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.

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 modele 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:

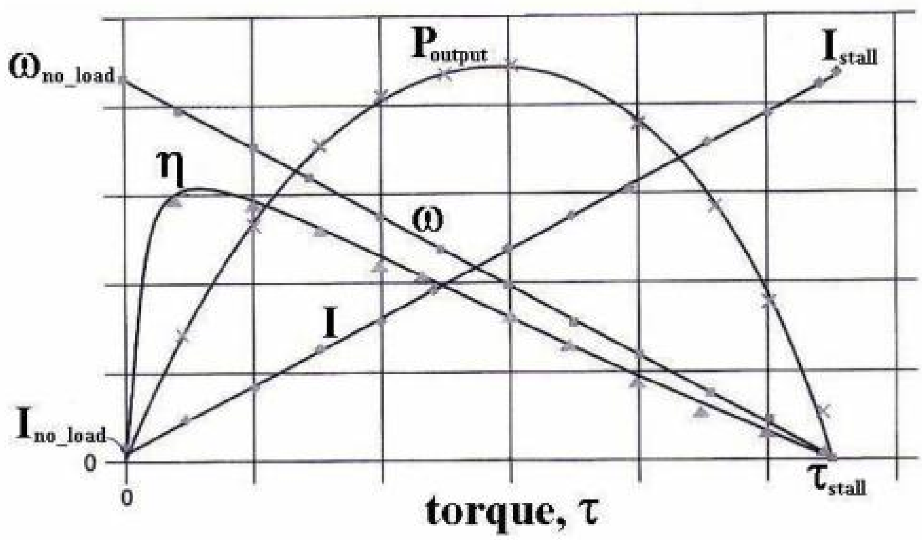
- τ – applied torque at a given moment (typically in N·m, ozf·in or lbf·ft);
- ω – angular speed of the rotor (in rad/s, multiply by 9.55 to get it in RPM);
- I_{input} – electric current that the motor is drawing (in A);
- K_v – the speed constant of the motor, which is the ratio between the motor speed 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 $0 \leq \eta < 1$ (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 $I_{input} = \sqrt{(V_{input} \cdot I_{no\_load} / R_{system})}$

Example: Magmotor S28-150

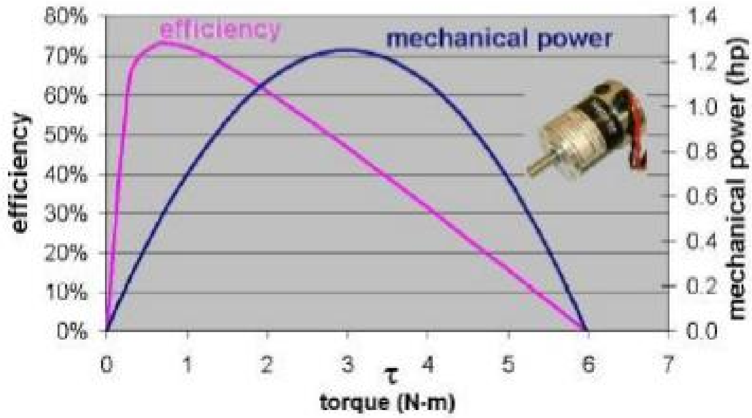
We will now work out an example using the presented equations. Consider the motor Magmotor S28-150 (pictured to the right) connected to one NiCd 24V battery pack. Therefore V_{input} = 24V, while the motor has K_t = 0.03757N·m/A, R_{motor} = 0.064Ω, and I_{no_load} = 3.4A. Also, $K_v = 1/K_t$ = 26.62 (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 0.004 Ω, 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 resistance s 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 3 HP, 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 ,028.

W = 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 efficient.



The maximum efficiency happens if Iinput=√(24 ·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.

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 typic The data in the table already include the power loss and weially a 20:1 reduction, which is already ght increase due to the gearbox, which embedded

in the values of Kexplains the relatively low powert (already multiplied by 20 with respect to the motor values without -toweight ratio. But, even disregarding that, the performance of this motor is still not too high. The reason many builders use gearbox), in Kit is due to its convenience, it is easily mounted to t (already divided by 20), and in its weight.he 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 shockmounted 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 S28400, 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 S28400 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 dis h 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.

