent elastance would have the same equation as the effective stiffness K, while the equivalent resistance would be numerically equal to the effective damping C. So, the circuit behavior would be similar to the one from the equivalent circuit pictured to the right.



Before digital calculators and digital computers were available, the first circuit shown above would be useful as an analog computer to calculate all the speeds and energy values of the impact problem.

After building the circuit, the I_b/r^2 inductor, which represents the spinning weapon, would have to be initially energized with an electric current i_0 numerically equal to the speed v_{tip} of the weapon tip, while all other components would be shorted out, with the capacitors discharged. The stored energy in this inductor would be numerically equal to the initial kinetic energy E_b of the bar. If the international system of units (SI) was used, the initial energy of both mechanical and electrical systems would be exactly the same, in Joules.

The circuit would then be connected as it was shown in the figure. During the first part of this simulated impact, the capacitors would be charged, equivalent to the compression between both robots, accumulating the same energy E_k that the equivalent mechanical system would elastically store. During the second part, the capacitors would be discharged, giving back the energy E_k to the system. As soon as the capacitors are first discharged, the electric currents in all inductors need to be immediately measured, and the simulation ends. The resonator circuit will continue to cyclically charge and discharge the capacitors, but only the first cycle is relevant to our simulation, because the impact ends after that. The subsequent cycles would only make sense if both robots would get stuck together after the impact, which is unlikely.

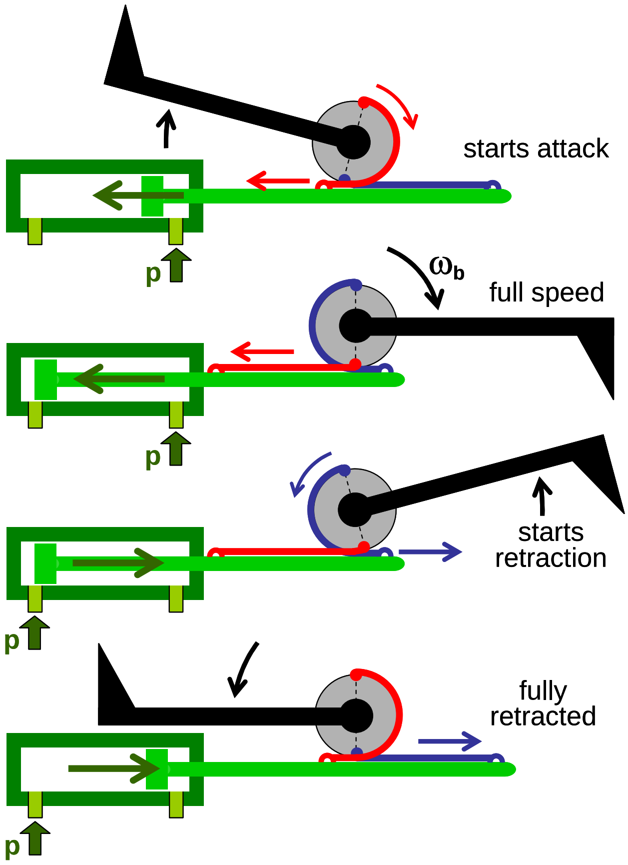
The initially energized inductor would contribute with E_v to the final energy of all inductors, making the total energy of all inductors at the end of the simulation equal to ($E_v + E_k$). And the dissipated energy in the resistors during the entire cycle, which can also be measured, would be E_c. Needless to say, these energy values E_v, E_k and E_c would be the same as the ones from the mechanical system.

And how about the speeds after the impact? Well, if you measure the electric currents in all inductors at the end of the first resonator cycle, immediately after the capacitors are first discharged, then you'll see that the currents in the inductors m_1 and m_2 would be numerically equal to the attacker and opponent chassis speeds v_1' and v_2', respectively. The speed of the weapon tip after the impact would be the current going through the equivalent inductor M_1, while the current through m_b would give the speed v_b' of the center of the weapon.

