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2014 Deans List Finalist -Midwest Regional

AN IDIOT'S 'COMPLETE' GUIDE TO FRC

A collection of the mistakes of a FIRST-class idiot. Don't repeat them!

Overview

This guide is designed to give new FRC teams a leg up in getting started and competing, and give veteran teams a training tool to bring new members quickly up to speed.

This guide is not intended to stand alone. It gives an overview of what's out there but doesn't go too into detail for anything, so augment it with Chief Delphi and Google searches.

That said, If you don't understand the way I've explained something in this guide, don't hesitate to email me at arpan.rau@gmail.com . I'd love to work with you.

I really recommend that, regardless of your role on the team, you read all of this guide. For example, you can understand Mechanical excellently, but if you don't understand sensors and strategy, you're hosed. I've also often ran into problems where I first have to isolate whether the problem is electrical, software, or mechanical- in which case a broad skillset is essential.

PART 1 : MECHANICAL

Yeah. Really. Mechanical comes first.
Know why? Because it rules, that's why.

Other resources

JVN's Mechanical Design Spreadsheet:

<http://www.chiefdelphi.com/media/papers/2059>

West Coast Products Belt calculator:

<http://www.wcproducts.net/how-to-belts/>

Mcmaster-carr:

<http://www.mcmaster.com/>

Vexpro:

<http://www.vexrobotics.com/vexpro/>

Chiefdelphi:

<http://www.chiefdelphi.com/forums/portal.php>

How to build your everything really really fast (Mechanical people, read this☺)

<http://www.instructables.com/id/How-to-Build-your-Everything-Really-Really-Fast/>

Google:

www.google.com

:P

Mechanical : An overview

The Mechanical members of a FIRST robotics team are responsible for the design and construction of the robot. A skilled mechanical team member understands basic Newtonian Physics, CAD*, and Mechanical best practices. They know how to design common FIRST mechanisms by heart and spend hours of free time browsing chief Delphi's image sections for CAD models to look at.

A good mechanical member never rests. Offseason or on, they are constantly spitting out conceptual designs for drivetrains, scoring mechanisms, and intakes for review by their peers. This constant CAD practice and design review is what enables them to turn around robot 'subsystem' designs in the ridiculously short timeframes necessary during the build season. If this seems intimidating, don't worry – it takes years to get to this point.

I won't cover how to CAD here; I've found that CAD is something that you learn by experimentation. To learn, download Autodesk inventor from Autodesk's student site and jump in with their tutorials. Email me if you have questions or want training projects to do.

The key to good mechanical design is to build your robot for a specific strategy. Know where you're going to score from, how you're going to get there, and how you're going to align to pick up and score game pieces.

*Cad is computer-aided design; a way to draw 3d models with computers. Effective teams CAD their entire robot before they build it.

Basic Physics: An Overview

Newtonian physics are the physics of motion. I'm sure that there are plenty of better guides for learning physics , so I'm only going to cover the most basic concepts – and in not much detail.

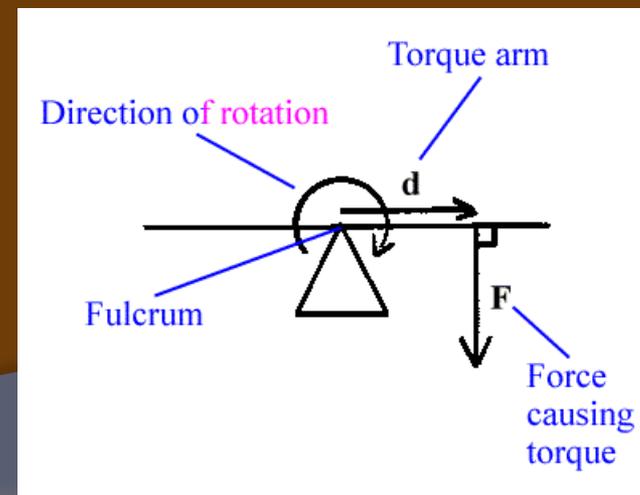
If you haven't taken a physics class, I recommend looking up these topics on minute physics' youtube channel after you read through this section.

Basic Physics: Force, Torque, Velocity, Angular velocity and Acceleration

In basic Newtonian physics, there are four unit types that we normally deal with (excluding momentum and impulse, which will be covered later) – Force, Torque, Velocity, Angular Velocity, and Acceleration.

Force is any influence that causes an object to change its motion. If I knock over a chair, I have exerted a force on that chair to make it move. The SI unit for force is the Newton.

Torque is a rotary force- something that causes an object to change its angular velocity. Torque about a lever is equivalent to the perpendicular force at any given point in the lever times the distance between the point of rotation (or fulcrum) of the lever and the point given. Torques can be clockwise or counterclockwise.



Basic Physics: Sums of forces and torques

A basic tenet of engineering is that , such that the system is not accelerating (constant velocity or static) ,

1. All torques in the system will sum to 0 and
2. All forces in the system will sum to 0

For more on how to set up and solve these types of problems, I recommend [this site](#).

Basic Physics: Force, Torque, Velocity, Angular velocity, Mass and Acceleration

Velocity is a vector expression of speed – in other words, it is a speed with a direction attached. Velocity is typically expressed in meters per second or, in FRC, feet per second.

Angular velocity is typically expressed in revolutions per minute, and describes how fast something rotates.

Mass (measured in grams or kilograms) is the amount of 'stuff' in an object. An object with more mass will be heavier and take more force to accelerate at a given rate (see newton's second law).

Acceleration is a change in velocity, typically measured in meters per second per second. If my car is going from 0 mph to 60 mph in 6 seconds it is accelerating at a rate of 10 mph per second.

Basic physics: Newton's three laws

Newton's three laws of motion are the core tenets of Newtonian physics.

They can be summed up by the following.

1. An object in motion will remain in motion and an object at rest will remain at rest unless acted upon by an outside force.

2. $F=MA$

3. Every action has an equal and opposite reaction

Good? Good. Let's move on to momentum.

Just kidding.

Basic physics: Newton's three laws: Newton's first law

Newton's first law is quite simple in practice. What it means is that an object that is moving will stay moving, forever, unless some force stops it – and conversely that an object at rest will stay at rest, forever, until something makes it move by applying a force to it.

We almost never see the first law in action because everything on Earth has two prominent external forces: air resistance and gravity. Throw a ball high into the air and it won't keep going at the same speed. It will come back, because gravity pulls it back.

In space, though, Newton's first law is painfully apparent. Spacecraft only fire their thrusters to change direction or speed; turn off all the engines, and your spacecraft will keep drifting forever at the same speed – until it encounters a planet or is stopped by the tiny force of solar radiation.

Cmon, GDC. I want a space game already.

Basic physics: Newton's three laws : Newton's second law

Newton's second law, $F=MA$, is in words Force equals Mass times Acceleration.

A correspondingly larger mass will take a larger force to achieve a given acceleration.

The best example of this is gravity. The acceleration of gravity is a constant – drop a feather and a bowling ball and, neglecting air resistance, they will hit the ground at the same time. (Youtube it if you don't believe me.)

An object with more mass weighs more- gravity pulls on it with correspondingly more force

To test $F=MA$, use a small piece of surgical tube (which will apply the same force to both) to shoot a penny. Then use it to shoot a bowling ball. See which goes faster. I am not responsible for any crushed toes.

Basic physics: Newton's three laws : Newton's third law

Newton's third law states that every action has an equal and opposite reaction.

To experience Newton's third law, I personally recommend sitting in a rolling chair and throwing something heavy, like a battery (really don't , it will spill.)

You will roll backward slowly. This is because just as you push on the battery to send it flying, the battery pushes on you.

Rockets use this principle to fly. They send out exhaust at high speed , and the reaction causes them to fly upward.

Why do you move slower than the battery? This is due to a principle called conservation of momentum, which we will cover in the next slide.

Basic physics: Momentum

Momentum is a vector that is equal to mass times velocity.

The important thing to remember about momentum is that it is conserved.

$$MV + mv = mv(\text{final}) + MV(\text{final})$$

(where m is mass, and v is velocity)

If a large, heavy frc robot throws a tiny, light minibot out of it, we can solve the conservation of momentum problem by knowing that

$$m(\text{robot})v(\text{robot initial}) + m(\text{minibot})v(\text{minibot initial}) = m(\text{robot})v(\text{robot final}) + m(\text{minibot})v(\text{minibot final})$$

Since the initial velocities are 0, we can find that the final momentum of the robot is equal to the negative of the final momentum of the robot.

Materials and Making: An overview

This is going to be a long section, covering most of the mechanical best practices and making processes I've learned about over my four years with Huskie robotics.

As a general rule, what you and your team are able to make is limited first by your knowledge and second by your available tools. Especially with the proliferation of cheap, predrilled aluminum tube such as vexpro versachassis, a skilled team can construct a competent robot using nothing more than a bandsaw and drill press. My favorite example of this is FRC 2169, King Tec , who builds absolutely legendary robots every year using nothing more than a bandsaw and drill press.

Materials and Making: Tools: A drill press

A drill press is one of the most essential tools in the arsenal of any FRC team. Along with a center punch, a drill press allows one to place round holes accurately in virtually any material.

Some tips to remember while using a drill press:

1. If cutting metal, use lubrication and go slowly.
2. Always clamp the piece you are working on to the press
3. Always use a centering punch to locate the hole before you drill
4. For very accurate holes in metal, start with a very small pilot bit and work your way up to the full size.
5. To very accurately locate holes, print out a 1 to 1 CAD drawing with center marks.

If your drill press is a larger, heavier variety, you can use it with a boring bar set to cut holes of any size.

Cheaper drill presses can be purchased for anywhere between fifty and two hundred dollars.



