Motor Selection workshop: Lecture notes

Work shop outline:

- Introduction to DC electric Motors
  1. What are electric Motors?
  2. Understanding how motors behave
- Little physics behind motors
  1. Concept of Power
- Motors specs and details
  1. Motor Curves
  2. Free Speed, Stall Torque, and Motor Power, and electric power
  3. Motors Power calculation, Available motor power
- Power requirement calculation and choosing the motor
  1. Figuring out how much power you need
  2. Choosing the motor and different consideration
  3. Internal thermal protection, back-drive-able motors
- Optimizing the motors
  1. What is Gears and gear ratio
  2. Efficiency, effective gear ratio
- Solve the whole problem / Putting everything together
  1. Finding required power and force for the job
  2. Deciding gear ratio and the right motor
  3. Power needed vs. effective power
- Advices for Setting up motors and other details of motors.
  1. Advices

Special thanks to Joe J. and Mike C. of team 47 Chief Delphi, and Andy Baker from team 45 Technokats, and many posters from Chief Delphi forum for making this possible!!! And a big thanks to Dr. Eugene Brooks of team 1280 for looking over the notes and correcting some mistakes.

Introduction to DC electric Motors

What are electric Motors?

An electric motor converts electrical power into mechanical power. All motors from the 2002 kit of parts are DC electric motors. It is one of the main methods to power different components on your robot. Without motors, a robot is only a pile of material sitting on the floor that look pretty. They move the arms/drive train/components on your robot to perform the tasks you desire. They are like muscle in your arms, or the engine in a car. It is important for you to understand how motors work, because you cannot fully apply them without knowing why they behave the way they do.

Understanding how motors behave

There are a few very important characteristic you have to understand first:

1. Motors convert electricity into mechanical energy

There is a clear distinction between electric power and mechanical power. Electricity stays in the battery and does not do any noticeable physical work. Mechanical power, on the other hand, does. It is the job of motors to convert one from the other.

2. The more electricity you give it, the more mechanical power the motor have

Motors are like RC cars you have when you were young. The more you push on the trigger on the remote control, the more electricity you supply to the motors, and the faster it goes. In another words, the amount of mechanical power is proportional to how much voltage you give the motor. That's where speed controller comes in: they control how much electricity goes to the motor. However, not every motor use a speed controller. Instead, they use a relay, which simply turn the motor on and off at full voltage (12v for this case).

3. DC motors slow down more and more as the load on increase

Loads are outside forces acting on the motors' output shaft. The more force acting against the motor's motion, the slower the motor move, and the stronger the motor push back. Say, a robot has an arm powered by a motor. When the arm move, the harder you push against the arm, the harder it pushes back at you. If you aren't pushing the arm back, you won't feel any force from it at all. If you put you whole weight on the arm, it might be strong enough to lift you up. This is very important here: the motor's output force and speed varies depending on the load acting on it.

Before we move onto the specifications, let's review some physics formula.

Little physics behind motors…

Concept of power:

Mechanical Power = Force X Velocity = Torque X Angular Velocity

We can see power as a unit to measure the net force applied to an object and how fast it is moving. In terms of motors, power measure how strong and how fast the motor is spinning. Mechanical Power is the multiple of force and velocity. If one of them is zero, the multiple is zero too.

Take baseball for example: If you are swinging a bat really fast but doesn't give much force to it, the ball won't fly far away when you hit it. Same if you swing the baseball ball with a lot of force, but very little speed. If you want to hit a homerun, you got to

swing the bat fast and hard. By maximizing both force and velocity, you maximize mechanical power.

Electrical Power = Voltage X Current   Electric power of motor (power source)
It is a similar concept with electrical power. The more voltage you supply, the more electrical power you get.

