MECHATRONICS

TECHNOLOGIES, PRINCIPLES, DESIGN, AND ANALYSIS OF COMPLEX ELECTRO-MECHANICAL SYSTEMS

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WITH CONTRIBUTIONS FROM

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Chapter 1

Introduction

"You have to be in a state of play to design. If you're not in a state of play, you can't build anything." - Paula Scher

Mechatronics is an amalgam of "mechanisms" and "electronics": systems that contain both mechanical and electrical components. It's a field that spans nearly every industry, so any one source (even this one) will not be complete with all the information you need. But this may be a good jumping off point. I'm writing this generally towards those in a competitive robotics environment, so will use many examples from there, but you soon find that those same technologies that shoot foam balls into goals can be used anywhere from assembly lines to emergency medical equipment or racecars.

This document is not intended to be all-encompassing. In reality, it's just an outline; a map. We live in an era where information is readily available on demand. This document really doesn't contain anything new. Its goal is to show you a plethora of things that exist in a breadth-first fashion before you dive down a particular rabbit hole. There are a few places where I'll dive deeper because I feel it's relevant to show you some of the nuances you should be aware of. By and large, my goal isn't to drill home every single thing because I'll fail at that and fail you in the process. Someone will come up with something new, or improve something discussed here, and this information will become outdated. I'll try to keep it up to date... but I will definitely fail!

This is partly why I've open-sourced this LaTeXdocument. It's not a wiki, because the linearity of a text enables the reader to know they've completed it, and this is more printable. I'd love it if the graphics were more unified, and I appreciate any contributions you might have while preventing this from becoming too big to be useful (as I fear it already is).

Some sections of this will be dry... The human mind is a weird thing. It's better at prompted recall than unprompted recall. You may not always be thinking about the many different types of bolts, but if you've seen one before, and you come across a problem that needs it, you might be able to figure it out - or at least know where to start looking.

I hope to keep this terse. We're going to go fast and I'm going to leave some things to your imagination or research to figure out exactly how they work. I love mechatronics and hope you do too, so I don't want to spoil it by chewing your steak for you.

> Somtimes you'll see boxes like these which will ask questions or prompt research. The answers won't be in this text! It shouldn't be critical for you to know, either, but if you are so inclined, do some additional research and you'll learn more.

With that... let's begin.

Chapter 2

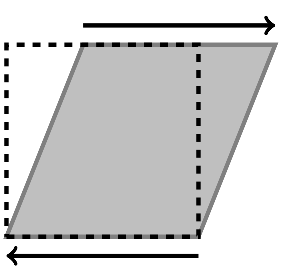
Physics & Terminology

"I learned very early the difference between knowing the name of something and knowing something." - Richard Feynman

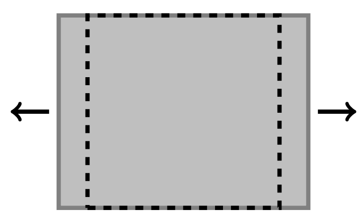
Engineers use a lot of nomenclature. While some nomenclature is windowdressing, most of it in engineering is useful in saying exactly what you mean. If you've been through physics, or hung around engineers enough, most of these terms should be self-explanatory. Gloss over this section and use it like a glossary if you come across a word you don't know.

2.1 Stresses and Deformations

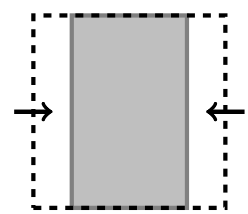
We use these terms to denote the shape of material deformation (indicated by the dashed lines and solid shapes), or the direction which a load is applied (indicated by the arrows).