Materials and Making: Tools: A Bandsaw

A Bandsaw is the other tool that I'd say every FRC team should have access to. Capable of making straight(with a guide) and freeform cuts in aluminum or wood , a band saw allows teams to shape sheet metal and cut tube.

When using a band saw, remember :

1. Don't put sideways force on the blade.
2. Really, don't. It will break.
3. Go slowly! Don't bind the blade.
4. When cutting a round profile, use relief cuts (like below) to take stress off of the blade.

A decent bandsaw will cost somewhere around \$150- \$200.



Materials and Making: Tools: A Miter saw



A miter saw is a chopsaw that can change angle. Our team uses miter saws exclusively to cut aluminum square tube.

It's worth noting that you cannot cut very short lengths of thin tube easily on a miter saw – the saw tends to tear the tube up.

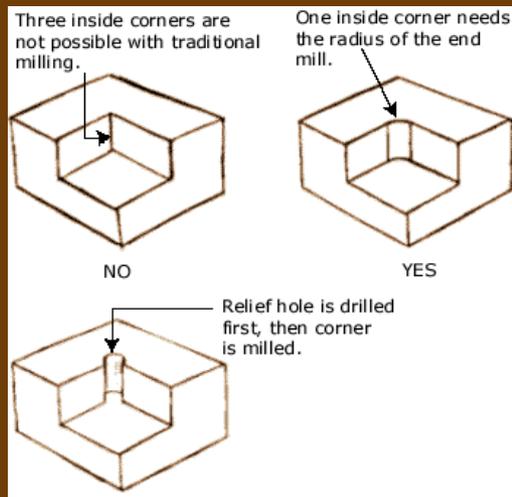
Whenever you are cutting anything on any saw, remember to account for the kerf- the width of the blade- while measuring for your cuts.

A cheap miter saw will run you a couple hundred dollars.

Materials and Making: Tools: A Milling machine

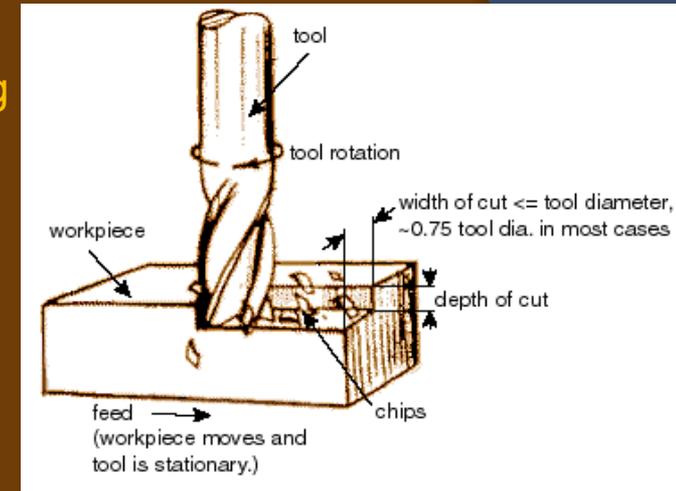
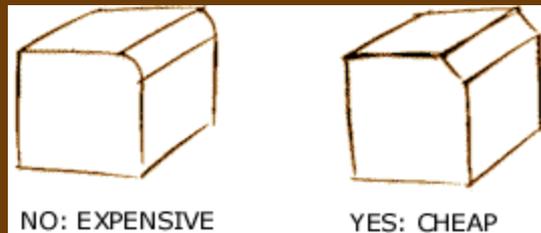
A Milling machine can be thought of as a drill press with a very precise moving table underneath it. Capable of precisely placing holes, shaping parts and cutting grooves, a milling machine is the next logical tool to buy for a team that owns a drill press and band saw.

Milled inside corners will always have a radius equal to that of the mill bit.



Materials and Making: Tools: A Milling machine

It's important to remember that a manual milling machine can do straight lines, but not curves (at least, not easily) .



A manual mill is (when operated by barely trained FRC students) a 2.5 axis machine. This means that it can cut in 2 axes where each feature (hole, groove, or cutout) has a certain depth.

I won't cover the specifics of how to use a mill here , because it should really be taught by a professional machinist. However, I will say that when designing milled parts it is essential to picture yourself as the machinist attempting to make the part.

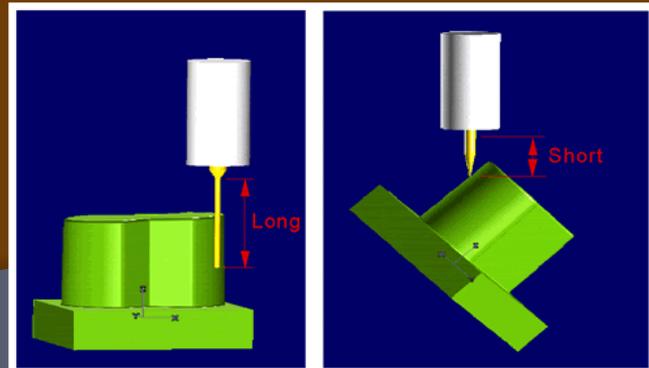
If you don't know how to make it, you shouldn't try to design it. If your team is purchasing a mill and you'd like practice designing parts for it, shoot me an email. A very cheap mill and basic tooling will run around \$2500

Materials and Making: Tools: CNC milling machines

CNC milling machines are computer – controlled milling machines. A CNC machine takes in Gcode, a type of machine code generated by software called CAM software. The CAM software typically reads CAD files and generates the path that the tool will take.

CNC milling machines come primarily in two varieties – three and five axis machining centers. In Three axis machining, the tool always descends into the part from one direction – the top. However, the tool can cut sloped features (as opposed to a 2.5 axis machine) In a five axis machine, the part can be rotated relative to the bit (or the bit angled relative to the part) to allow you to cut virtually any shape.

CNC machines can easily cut curves, but CNC mills are still limited by the inside-corner radius rule.



Materials and Making: Tools: CNC routers

While CNC milling machines are typically too expensive for teams to own (and are therefore generally owned by sponsors who give teams access) , CNC routers are a similar type of machine that can be purchased for under a thousand dollars.

CNC routers are effectively lightweight 3 axis CNC mills. They are capable of cutting wood, plastic, and aluminum (although aluminum cutting on a CNC router will be slow).

I personally recommend the shapeoko 2 hobby router as a good entry point into computer-guided cutting. It costs \$700.

Larger , table sized CNC routers can easily cost a few thousand dollars or more.

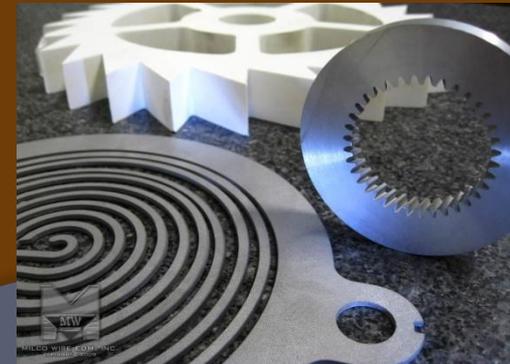
Materials and Making: Tools: Waterjets , Wire EDMs, and Laser cutters

Waterjets , Wire EDMs, and Laser cutters are typically computer-guided 2 axis machines, meaning that they can cut any 2-axis pattern but have to cut all the way through a given part .

FRC teams will typically use waterjet cutting, Wire EDM cutting and laser cutting to cut sheet metal , sprockets, or gears. For more on sheet metal techniques, see the sheet metal section below.

It's important to remember that waterjets will leave a kerf – an extra, fuzzy edge of roughly 5 thousandths of an inch - on any part. For parts that have other parts pressed in, oversizing holes by that much is essential.

If you need the hole size to be really precise, waterjet a small pilot hole to make sure the hole is in the right place and drill it out manually.



Materials and Making: Tools: Lathes

A lathe spins a part very fast and uses a stationary bit to cut it. It is excellent when things are radically symmetric. In FRC we will most often use lathes to cut grooves in shafts (for example, for shaft clips or collars) or round out hex shafts to put them through bearings. A small lathe can be around \$800.



Materials and making: Where to buy things

Mcmaster Carr and Grainger are fantastic for buying industrial hardware, tools, and stock metal – although McMaster is quite pricey.

For cheap tools, Harbor Freight is fantastic.

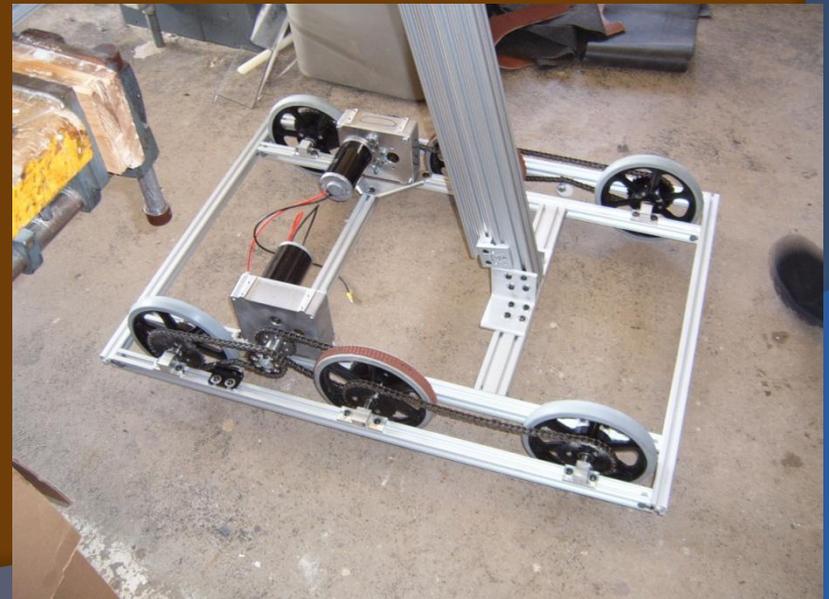
I can't recommend VexPro VersaChassis tube more to make lightweight structures. Just remember that the 1*1 extrusion is very, very thin – suitable for superstructures, but generally not for unprotected appendages or for a robot chassis. For those, use the 2*1 tube, which has thicker walls.