Velocity = Distance / Time	Measurement of speed
Angular Velocity = Rotation / Time	Measurement of rotational speed
Torque = Force X Distance	Measurement of rotational force

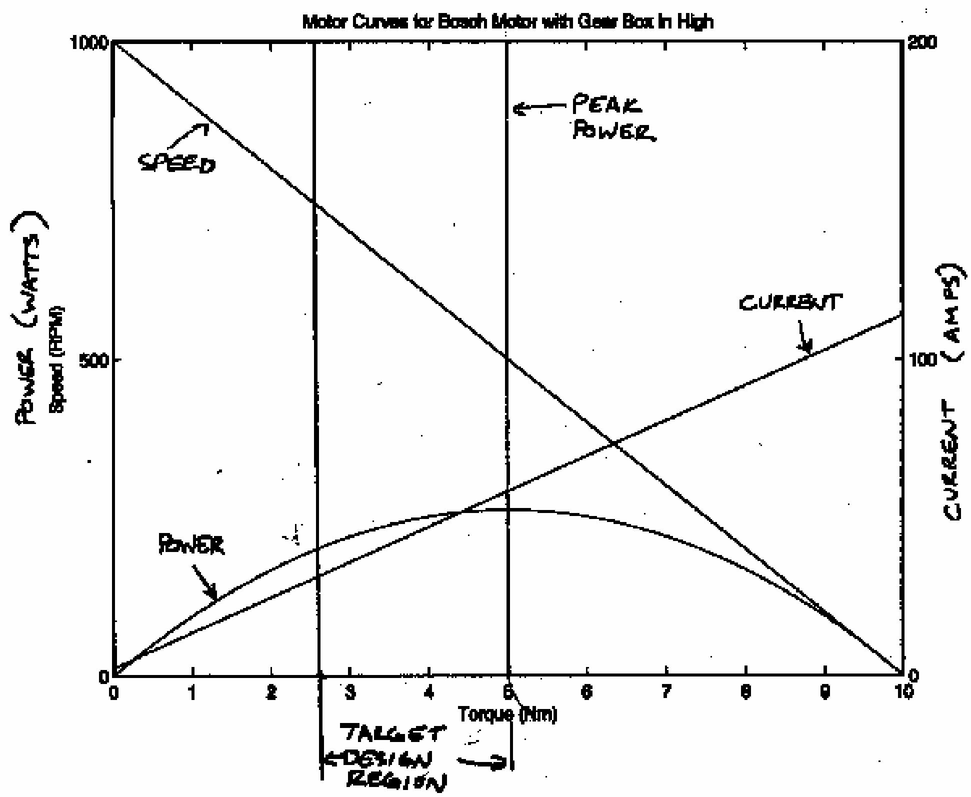
<u>Unit Conversion:</u>   Useful conversion units in calculations

1 lbs = 4.45 N
1 inch = 0.0254 meters
1 inch-lbs = 0.11 N-M
1 N-M/sec = 1 Watt   (unit conversion of motor power)
1 RPM = 0.104 Rad/sec

It's very important to note the conversion 1 Newton meter per second equal to 1 Watt. This is the conversion between electric power and mechanical power. When you supply 1 Watt of electricity, you get 1 N-M/sec mechanical power out of the motor. Now, with these in mind, let's move onto the motor spec and graphs.

Characteristics of motors…

Motor curves:



These are the curves you need to look at for motor performances. Some of the motors came with a spec sheet with these graphs, some don't, and you have to generate these curves with the numbers supplied in the specs.

1. Current vs. torque curve (labeled "current") A direct linear relationship. The more loads (measured in torque) the motor run against, the higher the current it draw. When the motor push harder and harder, current it draw get higher and higher.
2. Speed vs. torque curve (labeled "speed") As I mentioned earlier, the more load you put on the motor, the slower it goes. This is the curve representing exactly that relationship. It is an inverse linear relationship. It tells you the speed of the motor if you know how much load is acting on the motor.
3. Power vs. torque curve (labeled "power") Remember how power is Force times Velocity? This curve shows the exact amount of mechanical power at different degree of speed and torque. Notice the ends are zero power. (remember the baseball analogy?) The maximum of power happens at the peak of the curve, when torque pushing the motor is ½ stall torque, and when speed is ½ free speed.

Labeling and drawing the graphs

Label the axes with the number supplied in the spec sheets. The bottom axis is "Torque" ranging from zero to the amount of stall torque on the spec. The vertical axes are labeled differently depending on what curve you want to look at. For "speed vs. torque", you would label the vertical axis with "Free speed" ranging from zero to the amount of free speed on the spec. You would label the other vertical axes with "Current" ranging from zero to "Stall Current" and "Power" for "current vs. torque" and "power vs. torque" respectively.