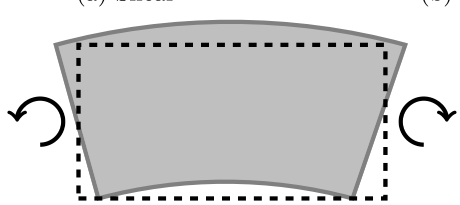
(a) Shear



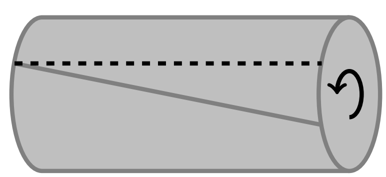
(b) Axial / Tension



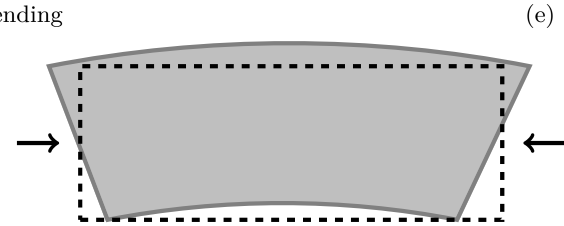
(c) Axial / Compression



(d) Bending



(e) Torsion



(f) Buckling

a) *Shear* is two surfaces sliding past each other, sometimes referred to as *parallelogramming*

b) *Tension* is a form of *axial* stress where material is being pulled apart.

c) *Compression* is a form of *axial* stress where material is being pushed together.

d) *Bending* is when a material bows with curvature. *Cupping*, *bowing*, and *crooking* refer to this phenomenon about different axes of a board.

e) *Torsion* is when material twists along an axis.

f) *Buckling* is bending that is induced by compressive loads.

2.2 Directions and Coordinate Systems

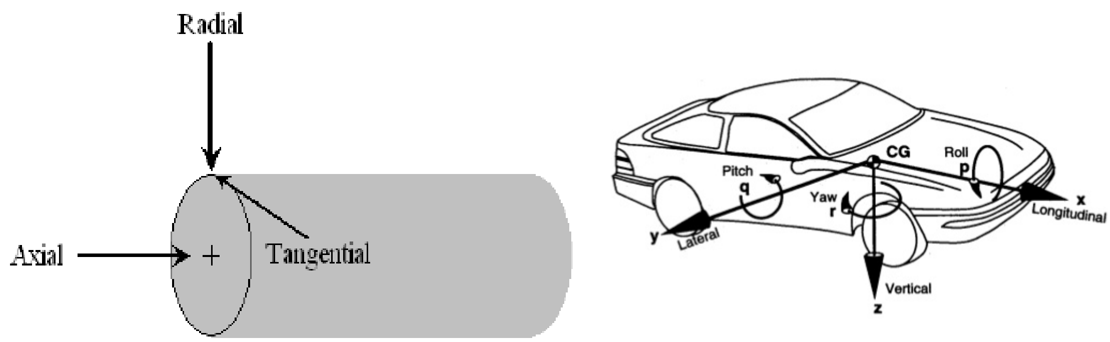


Figure 2.2: Cylindrical, and Cartesian Coordinates

a) The *axial* direction is along the axis of symmetry for a shaft, or along the axis of rotation for a rotating component.

b) The *radial* direction(s) are perpindicular to this axis of symmetry, and coincide at a point, emanating outwards.

c) The *tangential* direction(s) are perpindicular to both the radial and axial directions, curving around the axis of rotation.

d) For vehicles, the *longitudinal* direction is along the axis that the vehicle primarially moves forwards and backwards.

e) For vehicles, the *lateral* axis is left or right.

f) For vehicles, the *vertical*, or *normal* axis is up-down.

g) *Roll* is rotation about the longitudinal axis.

h) *Pitch* is rotation about the lateral axis.

i) *Yaw* is rotation about the vertical axis.

Engineers also use a little bit of jargon to refer to different geometric relationships that go beyond your typical geometry class.

a) *Orthogonal* is a synonym for *perpindicular*; at 90 degrees to.

b) An axis may be *normal* to a plane if it is perpindicular in two directions. If the plane and axis have specified positive directions, it may be *antinormal* if the positive directions are opposed to each other.

c) Axes and planes may be *parallel* to each other.

d) Axes and planes may be *antiparallel* to each other if the positive directions are opposed to each other.

e) A surface (with nonzero curvature) can be *tangent* to a line or another surface if they are coincident at a point or path which is not a sharp corner.

2.3 Basic Dynamics

a) *Mass* (m) is the amount of matter an object has.

b) *Force* (F) is motive for objects to change velocity.

c) *Acceleration* (a) is a change in an object's velocity over time. *Velocity* (v) is a change in an object's position over time. *Position* (x) is an object's location in space.