Materials and Making: 80/20

80/20 Aluminum extrusion is like an industrial erector set. It allows you to prototype very quickly and is flexible. It uses what are called t-nuts, meaning that you do not need to drill to bolt things to 80/20. Remember when using 80/20 to locktite everything! 80/20 always vibrates loose.

In my opinion , 80/20 has been made obsolete for most structural roles by versachassis tube, which is lighter.

You can , however, purchase linear slides for 80/20, making it very good for cheap arms. 1*1 inch 80/20 is plenty strong for most FRC applications. McMaster carr and amazon sell 80/20.



Materials and making: Tapping

Tapping is the mystical process of cutting threads inside holes so that you can insert a screw.

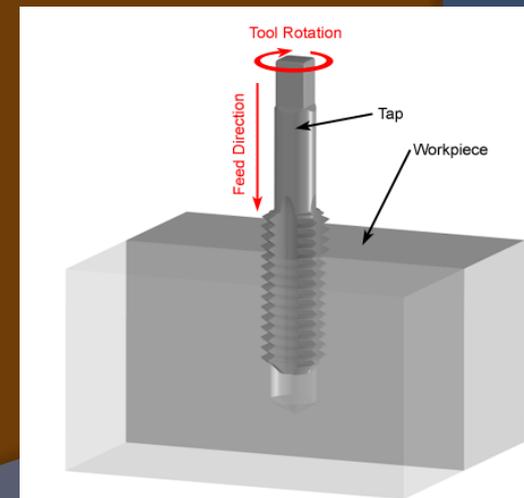
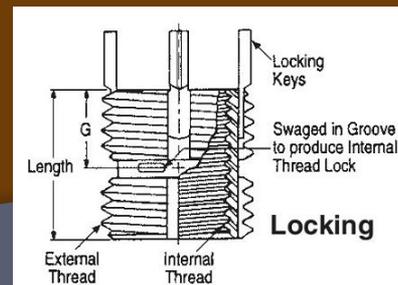
It's not really mystical ; I just find it really cool. The key thing to remember when tapping a hole is that a tap is about as brittle as glass. Go slowly, make sure the tap is perpendicular to the workpiece, and use lubricant.

Every turn or so in aluminum you should back up a half turn to break the chips that accumulate in the tap.

Again, be gentle. Breaking a tap makes for a bad day because removing them can be near impossible. I once nearly ruined a two thousand dollar space grade part by breaking a tap in it.

To remove a broken tap, I recommend heating the part if it is aluminum (the tap will expand slower than the metal around it) and using pliers, or drilling the hole out larger and then using an insert.

Aluminum threads are sticky and can cold-weld to screws, ruining the hole.. To remedy this, we use steel inserts called keylocking inserts to make permanent threads in aluminum. They thread into large aluminum threads once and then are locked in with a hammer. You can buy them from McMaster Carr.



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Materials and Making: Materials

The most commonly used metals in FRC are aluminum and steel. Aluminum is excellent for structural parts while steel's strength is often necessary for shafts, gears, and sprockets.

Metals come in different alloys and tempers with different characteristics. For example, aluminum 7075 is hard and brittle while 5052 is fairly soft.

The other materials that are common in FRC are plastics.

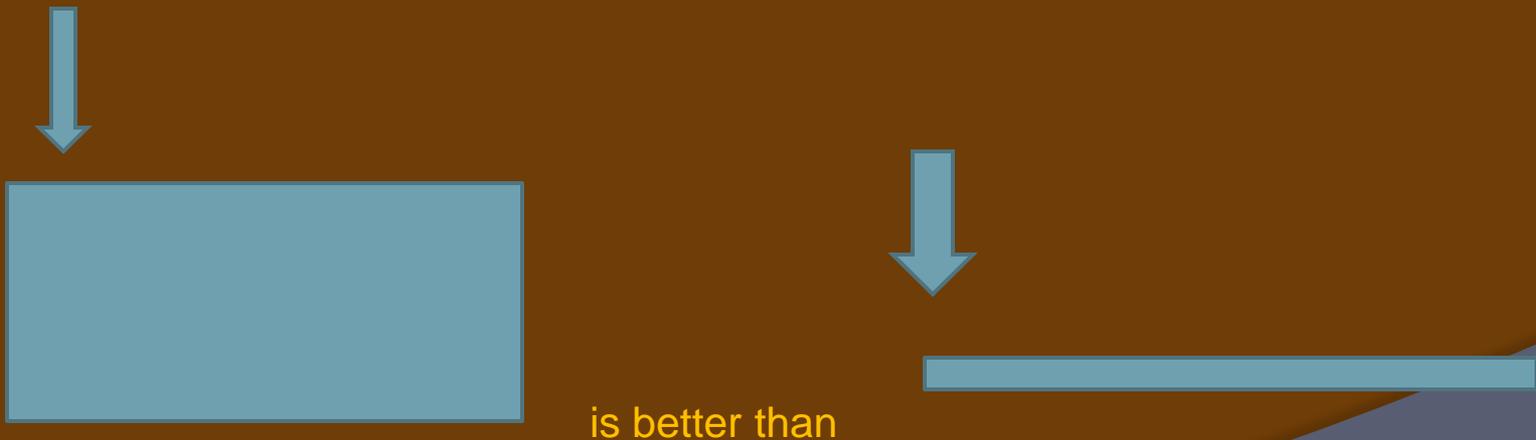
Polycarbonate (also called lexan) is excellent because it is capable of flexing enormous amounts under load. Our team likes to use polycarbonate to support our appendages, allowing them to take hard hits and simply flex away. We also always use polycarbonate boards to mount our electronics. Polycarbonate can be bent quite easily with a heat gun.

HDPE or high density polyethylene is a dense plastic that is often used because it is very easy to machine and quite rigid.

Materials and Making: Best practices: Sheets, flanges, and tubes

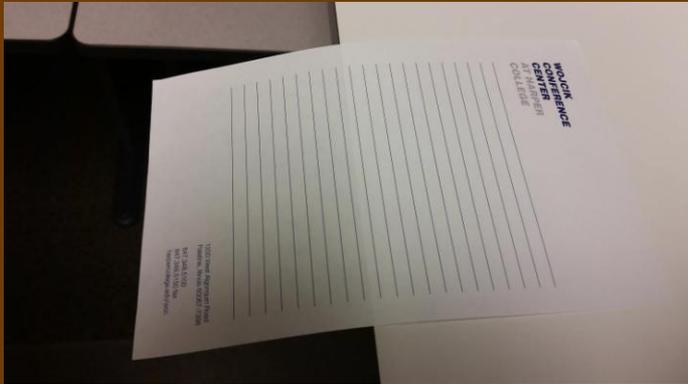
One of the most important mechanical concepts that I can teach you is that materials respond to force relative to the cross sectional area they present in the plane of the force.

This is a very complex way of saying that for the same sheet of any material oriented 2 ways and loaded by the arrow:



Materials and Making: Best practices: Sheets, flanges, and tubes

To demonstrate this, take a sheet of paper, hold half of it on a table, and try to bend it over the edge of the table. It probably bent under its own weight!



Now fold the paper along the center so that it is two halves perpendicular to each other.

Same paper, much stronger.

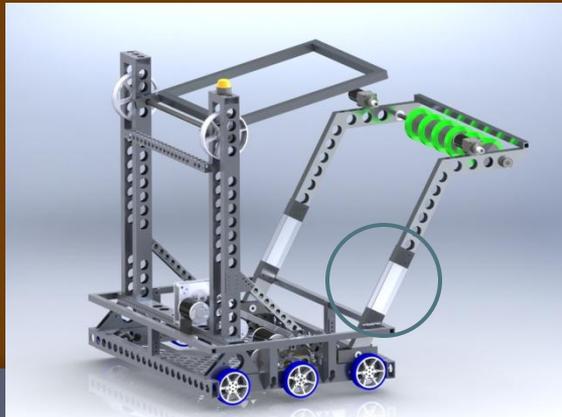


Materials and Making: Best practices: Sheets, flanges, and tubes

This is why when we do use sheet metal in FRC, we always fold it so that there is a large amount of cross-sectional area in plane with the forces.

It is also what makes tubes, C-Channel, and angle aluminum so strong. *When designing the frame for your robot, use tube (or sheet metal that is folded into Cs).*

This is also how you make a flexible appendage. This gorgeous collector on 2175's 2014 robot has polycarbonate sheets (circled) that are strong when supporting the arm up and down but flex when the arm is hit from the side.

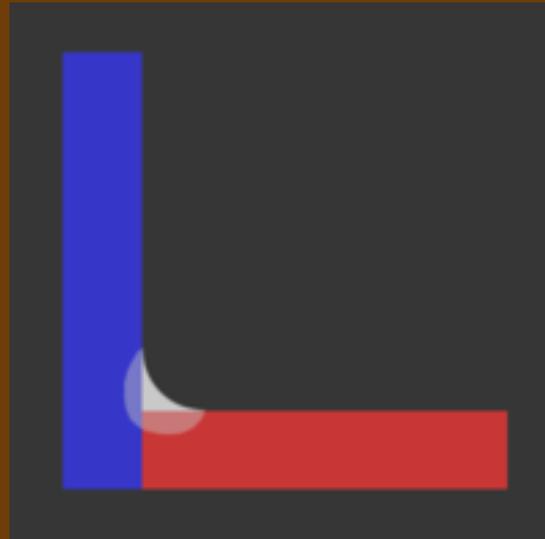


Materials and Making: Best practices: Filleting

Fillets are rounded edges on parts. For the inside corner of a load bearing part, it is vital that you include a fillet. Sharp corners are what we call stress concentrators- they serve as failure points when the part experiences load.