To draw each curve, here is what you should do:

Speed vs. torque: Draw a straight line from (0 torque, free speed) to (stall torque, 0 speed)
Current vs. torque: Draw a straight line from (0 torque, 0 current) to (stall torque, stall current)
Power vs. torque: Draw an upside down parabola, with the ends at (0 torque, 0 power) and (stall torque, 0 power), and the peak at (1/2 stall torque, max. power). I will show you the calculation for maximum power of motor below.

Free Speed, Stall Torque, and Motor Power, and electric power

In motor spec sheets, you will see different terms describing the performance of the particular motor it's for. I already mentioned *stall torque* and *free speed* above. Here's what the each term means:

Stall torque- The highest amount of torque a motor can generate, the motor will stall when facing this much load or more. Basically, the motor won't be able to move when it get pushed too hard.
Stall Current- The amount of current drawn when a motor is stalled, measuring the maximum amount of current it could draw.
Free Speed- The speed of the motor when spinning under no load, which is the fastest speed output by the motor.
Gear Box ratio- Amount of gear reduction on the included gearbox with the motor.
Maximum motor power- Maximum amount of mechanical power a motor could generate.

When I was learning about this, I asked, "What's the big deal about this max. power?" It turns out its everything. This number tells you which motors are stronger and which are weaker. It also tells you if you have enough power to perform the task you desire.

Quoting Dr. Brooks:

"Given that you can vary the gear ratio for a given robot speed, the gear ratio that produces the most acceleration for the robot is the one that puts the motor at the maximum power point. This is counter intuitive, in that a person sees motor torque as producing the acceleration, but a little calculus demonstrates otherwise."

Chances are, you won't get the same motors next year. So, let's go through the calculation for max. power so you can do this for new motors next year.

Motor Power calculation and available power:

Motor Power can be obtained from the following equation:

<u>Motor power</u> = ½ Free Speed X ½ Stall Torque

Free Speed in Rad/sec (1 RPM = 0.104 Rad/sec)
Stall Torque in N-m (1 in-lbs = 0.11 N-m)

(Free speed and stall torque all proportional to voltage…)

Look up competition manual for numbers. They can be found in "G.5.3 The Robot - Mechanical" section online at

http://www2.usfirst.org/2007comp/other/2007%20Guidelines_Tips_Good%20Practices_RevC.pdf

Example: Maximum Drill Motor Power with Gear Box (High):

Power = ½ Free Speed X ½ Stall Torque
= ½ 1,000 RPM X ½ 10 N-m
= ¼ X 104 Rad/sec X 10 N-m = 260 Watt

This is the maximum amount of power you can get out of drill motor in high gear.
<u>Available Maximum Power from FIRST 2001 Motors</u>

Bosch Motor Only	340 Watt
Chiaphua Motor	314 Watt
Bosch Motor w/ Gear box in HIGH	260 Watt
Bosch Motor w/ Gear box in LOW	230 Watt
Fisher Price Motor Only	140 Watt
Fisher Price Motor w/Gearbox	91 Watt
Delphi Sliding Door Motor (MFG: Taigene)	69 Watt
Globe Motor Only	63 Watt
Globe Motor w/ Gearbox	50 Watt
Delphi Seat Motor (MFG: Keyang)	31 Watt
Delphi Window Motor (MFG: Valeo)	22 Watt

Power requirement calculation and choosing the motor

Figuring out how much power you need

Now, when you look at the competition, there are all sort of objectives to accomplish. Every year is different. It might be picking up balls, lifting up a robot, pushing goals, etc. You need to separate each of them into individual cases, and figure out what is needed to perform the task to achieve the objective. You need to remember the formula for Power to do this.

Example 1:
Imagine the game of 2000 when you want to lift the robot up… Say a 130 lbs robot 1ft in the air within 2, 4 seconds. How much power is needed to accomplish this?

Power needed:

1a. Within 2 seconds-

Power = Force X Velocity = 130 lbs X 1ft/2sec = 580 N X 0.31 m/2sec = 87 Watt

1b. Within 4 seconds-

Power = 580 N X 0.31 m/4sec = 45 Watt

Example 2:
Imagine the game of 2001 when you have to lift a 5 lbs big ball 7ft in the air on top of the goal within 6 seconds, and you decide to use a 3.5 ft long 20 lbs arm by rotating it 180 degrees. How much power needed?