These three ideas are summed up in the equation of

$$\vec{F_{net}} = m \times \vec{a} \tag{2.1}$$

(for rigid objects which do not change mass). You may ask why the $\vec{F}$ and $\vec{a}$ have that little arrow over the top of them. That's to denote that they are *vectors*; they have multiple components. You can break this equation down simply into

$$F_x = m \times a_x \tag{2.2}$$
$$F_y = m \times a_y \tag{2.3}$$
$$F_z = m \times a_z \tag{2.4}$$

These concepts exist in an analogue for rotating components as well.

a) *Moment of inertia* or *MOI* (I) is a measure of how spread out an object's mass is. A point mass (black hole) has a MOI of zero. A golf ball would have a small MOI, and a beach ball would have a large MOI, even if the beach ball has less mass.

b) *Torques* or *moments* (T or M) are twisting forces. They can be quantified by how much force is applied multiplied by the lever arm which it is applied by.

c) *Angular acceleration, velocity, and positions* (α, ω, θ) are just like their linear counterparts, except they are measured as rotation about an axis.

$$\vec{M} = \frac{d}{dt}[I]\vec{\omega} \tag{2.5}$$

(which again holds for rigid objects). You may ask why the moment of inertia $[I]$ has those brackets around it. That's to denote that it's a *matrix*. This means that breaking the equation down is difficult if there are multiple rotations. The $\frac{d}{dt}$ is a derivative, a concept from calculus which represents change over time. Luckily, for the simple case of an object of constant moment of inertia, and spinning only about one axis x,

$$M_x = I_x \alpha_x \tag{2.6}$$

which isn't so scary, and is just like the linear case.

Energy is a property that can be transformed in many ways to do useful *work*. There are many forms of energy (spring, gravitational, electrical, chemical) and many different processes that can be used to transform it (combustion, releasing a spring, lifting a heavy object). *Power* is a measure of energy transformation / transfer per unit time.

Congratulations! You've just learned the basics to 80% of newtonian physics.

2.4 Basic Electronics

There are a few basic electrical terms which can be confusing at first since they are not everyday, lived phenomena.

a) *Current* I (measured in *Amperes*, or amps, A) is (roughly) a measure of how many electrons pass through a cross-sectional area (e.g. a wire) per second.

b) *Voltage* V or *Electric Potential* (measured in *Volts*, V) is a measure of the motive force that is available to push electrons. It is always a relative measurement taken between two points. If it is given as a plain number (e.g. "this terminal has 12 volts"), then there must be an assumed *ground* that the measurement is taken from.

c) *Resistance* R (measured in *Ohms*, Ω) is a measure of how much voltage is required to get a certain amount of current to flow though. Ohm's law expresses this as $\Delta V = I \times R$; the voltage drop across a wire is proportional to both the current passing through it and its resistance. Resistance of a wire can be reduced by using a superior material (copper rather than aluminum), using a larger cross-section (or wire *gague*), and shortening the wire.

These concepts are often related to hydraulic systems; voltage is much like pressure, and current like flow rate.

This also leads us to a few laws known as *Kirchoff's laws*.

Kirchoff's Voltage Law states that "the sum of the voltages across all components in a loop add up to zero". Mathematically,

$$\sum_{loop} \Delta V = 0 \tag{2.7}$$

Some thinking would reveal that this is merely a different way of stating that "all voltages are relative."

Kirchoff's Current Law states that "the sum of currents entering a node (a point where multiple components meet) add up to zero". Mathematically,

$$\sum_{node} I = 0 \tag{2.8}$$

This should make sense as the electrons must go somewhere. This is merely a different way of stating that "electrons cannot be destroyed."

Chapter 3

Construction

"The first little pig was very lazy. He didn't want to work at all and he built his house out of straw. The second little pig worked a little bit harder but he was somewhat lazy too and he built his house out of sticks. The third little pig worked hard all day and built his house with bricks. It looked like it could withstand the strongest winds." - English Folk Tale

The parable of the three little pigs reminds us that how we build things is important. And while at first blush, the story seems to be about how you should always build strong out of brick, sometimes we should learn from the first pig, and build fast for prototyping. Having a suite of different fabrication techniques at hand can be incredibly handy.