In our 2013 season, before we learned to FILLET EVERYTHING, 3061 had two separate parts fail on sharp corners.

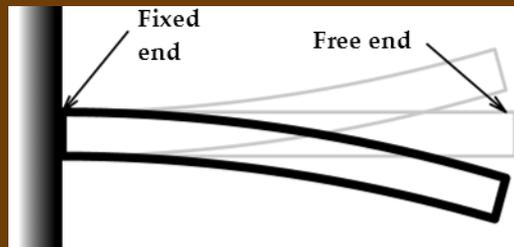
This entire slide can be summed up by FILLET EVERYTHING. Avoid sharp interior corners.



Materials and Making: Best practices: Avoiding the death cantilever

There is one single mechanical problem that has ended one 3061 season, scrapped one subsystem , and generally annoyed the living hell out of the entire team. It's called the cantilevered shaft. And you'd think that by now we know how to avoid them.

A cantilevered shaft is a shaft that is supported on one end and loaded on another.



I say “shaft” and not beam here because 3061 has a tendency to do this to rotating shafts. **SUPPORT THE OTHER END OF EVERY MOTOR SHAFT.**

For motors under very light cantilever loads (like drive motors in gearboxes or motors driving intake rollers) , supporting the other end is not necessary. Do yourself a favor, however, and solve the sum of torques problem involving the two bearings in the motor to check the loads they will experience.

Materials and Making: Best practices: Avoiding the death cantilever

For other live (rotating) shafts that are not motor shafts, solve the sum of torques and sum of forces problem on the shaft to calculate the forces on the bearings** in the shafts. Compare that to $\frac{1}{2}$ the dynamic load of the bearing. If it is greater, support the other end.

Remember that turning a sprocket results in a linear force on the end of a shaft equal to the chain tension. This can be calculated by dividing the max torque the shaft will output by the pitch diameter of the sprocket.

If you don't want to do this math, just support both ends of every shaft*. In the long run, it will be for the best. Some shafts can get away unsupported but the risk is often quite high.

*In a West Coast Drive (see later) , the wheels are cantilevered. This normally gives trained engineers heart attacks but will save weight all over the place, so there – and only there- are cantilevered shafts okay in my books.

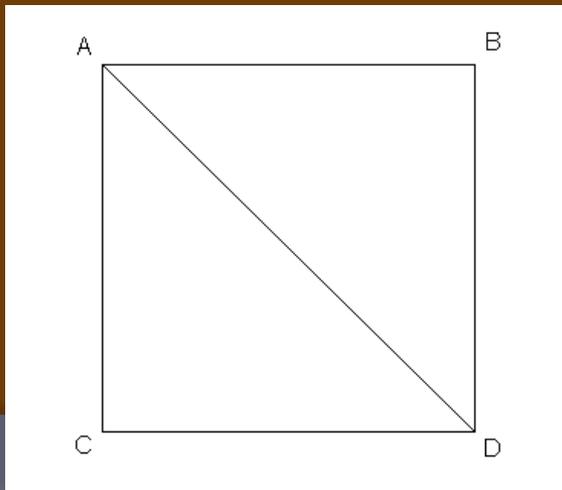
**Covered later

Materials and Making: Best practices: Lightweighting

Want to improve the rigidity of a square frame without making the whole thing too much heavier?

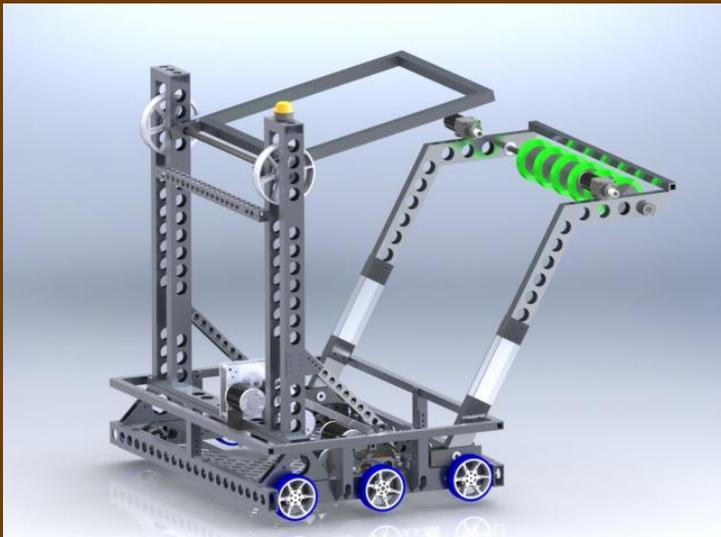
The best way to do this is by using a diagonal. When a square frame tries to deform, it stretches one diagonal and compresses another. Because metal is very strong under tensile loads (when being stretched), effective reinforcing while maintaining a light weight involves stretching either a cable or metal rod across a square frame.

When using cabling, use a turnbuckle to make the cable tight.



Materials and Making: Best practices: Lightweighting

If your part is too heavy and you want to remove weight while keeping things strong, remove weight from the plane which will experience very few loads. See the lightweighting on this 2175 bot(all the round holes) ?



This robot is designed to be very strong side to side, but is lightweighted in the up/down and front/back directions. This is normally a good practice with 2*1 square tube.

Materials and making: Press fits

When you need one part (say, a shaft or bearing) to press into a hole in another (say, a gear or tube), it is best to use a boring bar in a drill press or mill to size the fit exactly to that the bearing or shaft presses in to the desired firmness. The way to do this is simple : Bore out a hole of the supposed diameter of the bearing or shaft minus five thousandths and increase on thousandth of an inch at a time , testing the fit, until the part fits as desired.

In order to do this you will need a boring head and bar, which allows you to make any size hole.

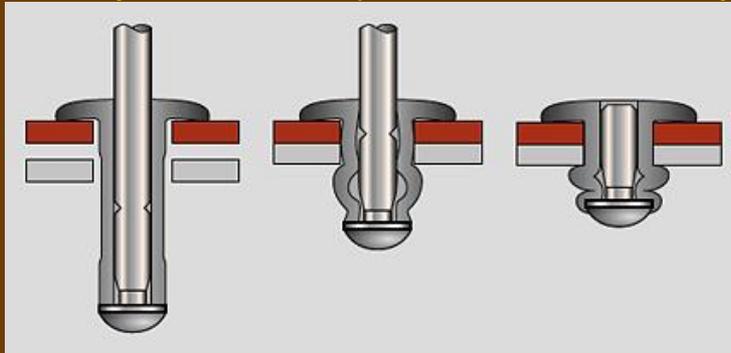
Failing to do this will result in parts that, once pressed in, can never be removed- or parts that slip right out.



Materials and Making: Fastening

There are three commonly used types of fasteners in FRC: Rivets, Bolts, and Welds.

This is what a rivet looks like as a cross section, first just inserted and then once clamped down : (The red and white parts are the plates being joined)



Parts that are riveted together are very stiff; rivets do not vibrate loose or flex much. However, rivets are generally weak – you need many of them. They also must be drilled out to be removed and can only bind together thin plates.

Most FRC teams use aluminum or steel pop rivets, which can be applied using a manual rivet gun.

Materials and Making: Fastening

Bolts, or cap screws, are an excellent all-around fastener. When using bolts it is important to remember that

1. Bolts can exert significant force – enough to crush tube. Use hardened washers and use a torque wrench to avoid crushing tube.
2. Standardized bolt sizes are a good idea. Our team uses ¼-20 bolts for major structural parts and #6 bolts for other parts and panels.
3. Bolts can and do vibrate loose. Use locktite blue on every bolt on your robot, or use nylock nuts. Remember that nylock nuts are one-use ; once they are removed once they must be replaced or they will not lock as well.
4. Always use washers
5. Bolts don't hold parts together. The friction created by bolts clamping parts together holds them. Bolts always need to be tight.

Materials and Making: Fastening

Welding is the art of using heat to physically join two pieces of metal. You cannot weld together dissimilar metals. (Welding steel to aluminum, for example, is not feasible).

One thing to keep in mind is that the heat of welding significantly weakens the surrounding metal. While welds are very rigid, they can serve as failure points.

(Photocred to FRC 706)



Things that spin : An overview

In this section, we'll deal with motors and power transmission; basically, everything involved in having a spinning shaft on your robot not fail. We'll also deal with how to calculate what reduction and gear ratio you need to make a given mechanism work .

Things that Spin: Bearings

A bearing is how you mount a spinning shaft to a static body, or a moving object to a static shaft. Designed to allow the “inner race” (inner ring) of the bearing to rotate freely relative to the outside (or outer race) under high loads, ball bearings aren’t very good at taking loads perpendicular to their face; for this, use thrust bearings, which instead of having an inner race and outer race have a top and bottom that spin independently (like a turntable).

Typically to mount a bearing, one will use a flanged bearing and press it into a hole on a part.

Bearings are available that are broached from hex shafts; they are specialty items available from Andymark or vexpro.



Things that Spin: Retaining a shaft

Ok, great. So you've got a shaft through 2 bearings now. How do you keep it from sliding out?

Answer: Shaft collars or, if you have a lathe, shaft clips. These can be purchased from mcmaster – carr. Shaft collars sit on the shaft and shaft clips sit in a groove turned into the shaft.