Power needed:

Power = Torque X Angular Velocity

There're two torque in this device: torque from the ball, and torque from the arm itself

Torque of ball = 5 lbs (how heavy) X 3.5 ft (how far from center of rotation)
Torque of arm = 20 lbs (how heavy) X 1.75 ft (how far is the arm's center of mass from center of rotation)

Total torque = torque of ball + torque of arm = (5 lbs X 3.5 ft + 20 lbs X 1.75 ft) = 630 in-lbs = 69 N-m

Angular Velocity = 180 degrees / 6 sec. = 5 RPM = 0.5 Rad/sec
Power = 69 N-m X 0.5 Rad/sec = 34.5 Watt

**This is the worst case when arm is parallel with the ground… It take less torque to rotate arm when it is point toward the ground or upward. Simply substitute 5lbs and 20lbs with 5lbs X cos(theta) and 20lbs X cos(theta), where theta is the angle between the horizontal position of the arm and the actual position of the arm. **

Choosing the motor and different consideration

After all the calculation, it's just a matter of looking up the right motor to match the power requirement. It is important to note that this "power requirement" is base on your expectation of speed of accomplishing the task. All of the motors can generate the amount of torque to finish the task. It's only a matter of how fast you want it done. Sometimes if you can't find a motor with enough power, you can extend the duration you want the task finished in, and figure out which motors can satisfy the requirement.

There are few things to keep in mind.

1. You want to leave the stronger motors for more important tasks. Such as the drill and Chiaphua motors for drive train and high speed ball collector. You should prioritize which components are most important, and choose the necessary motors for the job.

2. Other important features of motors

Internal Thermal Protection:

Motor power reduced when motors heat up. This is a feature of Sliding Door Motor, Seat Motor, and Window Motor. Avoid running these motors near stall because they will heat up quickly because a lot of electric power are turned into heat instead of mechanical power. The motors also will heat up when you use them in the matches extensively. The longer you use the motor, the hotter it gets, and the quicker it active the internal thermal protection. The thermal protection will reduce the power output to the motors, making them weaker than they actually are.

Other motors can take the heat while not losing major motor power. They still lose some motor power into heat, but there's no thermal protection to dramatically reduce power output, or even shut down the motor completely. For example, for the drive system, you would want to use drill or Chiaphua motors because they don't have I.T.P. and wouldn't shut down after driving around a long time.

Back-drive-ability:

Drill motors, drill motors with modified gear box, Fisher price motors, Sliding Door motors, and globe motors are back-drive-able. That means with enough torque, these motors can be driven backward, where as others have locking devices. These Motors will need electricity to hold their position under constant force. When the matches end and electricity is cut, these motors won't be able to counter the force. For example, if you are using these motors to power an arm that lift up the robot in the air, at the end of the match, there won't be power going to the motors to keep it in the same position, so the robot will slid back onto the ground.

On the other hand, motors with locking device can be damaged by too much external force, as well as the components using them. Instead of giving away, the motor/component will continue to resist the load until it breaks. Experiences tell us that the locking pin inside drill motor gear box can be broken under large amount of load. There can be other damages such as bending shafts, or breaking gear teeth… etc. Also, you will need electricity to move the motors with locking device, so it could get annoying when you want to retract device with the robot turned off.

Optimizing the motors

Even after knowing the calculation and numbers, we still don't understand how to apply the motors on the component, and how to optimize the motors to work at its best efficiency. In order to do that, you need to know what gear and sprockets, and what gear ratio is.

What is gear and gear ratio?

Let's talk about gears and sprockets. Motors use gears and sprockets to transfer power onto components. Few things gearing does:

<u>1. Transfer power from motor onto the components</u>

If you look at the motors, a lot of times it have a gear on the part that actually move (called the output shaft). This is set up so the power from the motor is transfered onto the gear, and then to something else connected to a gear. For example, the drive train uses sprocket and chain to transfer power from the motor to the wheel. It's a matter of looking at the motor, and figuring out a way to connect it to components and transfer mechanical onto them.

<u>2. Transform the mechanical power into different form</u>

Gears and sprockets can also be used to change direction of rotation or motion, and transfer power from one place to multiple places. You might have the need to drive 2 shafts in opposite direction, or connect the motor to different components, or need linear motion while motors only provide rotational motion, or the motor might be too fast for your component. You can use different setup of chain, sprocket, gears, lead screw, pinion & rack, to do all these.