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 ant weights 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).

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 $\tau_{stall} = (0.8kg – 0.1kg) \cdot 9.81m/s^2 \cdot 0.150m = 1.03N \cdot m$.

- 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).

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.

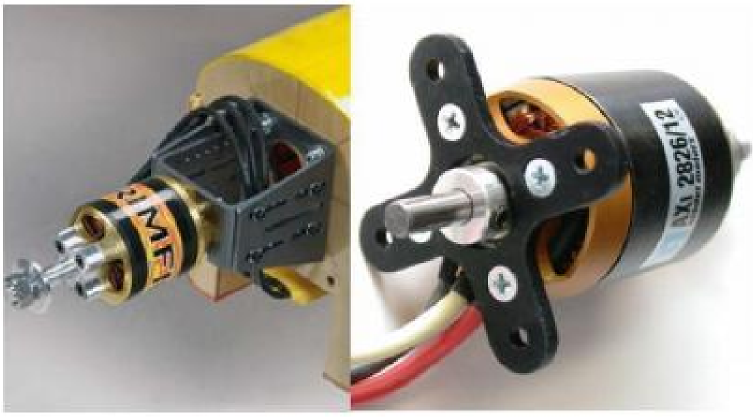
The better efficiency of brushless motors over brushed ones is mainly due to the absence of electrical and friction losses due to brushes. This enhanced efficiency of brushless motors is greatest under low mechanical loads and high speeds. But high-quality brushed motors are comparable in efficiency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

Power Transmission

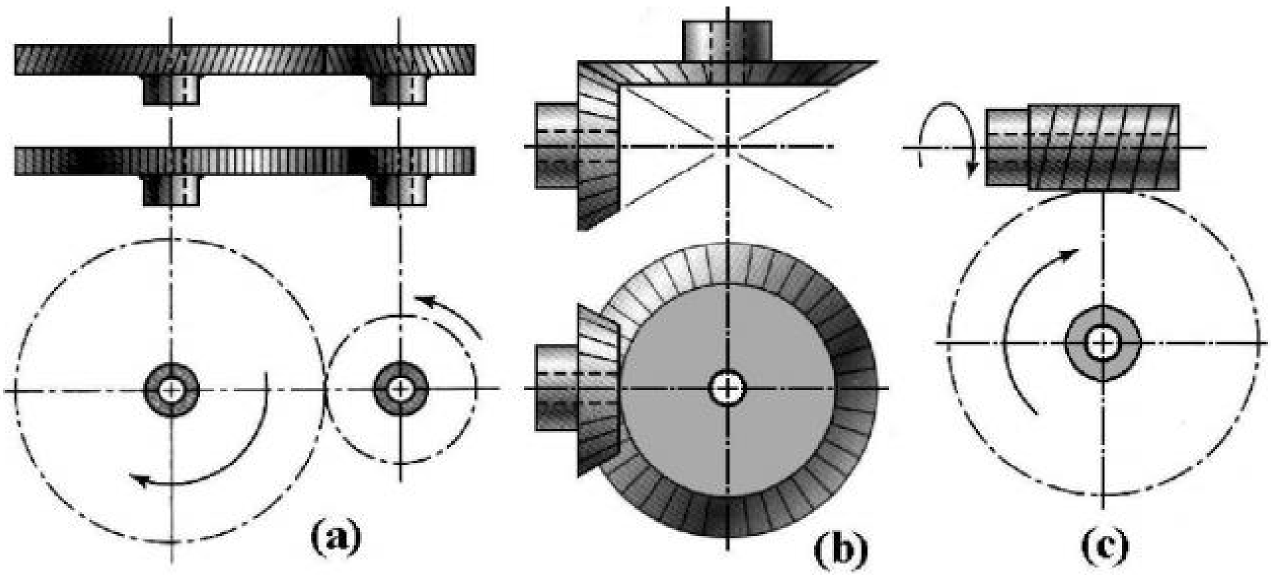
To transmit power from the motors to the wheels or weapon, it is necessary to use gears, belts or chains. Each one of those elements is described next. **Gears**

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 straighttoothed 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

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.