To keep things from sliding around on an already retained shaft, use shaft collars or spacers.

Things that Spin: Motors

As of 2014, teams have a massive amount of options to use for motors. Here's we'll examine most of them

1. CIM (Minicim, BAG motor):

A CIM motor is the heaviest duty motor available to an FRC team. Capable of producing massive amounts of torque and withstanding long runtimes, CIM motors are ideal for drivetrains or powerful wheeled shooters. As of 2013 the MiniCIM was made available, with 2/3rds the power at the same RPM as a CIM. (Allowing one to hook a CIM and a Minicim into the same gearbox)

As of 2013, the BAG motor was also introduced as a “micro-CIM”. BAG motors with planetary gearboxes attached are excellent for intake rollers, but they do have a reputation of burning out when high torque is applied for long periods of time.



Things that Spin: Motors

Also available to FRC teams as of 2014 are the BaneBots rs-775 and rs-550, and the Andymark 9015 motors. All these motors are excellent for medium to heavy duty applications, such as moving arms or powering wheeled shooters – or even augmenting drivetrain motors when properly reduced.

These motors have very high RPMs and will typically be used with a planetary gearbox.

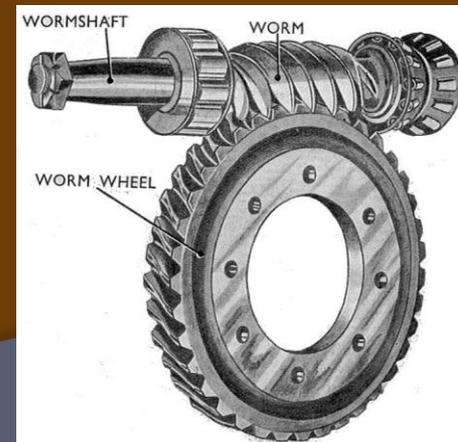
It's worth knowing that in my experience BaneBots can take weeks to ship things to FRC teams. If you don't have it on hand, you may not get it in time.



Things that Spin: Motors

The last motor option that I'm going to talk about here is a window motor. Window motors are excellent for light duty applications where something will need to be held in place, such as light arms or leadscrew shooter aiming mechanisms. They have a worm gear reduction built in, which means that they cannot be backdriven except by extreme loads. (grabbing the shaft of the motor and trying to turn it manually is impossible)

It's worth noting that window motors are a pain to mount and to interface to. Always try to support the other end of a window motor shaft. Window motors are available in both "left handed" and "right handed" versions which are different to mount; make sure you design for the version you own.



Things that Spin: Keys and Hexes

If one has a spinning shaft and wants a wheel, gear, or arm to spin when that shaft spins, there are two ways to transmit torque from the shaft to the wheel.

The first is having a small groove in the shaft and wheel/gear/arm called a keyway. You insert a small piece of metal called a key into the groove on shaft and then put the wheel or gear on, and the key transmits the torque.



Keys kind of suck, though. They can fall out, get shorn off, and basically fail in a dozen different ways. If you can avoid using a keyway, do so and use....

Things that Spin: Keys and Hexes

A hex shaft! Hex shafts have a hexagonal profile that, when pressed into a hexagonal hole, can also transmit torque. With hex shafts, one no longer has to worry about fiddly little keys.

Hex shafts are the bomb, but they come with some caveats. Make sure you have plenty of hex bearings on hand, because they tend to go out of stock during the season from everywhere but mcmaster-carr, where they cost \$20 apiece.

Making spacers to go on hex shafts can be painful. Vexpro manufactures cut-to length spacers for a dollar apiece.



Things that Spin: Gears

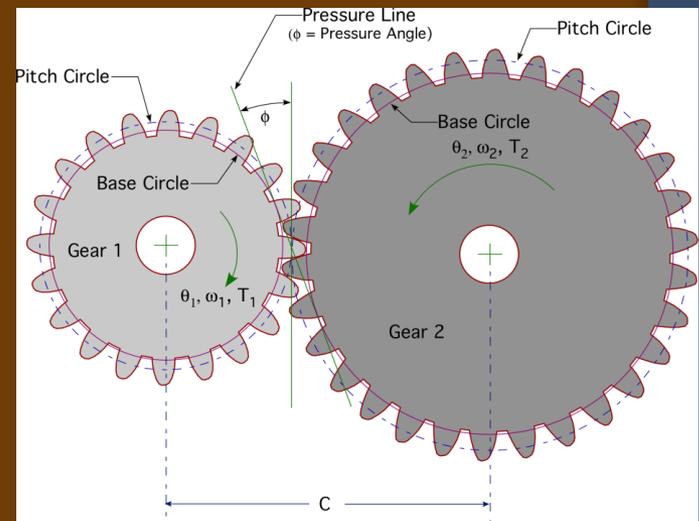
Gears are one way to achieve a reduction while transmitting torque from one shaft to another. A gear ratio is, like the ratio of two sprockets or pulleys, defined by the number of teeth on the driving gear divided by the number of teeth on the driven gear. Gears can be purchased from andymark, vexpro, and SDP-SI.

For example, if I have a gear with 12 teeth driving a gear with 24 teeth, the ratio will be $\frac{1}{2}$.

For that ratio:

If my driving shaft RPM is 5000, my driven shaft RPM will be 2500. If my driving shaft torque is 12 N*M, my driven shaft torque will be 24 N*M. In this way we can use gears to increase or decrease our RPM and available torque.

An increase in RPM always corresponds to a decrease in available torque and vice versa. To calculate exactly the current draw of motors and the output speed with different gear ratios, use the JVN mechanical design spreadsheet.



Things that Spin :Gearboxes

Most motors in FRC spin at 5,000 to 14,000 RPM. What do we do when we want something to spin at 100 RPM? We could build our entire robot out of gears, or use a compact, prebuilt gearbox. Gearboxes are ways of achieving a good reduction in a low space and weight package.

There are a few common types of gearboxes in FRC. Planetary gearboxes, like the one pictured, typically attach to the front of a single motor. They are an excellent way of achieving extremely high reductions efficiently , and can also do low reductions.

There are also worm gearboxes, which are ideal for lightweight arms, and gearboxes that are made specifically for drive trains.



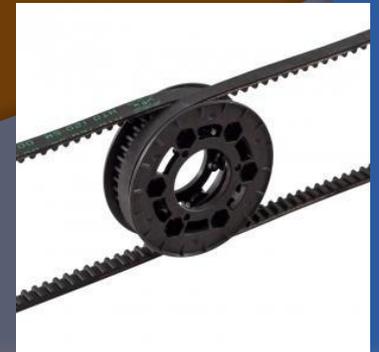
Things that Spin: Belts and chains

Belts and chains are how one transmits torque between two shafts that are farther apart than a few inches.

In FRC we use HTD timing belts, which can be purchased from Vexpro and SDP- SI. Pulleys can also be purchased from these sources.

Pulleys with different amounts of teeth will result in a reduction just like gears.

Use the West Coast Product belt length calculator to calculate the spacing of two shafts when using belts. If the spacing is not exact, the belt will fail or slip. Belts are lighter than chain but require more precision. If you can't be precise enough, you can use an adjustable idler pulley to introduce tension into the belt or make the shaft locations adjustable.



Things that Spin: Belts and chains

Chains are a slightly heavier, if more forgiving of design failure, method of transmitting torque across distances. In FRC we typically use ANSI-35 chain for large arms and ANSI-25 chain for everything else.

Chain must be broken to length with a chain breaking tool and then refastened with a master link. Once a (non-master) link of chain is broken it cannot be refastened without a master link.

While chain can run while a little loose, I recommend that you use a floating idler from mcmaster-carr to keep it from slipping.

In the drivetrain section we'll cover a few ways of tensioning both belt and chain.



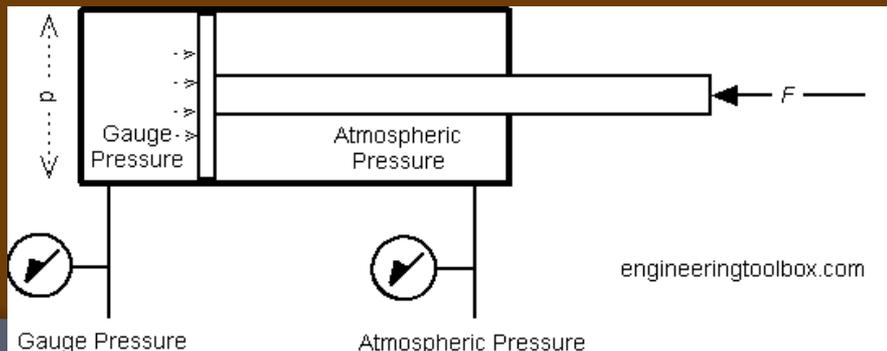
Pneumatics: Overview

Pneumatics are the other method of actuating things in FRC.

Pneumatics rely on compressed air; unless you know for a fact you will only be actuating a given cylinder a few times, you should have an onboard compressor to replenish your tanked air. You can calculate the force a pneumatic cylinder will output by multiplying the working pressure (60 psi as of 2014) by the area of the cylinder ($\text{radius}^2 \cdot \pi$)

Pneumatic cylinders are linear actuators. They extend and contract when air from a solenoid is applied to them. The important thing to remember is that pneumatic cylinder will bend and fail under side loading. All load applied should be parallel to the shaft.

In this part of the guide I'll cover how to use pneumatics in your mechanisms; in another part of the guide I'll talk about plumbing them.



Pneumatics :Cylinder mounting

You want to use a cylinder on your robot, but how do you mount it? There are two common cylinder mounting options: Clevis pins and foot brackets.