<u>3. Achieve max power by gear ratio</u>

One very interesting thing you can do with gears is setting up a gear ratio. Imagine putting two gears together, one 8 teeth gear driving a 16 teeth gear to move, you can imagine for every 1 rotation the big gear took, the small gear goes through 2 rotations. So, that's a 1:2 ratio. In general, you just count the teeth on the gear to tell the ratio. You can setup whatever ratio you want by using different gears.

The important thing is, since mechanical power from the motor is constant, the power transfer from one gear to the next is the same. Remember, power equal torque times angular velocity. So, even though the gear is slower, it spin with stronger torque. This means you can manipulate how much loads get transferred onto the motor by setting up a gear ratio between the motor and your component.   You can make it just about right for the motor to perform in its best combination of speed and torque. Because, even though the motor have enough power to do the task, it might be too fast or too slow. You want to setup a ratio such that the load onto the motor is around where Max. power is, so the motor work as efficient as possible.

<u>How does gear ratio work?</u>

Gear transmit load (force) at the teeth. Load = Torque / radius (pitch diameter)

The force comes from torque of the gear. When a gear is rotating, its teeth exert a force in the direction it's rotating. The bigger gear the gear is, the longer the "lever arm" (diameter of the gear) is, and the weaker the force on the teeth. When that gear mesh with a second gear, the force from teeth of gear 1 pushes the teeth on the gear 2. That generates a torque on the second gear. The longer the "lever arm" the second gear have, the bigger the torque it generates. Using the same ideas, you can create different combinations of gears and generate different amount of torque on the second gear, whether its weaker or stronger. That means, using gear ratios, you can multiple torque from the motor 2 times, 10 times, 100 times if you set it up right. Then you can look at how much torque you need and set up the precise ratio that generate the torque required.

Number of teeth is proportional to gear's radius, therefore we can calculate gear ratio by:

$$\text{Gear ratio} = \frac{\text{\# teeth of gear}}{\text{\# teeth of driving gear}}$$

8 teeth gear driving a 24 teeth gear have a 3:1 ratio (three-to-one ratio, 3 turn of 8 for 1 turn of 24) These calculation also apply to sprockets. In return, the 24 teeth gear have 3 times the torque.

Efficiency and effective gear ratio

<u>Efficiency</u>

One more thing to consider is efficiency. Small parts like Gear, sprocket, and chain don't transfer 100% power due to losses in friction and heat . In an ideal world, these gears will keep moving forever and ever, but it doesn't work that way. You simply have to take it into account, and remember that the more gears and sprocket you use the more power loses there are.

Efficiency for each stage of different small parts:
Spur Gears: 90-95%
Worm Gear: 10-60%
Nut on a Tread (not ball nut): 10-60%
Twist Cables: 30-70%
Chain: 85-95%
Cable: 0-98%
Rack & Gear 50-80%

<u>Effective gear ratio</u>

We have to calculate the effective gear ratio and figure out how much power is actually transferred to the other gear due to losses in friction and other forms of energy.

Effective ratio = gear ratio X efficiency
Effective gear ratio example:

Imagine two gear stages (total of 4 gears), a and b, with spur gears, each 2:1. Figure out the overall effective ratio.

Over all ratio = ratio of a X ratio of b
Effective ratio = gear ratio X efficiency
Overall effective ratio = (a-ratio*a-efficiency)*(b-ratio*b-efficiency)
= 2 * 90% * 2 * 90%
= 3.24

*An alternative point of view to the Effective gear ratio is to see that no matter what system you build, there will be power losses due to friction and heat and other forms of power. To quote Dr. Brooks:

"… the gear ratio is an exact mathematical object. The motor speed is related to the output speed by this exact number. Ideally, the torque or force produced on the output would be scaled by the inverse of the gear ratio, but you don't get the full calculated torque due to losses due to friction. So, you get to derate the motor power and torque curves appropriately in. Is "effective gear ratio" hiding this somehow? I tend to take the view of discussing the torque, and therefore power, lost to friction directly."