6.7. Hammerbot Design

Hammers usually need to be pneumatically powered to be effective. This is because they have to reach their maximum speed in only 180 degrees. Since most pneumatic actuators are linear cylinders, you'll need some type of transmission to convert linear into rotary motion. This can be done in several ways. One of the lightest solutions, adopted by the super heavyweight The Judge, is implemented using a pair of opposing heavy-duty chains, colored in red and blue in the figure in the next page. When the right port of the cylinder in the figure is pressurized, it makes the piston move to the left and pull the red chain, which generates a rotary motion in the hammer.

The hammer could have a spring mechanism to move back to its starting position after an attack. But the best solution is to have a double acting cylinder to retract the hammer at high speeds, with the aid of the blue chain shown in the picture. This allows the hammer to get ready in less time for the next attack. Also, and most importantly, it guarantees enough torque to the hammer in both directions to work as a self-righting mechanism in case the robot gets flipped upside down.



6.7.1. Hammer Energy

No matter which mechanism you use to generate a rotary motion, it is not difficult to estimate the energy and the top angular speed of the hammer in a pneumatic robot. If we assume no energy loss due to friction or pneumatic leaks, then the energy E_b delivered by the cylinder is approximately equal to its operating pressure p times its internal volume V, so $E_b \cong p\cdot V$. If the hammer has much more inertia than the cylinder piston and the transmission mechanisms, then we can say that this energy is entirely converted into kinetic energy of the hammer, $E_b \cong I_b\cdot\omega_b^2/2$, where I_b is the hammer moment of inertia and ω_b is its top angular speed right before hitting the opponent.

For instance, assume your hammerbot uses a pneumatic cylinder pressurized at 1000psi, with a 4” diameter bore and an 8” stroke. The hammer should be able to hit the arena floor before using its entire 8” stroke. So, when hitting a tall opponent, the piston will surely have traveled significantly less than 8”. If, for instance, the actual useful stroke during an attack is 6.5”, then the useful cylinder internal volume is $V = 6.5\text{”}\cdot(\pi\cdot 4\text{”}^2/4) \cong 81.68\text{in}^3$. Since $p = 1000\text{psi} = 1000\text{lbf/in}^2$ (pounds-force per square inch), we get $E_b = p\cdot V = 81{,}680\text{lbf}\cdot\text{in} \cong 9{,}229\text{J}$. The piston force would be $F = p\cdot A = 1000\text{psi}\cdot(\pi\cdot 4\text{”}^2/4) = 12{,}566\text{lbf}$ (5,700kgf or 55,896N), where A is the internal cross-section area of the cylinder.

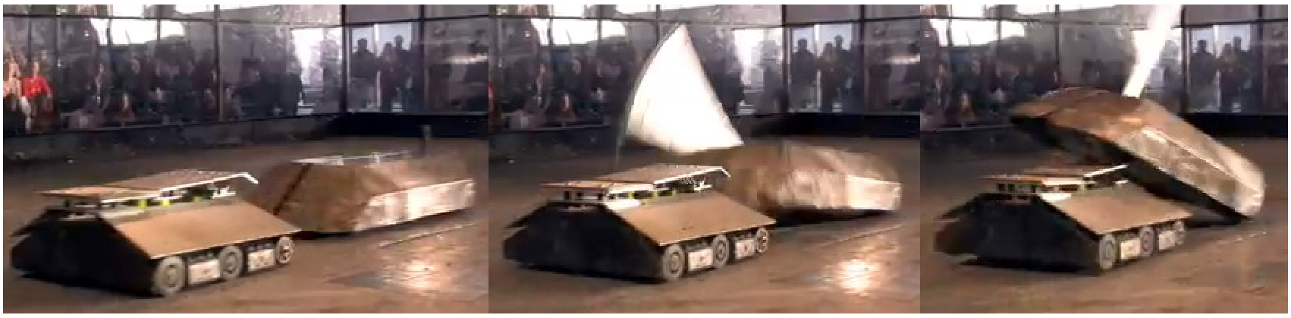
Note that this energy would be obtained while pushing the piston. When it is pulled, the energy is slightly lower, because you have to subtract the piston rod volume when calculating V. If, for instance, the piston rod has a 1.25” diameter, then $V = 6.5\text{”}\cdot[\pi\cdot(4\text{”}^2-1.25\text{”}^2)/4] \cong 73.70\text{in}^3$, and therefore $E_b = 73{,}700\text{lbf}\cdot\text{in} \cong 8{,}327\text{J}$. The force would also be slightly smaller, due to the smaller area $A = \pi\cdot(4\text{”}^2-1.25\text{”}^2)/4 \cong 11.34\text{in}^2$, resulting in $F = p\cdot A = 11{,}340\text{lbf}$ (5,144kgf or 50,443N).