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 Vbelts (right figure, showing quadruple-sheave pulleys), manufactured in standard sizes in rubber or polymeric base, in general reinforced with high resistance fibers.

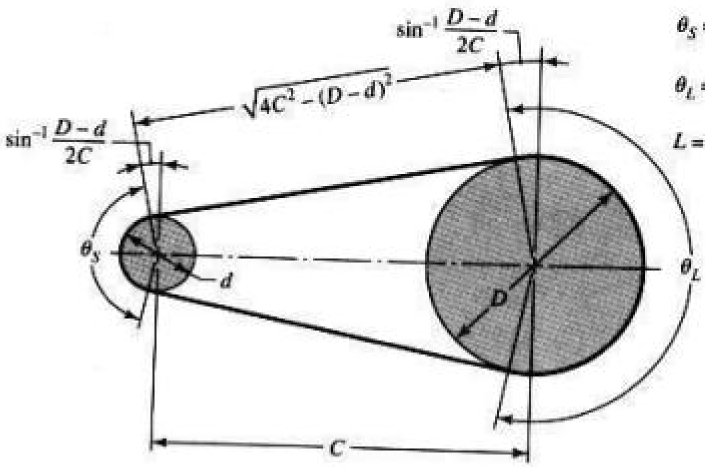
Timing belts (pictured to the right) keep the relative position between the pulleys, synchronizing the movements and preventing sliding. They can be used to transmit power to the drive system. They can also be used in the robot weapon system, but in this case it is recommended to use some type of torque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

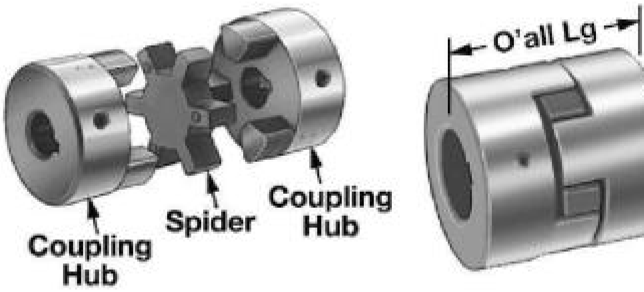
Chains

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.

Flexible Couplings

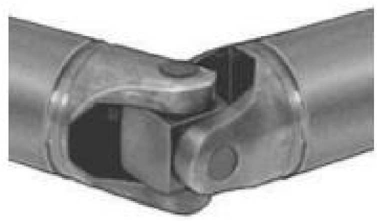
Flexible couplings allow a shaft to efficiently transmit power to another one, even in the presence of misalignments. They consist of 2 rigid coupling hubs, usually made out of cast iron, fixed to each shaft usually using keyways, and of an elastic element (rubber spider) between them, see the picture 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 g ears 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.

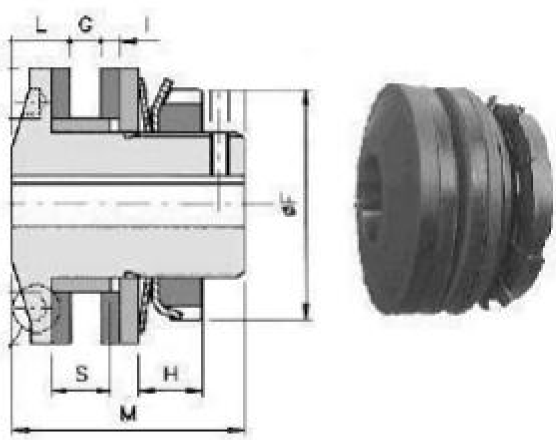
Avoid using these couplings to power impact weapons, it is likely that the rubber spider won't take the high impact torques.

Another method to couple misaligned shafts is through universal joints (a.k.a. universal or Ujoint, 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.



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.

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.