The most important thing to think about is where you are losing power in your system. Is it the gear box? Is it the chain tensioners? Is it the bearings or the lack of lubrication? Know these sources and you won't overestimate the amount of power you can harvest from your DC Motors.*

Solving the whole problem…/Putting everything together

At this point, you can put together everything from power calculation to motor characteristic to gears and sprocket, and use them to solve the two problems: What motor(s) can we use to complete certain task the way we want it to? How can we set up motor with the component?

Calculating power requirement:
Think back to power calculation example 2- Using a 3.5 ft long 20 lbs arm to lift a 5 lbs big ball 7ft in the air by rotating it 180 degrees. We found out that it takes 34.5 Watt to complete the motion in 6 seconds.

Choosing the right motors:
This can be done with Bosch drill Motor w/ gearbox (260W & 230W), Fisher Price Motor w/ gearbox (140W), Sliding Door Motor (69W), and Globe Motor w/ gearbox (50W).

Try using Globe motor w/ gearbox. Even though its back-drive-able, we don't need to hold the arm in the air after each match, so it will work as long as we keep supplying power to the motor when we use it.
Calculating working torque and applying gear ratio
Maximum Torque required for this task = (5 lbs X 3.5 ft + 20 lbs X 1.75 ft)
= 630 in-lb

Best to design a gear ratio such that the load reflected back to motor is around 20%~50% stall torque when motors are most happy. Globe motor w/ gearbox has a stall torque: 170 in-lbs

20%~50% S.T. = 34 in-lb~85 in-lb
Max. torque / working torque = 630 in-lb / 34in-lb ~ 630 in-lb / 85 in-lb
Gear ratio requires to increase torque up to Max. torque= 18.5:1 ~ 12.6:1

We will run motor at 45% of stall torque with a little room before maximum motor power:
Working Torque = 170 in-lb * .45 = 77 in-lb

Gear ratio = 630 in-lb / 77 in-lb = 8.2:1
Choosing the gears/sprockets
Many combinations between gears or sprockets can be used to obtain a certain ratio.

Two of many options: (Basically, the less gears, the more efficient)
One stage of 10:1 gear ratio with 0.9 efficiency, or
Two stages of 3.3:1 with 0.9 efficiency per stage.

Effective gear ratio = 3.3 * .9 * 3.3 * .9 = 8.82:1

Effective Power:
Calculate effective power to double check if motor really has enough power for task, since no gear/sprocket system has 100% efficiency. 100% efficiency only when direct drive from motor.

Globe motor with gearbox @ 45W ~ 50W
Effective power = motor power * total component efficiency… We will just consider the gears' efficiency for this purpose
.
Effective power = 45W ~ 50W * (.9 * .9)
= 36.5 W ~ 40.5 W

It take 34.5 W to complete the task, and the way we set up this motor, we will be getting at least 36.5 W out of the globe motor w/ gear box. So we know this motor is good enough for this component.

(50W only true at near peak power range with perfect gearing. Usually power loses cause by heat and friction.)

Advices for Setting up motors and designing components…

- Use springs to help your motor along
- Use more motors if necessary
- Control motor motion with limit switches, sensors, and programming
- Think about space and weight limit on robot at all time!!!
- Avoid using thermal protected motors in continuous high torque motion for a long time
- Less load on motors for lower current
- Reduce side load on motor/output shaft
- Make use of accessories of motors (i.e. Window tape drive)
- Mount motors properly and stably
- Make sure you have easy access to motors in case you need to replace them
- K.I.S.S. The simpler your component is, the higher the efficiency and less things to worry about.

Which motor is good for what device…

Here is a list of what FIRST teams use which motor for what device in the past years.

- High power motors like Drills and Chiaphua are used for drive system
- Strong motors like Van Door motors is good for toughest job other than drive system
- Globe and window motors are great for actuations and low power task
- Seat motors are good for ball collectors or actuating something by driving a lead screw
- Torque and servo motors are good for triggers only

Any Further Questions?

E-mail me at: wheres_kenny@hotmail.com if you have any questions, or just want to chat about robotics in general (AIM: LKen5412). I will be more than happy to help out anyone with problems on their robot, although I am not as active in the build season of FIRST anymore.

Visit www.chiefdelphi.com and read messages from teams across the country about this competition, specifically, the Motors Forum.

http://www.chiefdelphi.com/forums/forumdisplay.php?f=52

You are all welcome to post your questions and thoughts in the forum. The white paper section also has some great papers about motor mount design and drill motor advice.