3.1 Materials

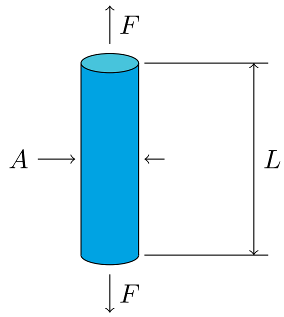
There are a lot of different materials to build with, all with different properties. Some are natural and some are completely synthetic, but all can be measured, quantified, and compared. Important properties we'll focus on are:

- Density (weight)
- Stiffness
- Hardness
- Strength
- Toughness
- Thermal capabilities
- Frictional and chemical interactions

You'll notice that stiffness, strength, hardness, and toughness are all different characteristics. They are distinctly different properties in engineering.

3.1.1 Stress-Strain Properties

To show this, we'll first consider a *stress-strain curve*. This curve is created by pulling on a specimen of material like shown, interpreting the force and deflection data into *stress* σ (force per cross-sectional area) and *strain* ϵ (percent deflection).



$$\sigma = \frac{F}{A} \tag{3.1}$$

$$\epsilon = \frac{\Delta L}{L} \tag{3.2}$$

Figure 3.1: Stress-strain test, and the relationship between the variables.

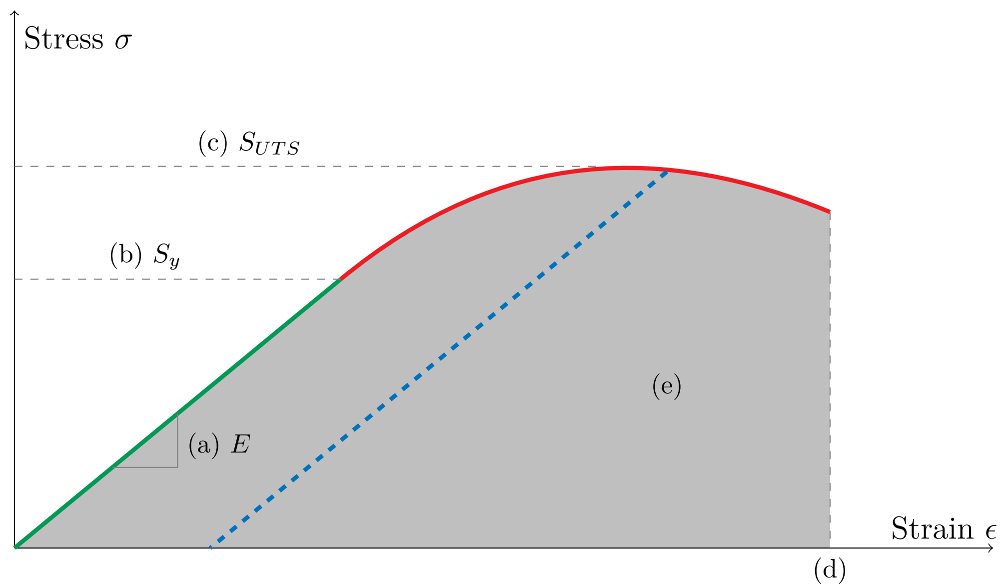


Figure 3.2: Exemplary stress-strain behavior.

The portion of the curve that is linear (highlighted in green) is referred to as the *elastic* portion. When the material is operating in this region, it will always snap back, like a rubber band. If, however, we dip into the *plastic* portion of the curve (highlighted in red), when we release the material, it will have permanently deformed (following the diagonal blue dashed line).

The key aspects of the curve can be boiled down into a few properties.

a) *Young's Modulus*, or the *Elastic Modulus* (E) is the slope of the elastic portion of the curve. A higher E denotes a stiffer material.

b) *Yield strength* (S_y) is the highest stress seen in the elastic portion of the curve.

c) *Ultimate tensile strength* (S_{UTS}) is the highest stress the material can see.

d) *Percent elongation at break* is the highest strain seen by the material before it breaks. A higher elongation means the material is more *ductile*, while a smaller one means the material is more *brittle*.

e) *Modulus of toughness* is a measure of how much *energy* the material can absorb. It can be visualized as the area under the curve (think about a shock absorber- it deforms a lot while resisting the load, so can absorb a lot of energy). Materials that are brittle have low toughness.