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 $2 \times 66A \times 0.05h \times 50\% = 3.3A \cdot h$ (approximately, ignoring the consumption when the robot is not accelerating). Therefore, for the drive system, 1 battery pack with 24V and $3.6A \cdot h$ 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 $2 \times 162 = 324A$ 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 paral lel to power a single motor, we would have an equivalent electrical resistance of half the one of a single pack, $R_{battery} = 0.080\Omega / 2 = 0.040\Omega$, 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 0.080 Ω 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 $\omega_{no\_load} = 5{,}968RPM = 625rad/s$, generating a top speed $v_{max} = (\omega_{no\_load} / n) \times r = (625 / 7.14) \times 0.0762m = 6.67m/s = 24km/h$ (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 $\omega_1 = K_v \times (V_{input} - R_{system} \times I_{max}) = 254 \times (24 - 0.148 \times 66) = 3{,}615RPM = 379rad/s$. The robot speed when the wheels stop skidding is given by $v_1 = (\omega_1 / n) \times r = (379 / 7.14) \times 0.0762m = 4.04m/s = 14.5km/h$ (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 $a_1 = 0.9 \times 9.81 = 8.83m/s^2$. 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 $a_1 = 0.9 \times 9.81 \times 50kg / 55kg = 8.03m/s^2$.

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

$$\tau = K_t \cdot (I_{input} - I_{no\_load}) = K_t \cdot (I_{stall} - I_{no\_load} - K_v \quad R \qquad)$$

Therefore, the torque at each wheel is τ × n, which generates a traction force of τ × n / r. The 2 wheels generate together twice that force, and then from Newton's second law we obtain the equation 2 × τ × n / r = 55kg × a2. This robot's acceleration a2 varies because it depends on the motor speed ω:

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

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 = (ω / n) × r = ω / 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 × 6.67m/s = 6.34m/s) can be calculated:

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

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.

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 $m = \pi \cdot (65^2 - 40^2) \cdot 180 \cdot 7.8 \cdot 10^{-6}$ kg/mm^2 = 11.6kg (about 25.6lb). The rotational moment of inertia with respect to the horizontal spin axis is $I_{zz} = m \cdot (R^2 + r^2)/2 = 11.6 \cdot (65^2 + 40^2)/2 = 33785 kg \cdot mm^2 = 0.0338 kg \cdot m^2$.

The weapon motor is one Magmotor S28-400 (pictured to the right) connected to 2 NiCd battery packs in parallel, therefore V_{input} = 24V, K_t = 0.0464N·m/A, R_{motor} = 0.042Ω, and I_{no_load} = 4.5A. 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 = 0.086Ω. 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 ω_{no_load} = 206 × (24 – 0.086 × 4.5) = 4,864RPM = 509rad/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:

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

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

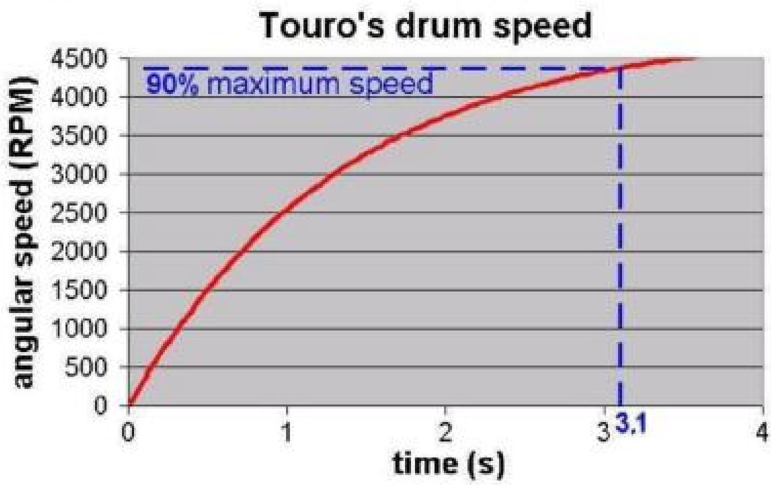
$$T = I_{zz} \cdot \frac{d\omega}{dt} \Rightarrow 12.74 - 0.025 \cdot \omega = 0.0338 \cdot \frac{d\omega}{dt}$$

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

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

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. Besides, fully charged 24V NiCd batteries are able to deliver up to 28V, which wouldmore 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 $2 \cdot a$ and width $2 \cdot b$, 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.