Clevis pins look like this and allow the cylinder to float (to swivel freely).

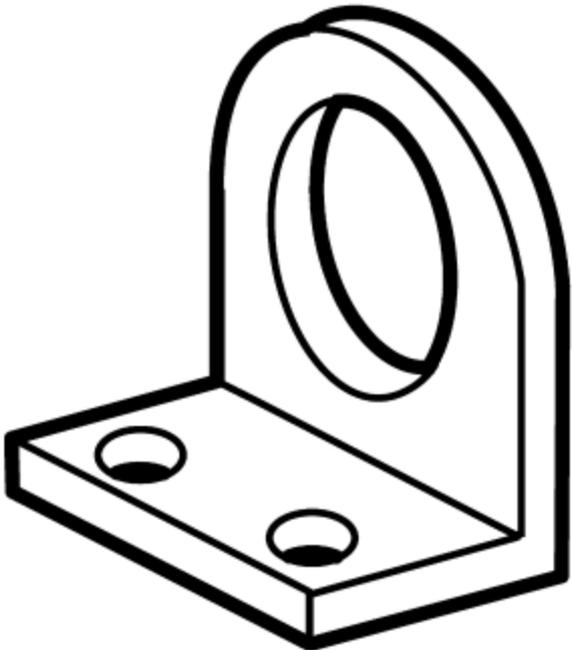
When using pneumatics to achieve a rotary motion (like opening a flap), use a clevis bracket on the back of and on the nose of the cylinder.



Pneumatics :Cylinder mounting

For a cylinder where the part being moved is being moved linearly and the cylinder can stay in the same place, use a foot bracket. A foot bracket is very simple ; the large thread on the front of the cylinder body fits in and you bolt the cylinder on.

When using a foot bracket, it can be advantageous to also support the back of the cylinder using a clevis bracket for a more solid mount.



Mechanisms! : Overview

Now you know the basics of mechanical design. Great. Now it's time to learn about mechanisms that appear commonly in FRC and common pitfalls to avoid while designing them.

This will be broken down into three sections: Drivetrains, Shooters, Arms, and Intakes .

I'm good at counting.

After we're done here we'll take everything we've learned and walk you through the creation of the 'ultimate' drivetrain.

Mechanisms: Drivetrains: Overview

A drivetrain is how an FRC robot gets about. Every year so far, FRC robots have used wheels, so drivetrains are often ongoing development projects for teams.

Here we'll cover some basic types of drivetrains and their advantages and disadvantages. There is no best type of drivetrain – some teams find that with their resources there is one type that they prefer – and, of course, what drivetrain you use is highly game-dependent.

Mechanisms: Drivetrains: Speeds

Before we get into the specific types of drivetrains, let's talk about something a lot of FRC teams don't know about their robots: Speed.

When you design a drivetrain, you design it for a specific speed (or 2 speeds if you have shifters), typically calculated in feet per second. Use JVN's mechanical design calculator to figure out what gearboxes to buy.

With a full weight robot and a 4 cim drive, avoid going faster than 14 feet per second (in order to be able to go to full speed).

With a full weight robot and a 6 cim drive, I'd personally avoid going faster than 16-17 feet per second. Anything faster and pushing matches will blow your main breaker of the robot.

Realistically, an FRC robot should never need to go faster than 15 feet per second, unless they have a magic (well practiced) driver like 254. Faster than 15 feet per second robots get impossible to control unless an alternate control scheme like kaj (split-arcade/halo) drive is used.

Mechanisms: Drivetrains: The art of pushing

Okay. Now we know how fast to go. What about how slow? Some teams will tell you that, if you have a 2 speed drive and a dedicated pushing speed, that speed should be as low as possible.

This is a common misconception, but it is false. Team 3061 has not been outpushed since 2012. How?

We understand one thing:

Below a certain speed you will spin your own wheels. Friction (or traction) is determined by multiplying a coefficient of friction (a constant for the material that interestingly enough does not significantly increase with area unless using a paction-type tread) by the weight of the robot. If the wheel is slipping relative to the ground, the coefficient of friction is much, much less than if it is stable relative to the ground. This is why cars have antilock braking.

Most robots with powerful drivetrains will spin their own wheels and be “traction limited”, meaning that the speed of the drivetrain – and amount of available torque- is irrelevant lower than around 6-7 feet per second.

To really win pushing matches, implement traction control to check if your wheels are spinning using encoders. Otherwise it will come down to the tread material used. Our team uses blue nitrile tread from mcmaster carr, which pushes very well even when our wheels are spinning. Blue nitrile tread interlocks with the carpet, meaning the more you have in contact, the better. It has less traction than paction tread but wears much more slowly.

You can find the coefficient of friction of various treads by googling.

Mechanisms : Drivetrains : Tank

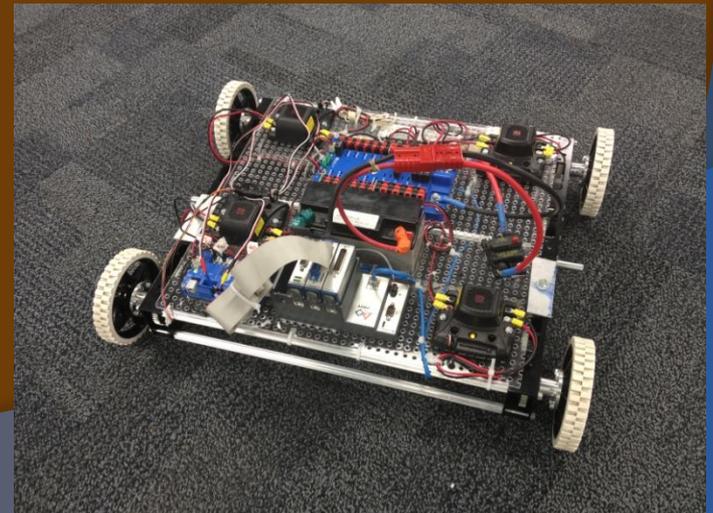
Tank drive is the most basic type of drivetrain in FRC. If your team is a rookie team, use the kit drive. I promise, it will save you time and money and perform better in the long run.

Tank drive is simple: 4, 6, or 8 static wheels where the left and right side of the drivetrain is driven independently. Reversing the left side of the drive while the right side continues forward will cause a left turn, and vice versa.

Turning a tank drives involves dragging the wheels sideways across the ground. The longer the wheelbase of the robot, the harder it is to turn, since torque is force \times perpendicular distance and the distance to the back wheels is longer.

To fix this problem, we use tank drives with 6 and 8 wheels and drop the center 2 (or 4) wheels by .125 inch. This way the robot is as stable as if it had the full length wheelbase, but sits on only 4 wheels that have a shorter wheelbase.

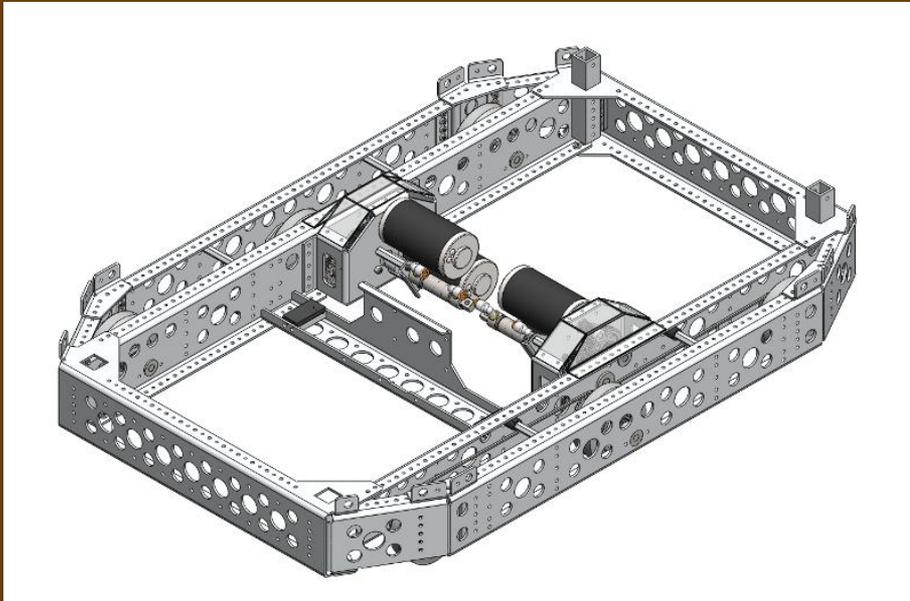
8 wheel drive is generally only advantageous over 6 wheel drive if weight is not an issue and you need a very stable robot platform (6 wheel drive will tip from the back 2 wheels and the middle wheels to the front 2 wheels and the middle wheels).



Mechanisms : Drivetrains: Tank

Most teams that build their own tank drives will use milled square tube to build a west coast drive (right) – a very lightweight tank drive characterized by cantilevered wheels and live axles. Modern WCDs can be made with a drill press and chopsaw. Check out vexpro's versachassis system for more information.

Some teams, like FRC 1114 and 971, use folded sheet metal. If you use folded sheet metal, team 1114's site is a great resource.