So, it is slightly better to design the transmission system such that the hammer hits when the piston is extended. But, depending on the transmission design, this might place the cylinder in the front of the robot, more exposed to attacks, and limiting the reach of the hammer head.

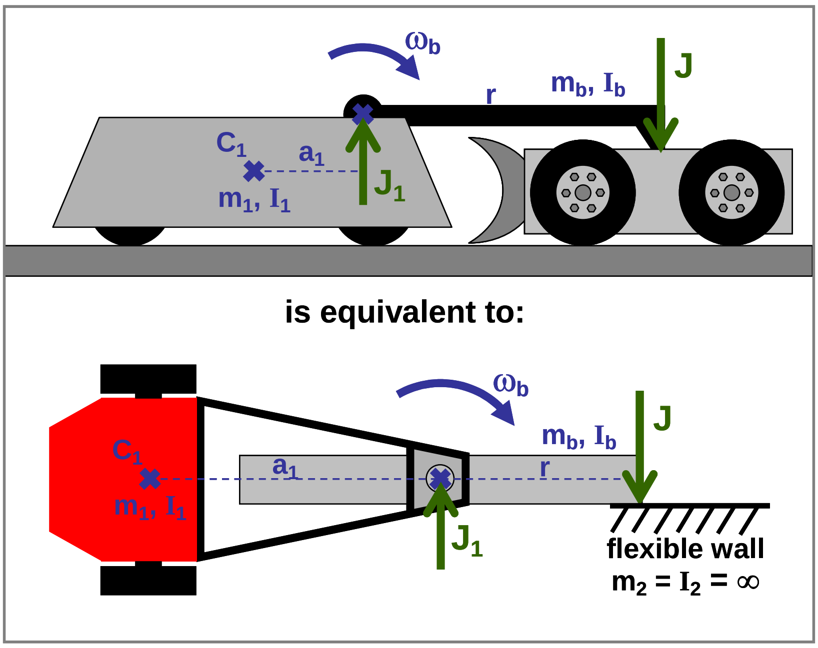
6.7.2. Hammer Impact

If in our example above the hammer handle is 36” (0.91m) long with a mass of 15lb (6.8kg), with a 10lb (4.5kg) hammer head, then its moment of inertia is $I_b \cong 6.8 \cdot 0.91^2/3 + 4.5 \cdot 0.91^2 \cong 5.6 kg \cdot m^2$. If we place the cylinder in the back of the robot, using the mechanism from the previous figure, then the energy E_b = 8,327J $\cong I_b \cdot \omega_b^2/2$ from the pulling motion would accelerate the hammer up to ω_b = 54.5rad/s = 521RPM, resulting in a hammer head speed of 54.5rad/s·0.91m = 49.6m/s (179km/h or 111mph).

Note that the robot will tend to move backwards during the acceleration of the hammer, therefore it needs to compensate for that by braking its wheels. The chassis will also tend to tilt backwards, from the reaction force of the hammer accelerating forward. Powerful hammerbots may even see their front wheels lift off the ground because of that, as seen in the middle picture below, which shows The Judge tilting backwards right before it even touches the opponent. Excessive tilting may leave it vulnerable to wedges or launchers that might sneak in underneath (as shown in the picture below to the right, right before The Judge was launched by Ziggy). To avoid that, it is a good idea to move forward the center of mass of the hammerbot.



The picture above to the right shows that the tilting angle of the chassis is increased even more after the hit, due to the reaction impulse J_1 from the impact, pictured to the right. The speeds after the impact and all the involved impact energies can be calculated from the very same equations used for spinners. Since the attacked robot is hammered against the arena floor, it usually does not move its center of mass, it only deforms due to the attack, so the impact problem is similar to an offset bar spinner hitting a flexible but very heavy wall, as shown in the picture to the right.