3.1.2 Hardness

Hardness is a property of a material's surface - how much it will permanently indent or scratch. It is not measured by this graph (although it does have some correlations), and is a relative, rather than absolute measurement. There are many different scales. You may have heard of the Mohs scale, introduced to determine the hardness of different minerals based on which can scratch each other. However, most engineering measures will work by indenting an object and measuring how much of an indentation was left behind, which allows for a higher degree of quantification. There are many different scales that are better suited to different materials.

Brinell and Rockwell scales are well suited to metals.

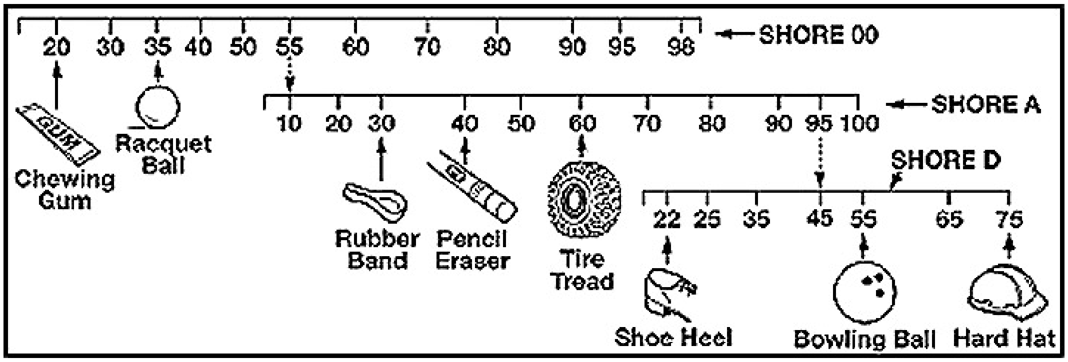


Figure 3.3: Shore Hardness scales, with some examples

Shore or *durometer* scales are suited to measuring elastomers (i.e. rubber). Again it is important to note there are different scales. 90A is much softer than 90D durometer. Material rated as 95A may be quite different than 45D, although they look like they are the same on the above chart. Colorants are often added to elastomers to make distinguishing between different hardnesses by eye easy.

Elastomers are much harder to measure in other ways, and are often given ratings only by their durometer. While this is technically only a measure of hardness, it correlates reasonably well to other material properties like overall stiffness (harder being stiffer) and grip (softer being more interactive, or frictional).

3.1.3 Thermal Properties

The thermal properties of a material may also be important to your application. There are three main ones to keep in mind if you are dealing with heat:

Thermal conductivity is how well the material transfers heat. If you're designing a heat sink, you want a high thermal conductivity.

The *melting point* or *glass transition temperature* are temperatures at which the material undergoes fundamental phase changes. You obviously need to make sure your part doesn't outright melt, but you should also have a bit of margin, as the phenomenon called *creep* can cause parts that are at elevated temperatures to deform over time, even though below melting point.

The *coefficient of thermal expansion* measures how much material expands as it heats up. If you're working with tight-tolerance equipment (or extreme temperatures), you may need to keep an eye on this.

3.1.4 Other Properties

Frictional characteristics and chemical interactions are very complex, and if you care about these, it will require some research beyond mere datasheets.

Density is another property to be mindful of. Most properties given do not take this into account, and this is why many engineers may speak of a *strength-to-weight ratio*. This is simply dividing the material property in question by the density of the material. This is a sensible comparison in many cases where weight is a concern. If we wanted to create a component to bear a certain load, we could use a material that was very strong but heavy, or use more of a lighter, but weaker material.

3.1.5 Material Comparisons

To actually get data to make material comparisons:

- MatWeb has a wide range of material properties.
- MakeItFrom has a similarly wide range of materials, and includes a comparison tool to help evaluate different options.

Table 3.1 lists some common engineering materials' properties.