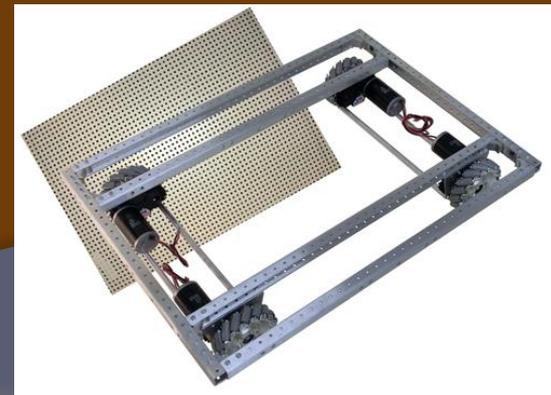
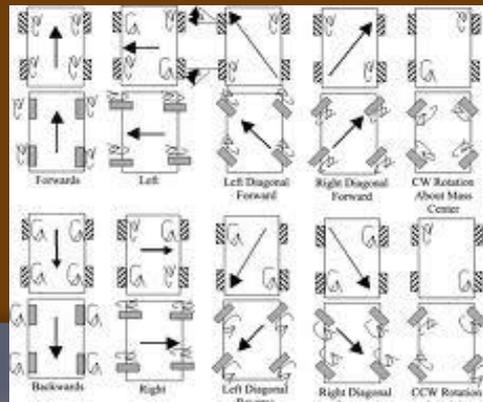
Mechanisms : Drivetrains : Mecanum

Mecanum drive is a relatively simple type of omnidirectional drive. A mecanum robot uses 4 independently driven mecanum wheels. Mecanum wheels have 45 degree rollers that cause the thrust from each wheel to point at a 45 degree angle to the front of the robot. By varying the relative speeds of all 4 wheels the robot can move in any direction.

Mecanum drives generally cannot push because the rollers on their wheels mean that they have much less available torque and a lower coefficient of friction than most tank drives. It's important to note that though mecanum drives are omnidirectional they typically have to be geared too slowly to be truly maneuverable.

Mecanum drives must have slightly flexible frames or wheels; else one wheel could lose contact making the drive uncontrollable.

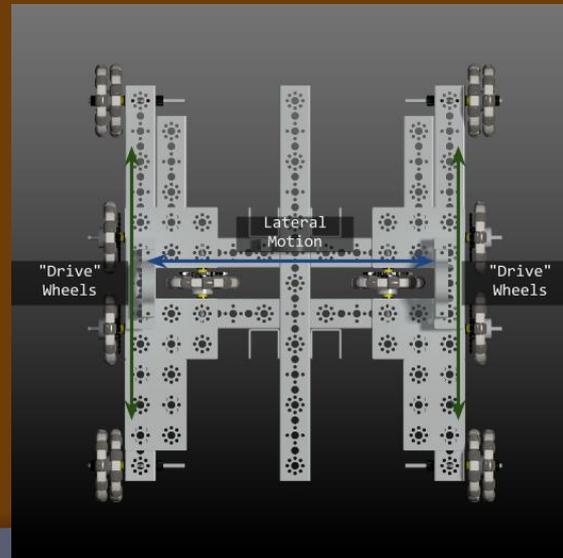
While I've met a few teams (looking at you , knightcrawler) , that had killer mecanum drives, most teams cannot implement these well and would be better served building a tank drive. As of 2014, Mecanum drives have never touched Einstein Field.



Mechanisms : Drivetrains : Omni (Kiwi / Slide)

Omni drivetrains are omnidirectional drivetrains that make use of omni wheels. Omni wheels have rollers embedded around their circumference and therefore offer no resistance to being pushed sideways. By placing these in the corners of a 3 or 4 sided drive, one could theoretically move in any direction. I've never seen this type of drive been effective.

That said, a "slide" drive, where the 4 omni wheels are arranged like tank wheels with one perpendicular wheel in the center to strafe, can often be quite maneuverable though it sacrifices pushing power. The key with a slide drive is to have the perpendicular wheel on a suspension of some sort so it does not lose touch with the ground. Most teams that build slide drives build them as part of a nonadrive (See next page)



Mechanisms: Drivetrains: The Hybrids: Octocanum, Butterfly, and Nonadrive

For some teams, one drivetrain isn't enough. They want more! These teams build hybrid drive trains that pneumatically switch between a tank drive and a more colorful alternative, such as Mecanum (octocanum), 4 Omni wheels (Butterfly) or a Slide drive (Nonadrive). Numerous variations and simplifications exist such as Tex Coast (Grasshopper). These drives are inherently 2 speed and also modular, meaning that part replacements are normally quick.

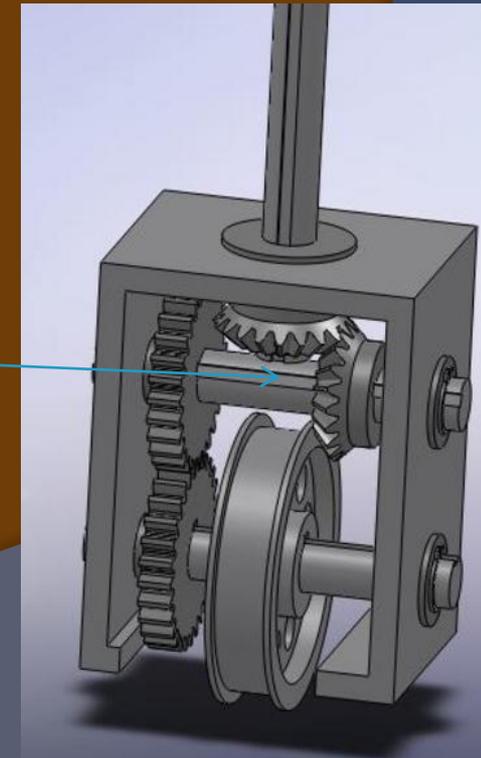


Mechanisms: Drivetrains: Swerve

Swerve is the most difficult type of drive to execute. In a swerve drive, all four wheels are independently swiveled and driven to allow the robot to move in any direction. Other versions where some wheels swiveling and drive gearboxes are linked are normally called crab. Swerve is modular, like most hybrid drivetrains.



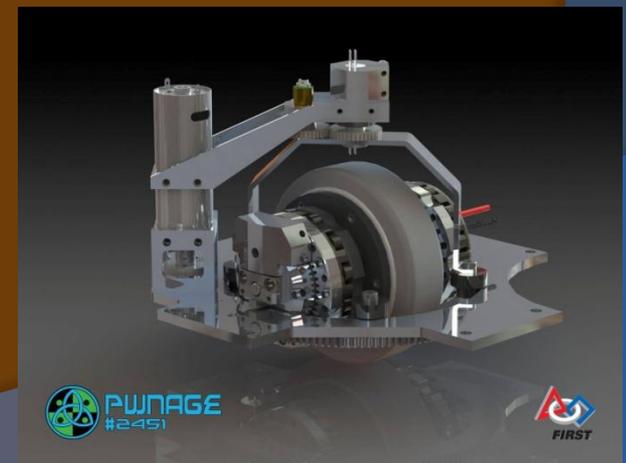
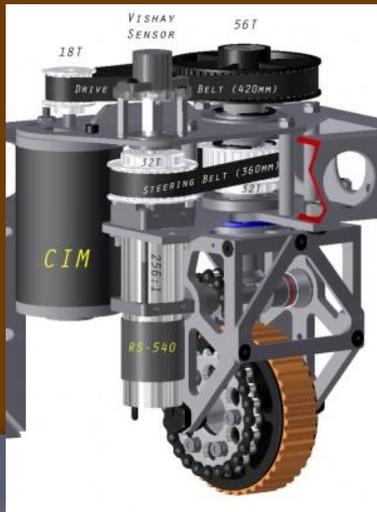
I don't think I've mentioned bevel gears yet. They work at right angles!



Mechanisms: Drivetrains: Swerve

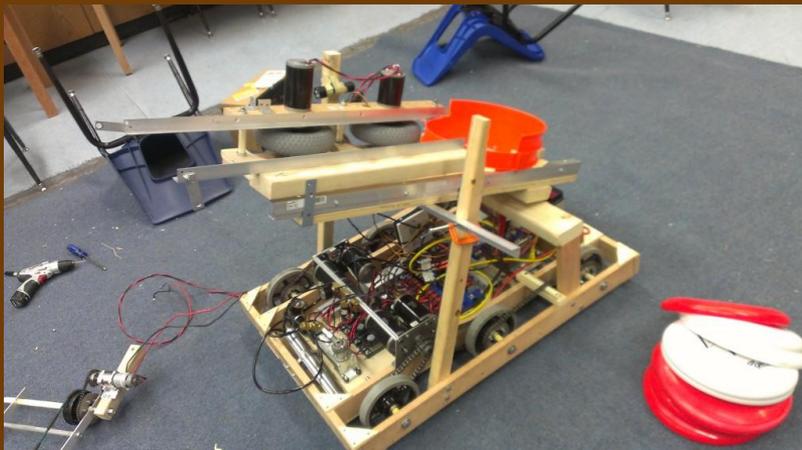
Swerve modules can be sorted into two main types. In a coaxial swerve (on the left) , the power that drives the wheel is sent through a center coaxial shaft (a shaft inside a shaft) which the wheel also swivels about. In a CIM-in wheel, or Midwest, swerve, the wheel rotates using the CIM motor that drives it as an axle, with a homemade bearing around the CIM. (FRC 2451, Pwnage, has much more information on their Midwest swerve if you are interested).

Swerve is typically extremely maneuverable. It can hold a location on the field okay against most robots but typically can't push as well as a heavy tank drive. Swerve drives rely on incredibly agility to get from point A to point B and so-so pushing power to stay at point B.



Mechanisms: Shooters

I classify a shooter as a mechanism designed to project game pieces more than a few inches away from where the game pieces leave the robot with accuracy. There are three types of shooters commonly seen in FRC: Catapults and Wheeled shooters (though, of course, numerous others exist).