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:

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

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

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

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

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

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:

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

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.

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

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

therefore two 24V battery packs with $3.6\text{A}\cdot\text{h}$ each (totaling $7.2\ \text{A}\cdot\text{h}$) 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 $2.4\text{A}\cdot\text{h}$ each (totaling $4.8\text{A}\cdot\text{h}$), 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

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

$4.1\ \text{A}\cdot\text{h}$ which would be enough if both batteries can actually deliver $4.8\text{A}\cdot\text{h}$.

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.

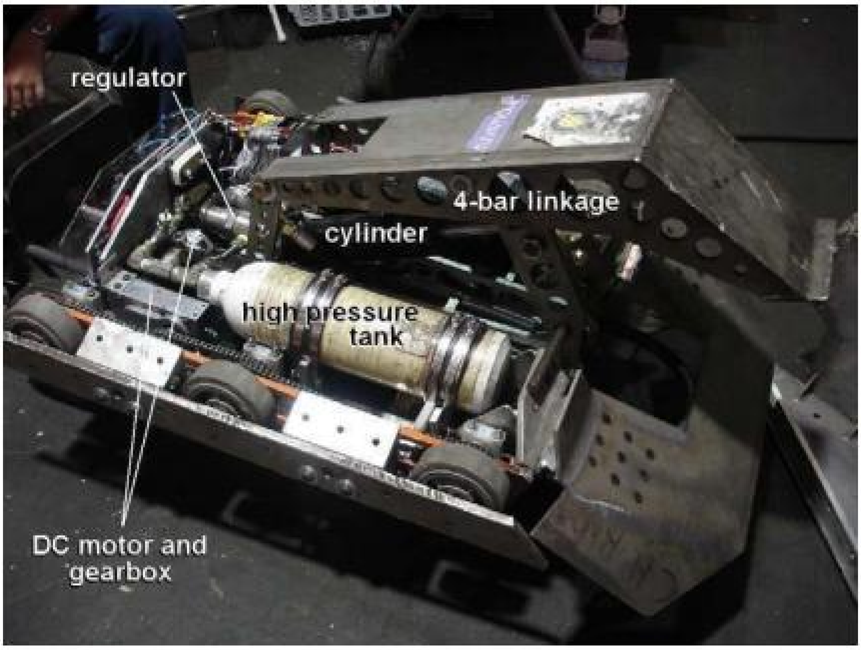
In a simplified way, the pneumatic systems consist of one or more storage tanks, connected to a pressure regulator, accumulator, solenoid valve, and pneumatic cylinder, not to mention the safety valves.

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.

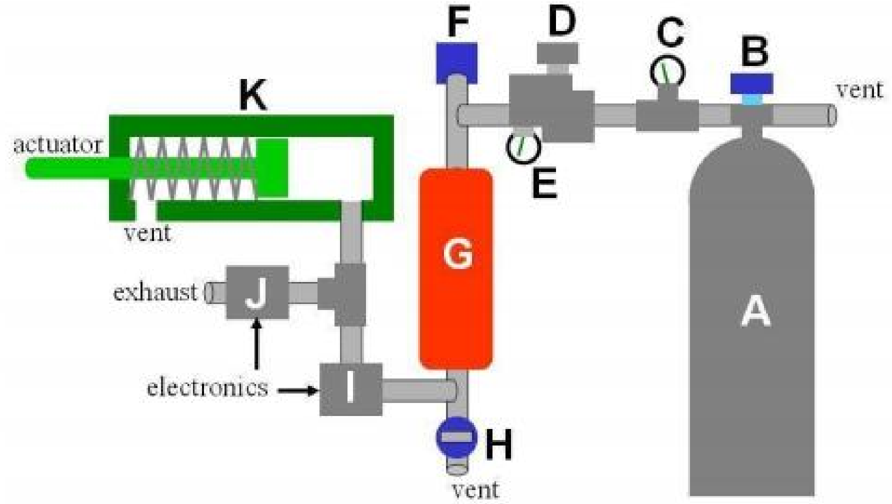
Regulators are components that transform the high pressures of the pneumatic tanks (about 1000psi for CO_2 and 2000 to 3000psi for air or N_2) into lower pressures that can be used in conventional pneumatic system s, typically between 150 to 250psi.