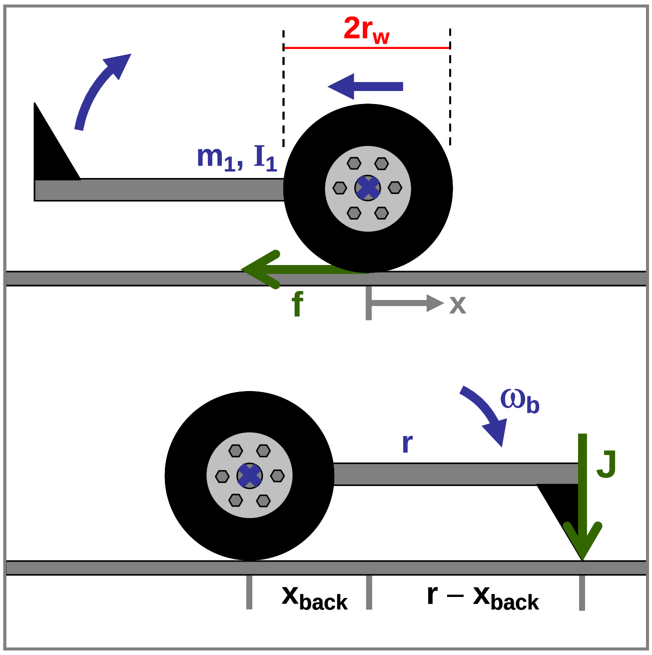


The attacked robot would then have an infinite effective mass M_2, while the hammerbot's M_1 would have the same equation from an offset spinner, where m_1 and I_1 are the chassis mass and moment of inertia in the direction that the hammer rotates, m_b and I_b are the corresponding values for the hammer, and a_1 is the horizontal offset between the chassis center of mass C_1 and the hammer pivot. The speeds of the attacked robot after the hammering are then $v_2' = \omega_2' = 0$, while the hammerbot chassis gains a vertical speed v_1' in the direction of J_1, and it may spin backwards, if $a_1 > 0$, with an angular speed ω_1' calculated from the spinner equations.

Note that, if the back wheels of the hammerbot are still in contact with the ground immediately after the impact against the opponent, then a second impact will probably occur. With the back wheels gaining a downward speed after the impulse J_1, they will press against the arena floor and receive a vertical reaction impulse J'. This back wheel impulse J' is good for the hammerbot, because it avoids its chassis from tilting too much backwards. The final linear and angular speeds v_1'' and ω_2'' of the hammerbot chassis can be calculated using the very same equations from the second impact that happens when a robot is hit by a drumbot or vertical spinner, as studied before.

6.8. Overhead Thwackbot Design

Overhead thwackbots need to be well balanced with respect to the wheel axis, otherwise they won't be able to have enough torque to lift the weapon to strike. This balancing can be done using counterweights opposite to the weapon, to place the center of mass C_1 of the entire robot on the wheel axis.



Overhead thwackbots have a few similarities with hammerbots. The main difference is that they use the drivetrain power to accelerate the weapon. This limits the weapon top speed, because a high gearmotor torque would end up making the wheels slip. Both wheels usually bear altogether a ground normal force equal to the robot weight $m_1 \cdot g$, where m_1 is its mass and g is the acceleration of gravity. If μ is the coefficient of friction between the tires and the ground, then the maximum traction force f that the tires can generate together is $f = f_{max} = \mu_t \cdot m_1 \cdot g$, see the picture to the right.

If the wheels have a radius r_w, then the maximum torque τ that both wheels can generate altogether to accelerate the weapon is $\tau_{max} = f_{max} \cdot r_w = \mu_t \cdot m_1 \cdot g \cdot r_w$. The wheel gearmotors need to be able to provide altogether this torque τ_{max}. Less than that would result in a slower weapon impact speed, while more torque would make the wheels slip. If using DC motors, it is a good idea to have a current controller (instead of a voltage controller from most speed control electronics), to