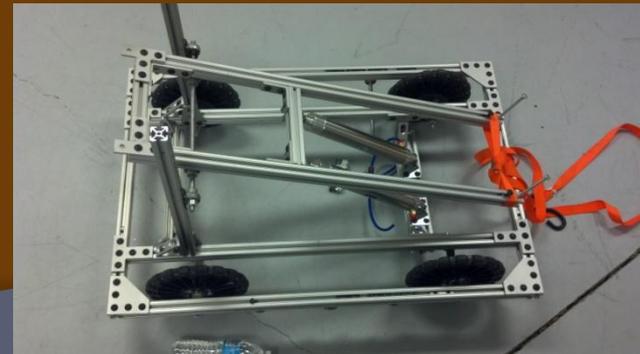
Sidenote: To precisely adjust the angle of a shooter, leadscrew mechanisms hooked up to window motors rule.



Mechanisms: Shooters: Catapults

A catapult uses a long lever arm to throw a projectile. Catapults are normally great when you are moving fairly low numbers of game pieces as they take time to reload after a shot. There are three types of catapults that I often see: Pneumatic , Springloaded, and motor driven.

Pneumatic catapults use air to launch a projectile. The trick with pneumatic catapults is to use a working-pressure air tank. What does this mean? Air cannot flow very quickly through the solenoid valve, so you latch the catapult arm somehow and actuate the solenoid for the firing cylinders, pre-pressurizing the firing cylinders and air tanks that are after the solenoid. Unlatch the arm and air flows directly from the working pressure air tanks to the cylinders, resulting in a fast catapult launch.

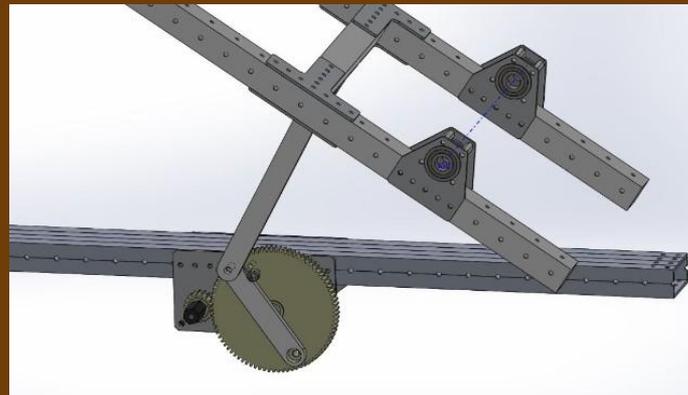
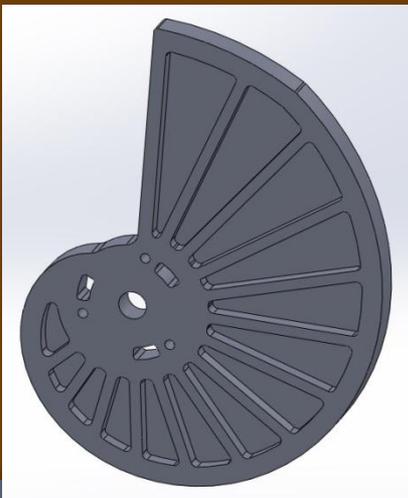


Mechanisms: Shooters: Catapults

A springloaded catapult uses either a cam(left), choo-choo type mechanism (right) , or winch that shifts into neutral to pull on springs that launch the ball. They can be quite powerful and, unlike pneumatic catapults, can reload in just a few seconds.

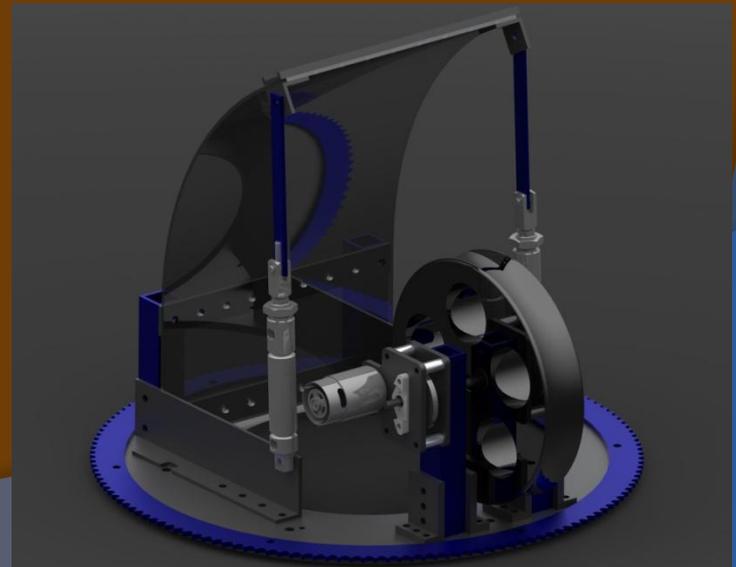
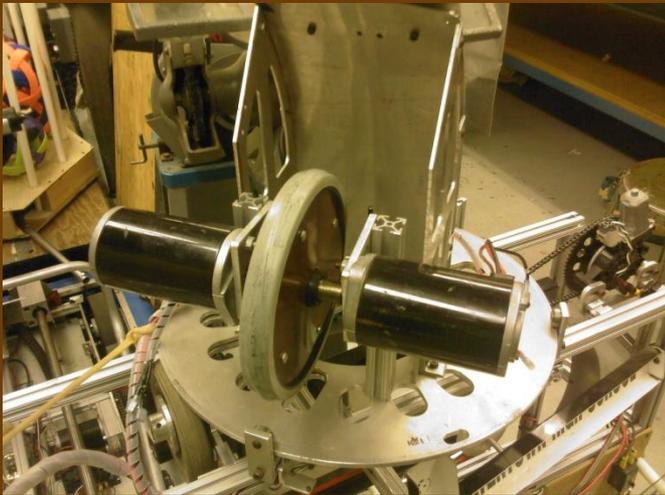
Motor driven catapults are exactly how they sound- a massively reduced motor (typically a CIM or Minicim) which is hooked to the arm. They are great for throwing game pieces just a few feet, but I've never seen one that was very powerful.

For effective examples of catapults, check out the 2014 game, Aerial assist.



Mechanisms: Shooters: Wheeled shooters

Wheeled shooters are a fantastic solution to most games where teams must shoot balls of some sort. Or Frisbees (See the 2013 game). Though they can lack accuracy when the balls vary in squishyness and generally require encoder feedback and PID controls to be very accurate (see sensors and software, respectively), they get back up to speed very quickly and can launch large amounts of projectiles accurately in a short period of time. Most wheeled shooters use one large flywheel and an adjustable backboard, which puts backspin on the projectile.



Mechanisms: Intakes

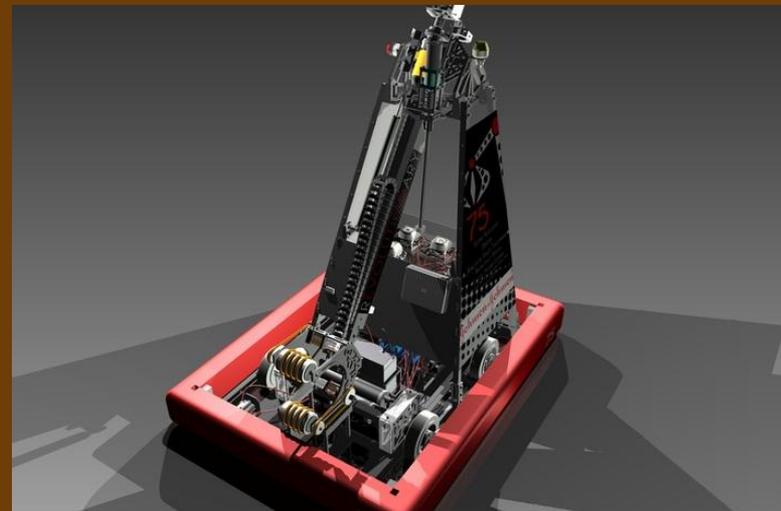
In most FRC games where you are picking something off of the floor, roller intakes are the way to go. They can pick up objects of practically any shape and do not take much driver time to align. Whether you are intaking into a gap in your bumpers, over your bumpers, or into a claw, roller intakes have some general rules:

1. Make sure that your roller is moving fast enough for your robot with the JVN design spreadsheet.
2. Make sure that your roller is much wider (at least 6-8 inches) than the gamepiece to be picked up so that your driver can align.
3. If possible, leave the sides of the intake open to at least the depth of your roller to allow your driver to turn into gamepieces that he misses.
4. Lightweight roller intakes can easily be retracted and deployed with clevis-mounted pneumatic cylinders or heavily reduced BAG motors.



Mechanisms: Arms: Overview

Need to put a game piece into a precise location that's within your robot's legal reach? Time to make an arm. Arms are tricky to do correctly. I categorize arm mechanisms into two types: Extending mechanisms and rotating (or "elbow") mechanisms. Many manipulators in FRC will have both extend and rotate.



Mechanisms: Arms:Rotating

A rotating arm is a straight arm that does not change length but instead rotates about an axis through one end. Rotating arms are typically driven with a pneumatic cylinder (either with the cylinder hooked directly to the arm or with a 4-bar linkage – google that) or with a heavily reduced motor. The key to rotating arms is to use a spring to counteract the force of gravity so that the arm is weightless – this makes it very easy to position the arm precisely.

Also, remember to *AVOID THE DEATH CANTILEVER*. It's very easy to forget to support the end of a shaft which drives an arm, a mistake that will almost certainly junk your subsystem.



Mechanisms: Arms: Extending

An extending, or telescoping, arm can be driven three ways: A cable/belt (left) , a rack and pinion(right), or a leadscrew (see shooter page). Cables/belts are fantastic for multi-stage arms and are fairly lightweight. Rack-and pinion mechanisms are heavy duty and precise, though heavy. Leadscrews are very precise but typically fairly slow to extend or retract.