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 safety valves.

The cylinders are actuated through solenoid valves, which usually are of two types: two-way twoport, 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 4bar 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.



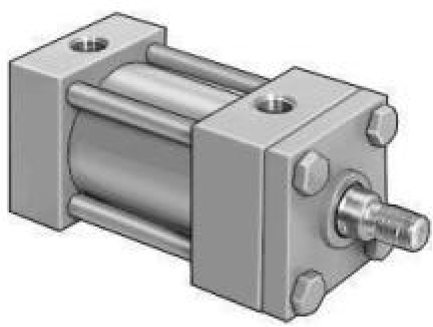
The figure below displays the schematics of a single-acting cylinder. The items A, B, C and D of the diagram represent the high pressure line, and the remaining elements are the operating pressure line.



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.



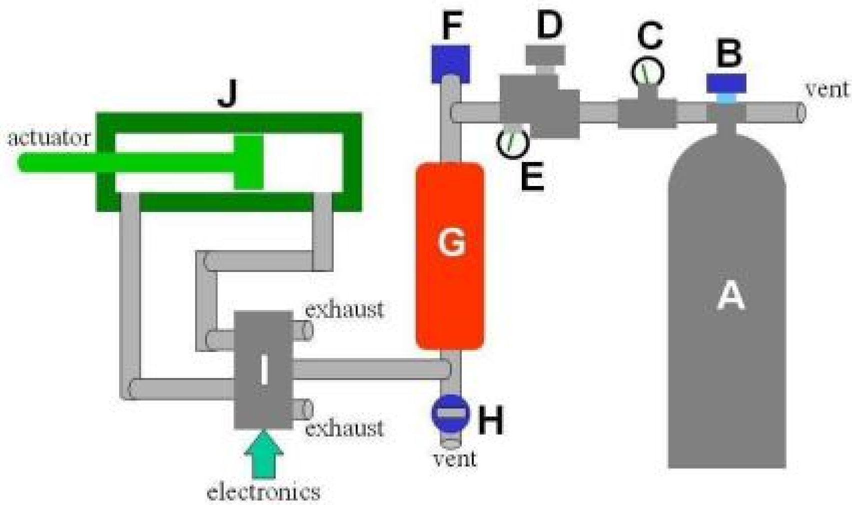
Even so, as pointed out by Mark Demers, builder of Ziggy, an unmodified 2500psi cylinder which is not designed for impact loading at stroke end doesn't guarantee it will hold up at 1000psi pneumatic:

“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. 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 SubZero, 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.

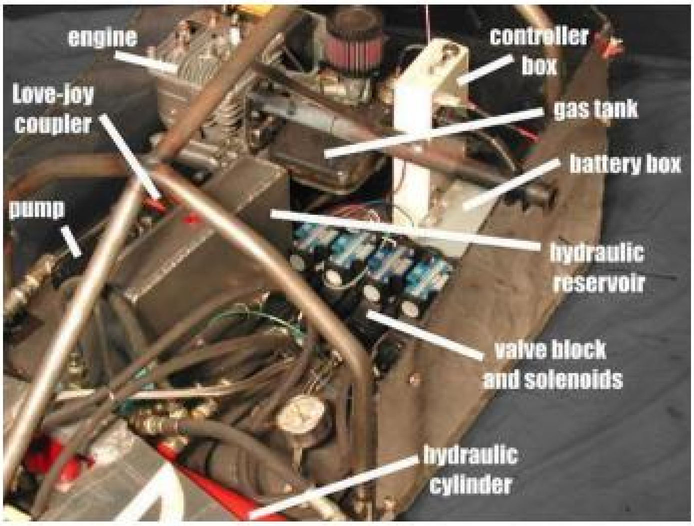


A few tips to increase the speed of your cylinder are: use a larger accumulator; use hoses and connections with the largest possible diameter; avoid sharp corners in the path of the hoses and pipes; leave the gas exhaust path as free as possible, directed towards outside the robot.

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.



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.