Material	Density [g/cm^3]	Elastic Mod. [GPa]	Yield [MPa]	UTS [MPa]	% Elong. at Break	Max Mech. Temp [C]	
Aluminum 6061-T6	2.7	69	270	310	10	170	
Aluminum 7075-T6	3.0	70	480	560	8	200	
Steel, 4130-N	7.8	190	440	670	26	420	
Steel, 4340-N	7.8	190	860	1280	12	420	
Steel, 1020, Hot Rolled	7.9	190	240	420	28	420	
Stainless Steel, 304, Annealed	7.8	200	230	580	43	710	
Titanium Grade 23 (Transformed-Beta)	4.4	110	870	930	6.7	340	*
Polycarbonate (PC)	1.2	2.3	62	66	110	120	
Acetal (Copolymer)	1.4	2.8	*	61	65	100	
ABS	1.1	2.0	*	41	20	80	
PETG	1.3	2.2	*	53	**	70	
Nylon 11	1.0	1.3	*	51	130	180	
Polypropylene (PP) (Homopolymer)	0.9	1.4	*	36	80	120	
PLA	1.3	3.5	*	50	6	50	
Acrylic	1.2	3.2	*	71	4	100	

Plastics have odd stress-strain curves, so often don't rate the yield point.
** Extremely ductile; no data available

Table 3.1: Common materials and their properties. Values obtained from MakeItFrom.com.

A few interesting things to note:

a) Aluminum can be as strong as steel, not even considering the difference in density. The grade of steel and aluminum you're using is very important when comparing the two.

b) Titanium is a truly incredible material. It is not quite as light as aluminum, but it is as strong as many high grades of steel!

c) Among most metals, the *stiffness-to-weight ratio* is about the same. If you want something to be stiffer without adding weight, only changing the type of metal won't help you out much.

d) Plastics are much weaker, but they can be quite useful due to their low density: simply use more.

e) Not all plastic is created equal.

f) Polycarbonate and Nylon are particularly good materials for their mechanical properties, especially in impact resistance. Their elongation at break is **more than 100%**!

> You'll notice that many of the materials listed have a hyphenated code (-T6 and 6061-T6, -N in 4130-N). What does this mean? Does it affect the elastic modulus?

3.2 Form Factors

Just because the material you want exists doesn't mean that it's widely available in the shape you want. There are a lot of different shapes that a material may be available in, and there are trade-offs with each different form factor.

3.2.1 Cast from Ingot

Figure 3.4: Left: the casting process. Right: A cast differential housing.

Casting is the process of pouring molten material into a mold to produce a complex shape. This shape isn't perfect, as the mold is usually made of sand (in order to withstand the molten metal) and the pouring process can introduce voids and imperfections, so the material properties are usually not as good. Cast parts have notably inferior material properties from billet or forged counterparts.

3.2.2 Billet and Plate

Figure 3.5: Pieces of round billet.

Billet material has been poured in a more tightly controlled environment. The resulting material is free of voids and has superior mechanical properties. You can obtain billet plate, bars, or round stock of nearly any material. This material can be held to reasonable tolerances (and by its simple-shaped nature, can be brought into exact dimension by machining quite easily).

3.2.3 Extrusions

Extruded material has been squeezed through a die while molten, and then cooled. Think of a pasta machine. This die can be anywhere from a simple shape like a flat bar, to box tubing, to a very complicated profile with t-slots such as 80/20. Aluminum is the most common material to be extruded. Extrusions have good material properties, and can be held to tight tolerances.

(a) Angles (b) Box tube (c) Box tube (d) Pipe and tube (e) T-slot framing

Figure 3.6: Common Extrusions

a) *Angles* are measured by the leg width and the thickness. Only one dimension for leg lengths may be given if the leg lengths are equal. There may or may not be a radius in the corner, and radiuses on the tips of the legs.

b) *Box tube* is measured by the outer side lengths and the thickness. It may or may not have an inner or outer radius - if it isn't specified, it probably doesn't.

c) *Channel* is measured by the outer side lengths and the thickness. Usually it has straight walls of equal thickness, but it may have tapered, unequally sized walls.

d) *Pipe and tube* is measured either by diameter and thickness, or by nominal pipe size and schedule. '1 inch' tube might refer to 1" nominal pipe, which actually has an inner diameter of 1.049", or a piece of tube with a 1" outer diameter. Make sure you know which you're buying.

e) *T-slot framing*, known often by the brand name *80/20*, has several slots on the outside which t-slot nuts can be slid into. This makes creating configurable/adjustable frames easy, although the framing is quite heavy.

3.2.4 Welded / DOM Tubing

Steel is not easily extruded, so making hollow shapes must be tackled differently. Steel tubes are usually formed by taking sheet steel and rolling it into a tube, then welding it together. This process leaves a weld seam which can produce odd material properties, dimensional issues (as when making telescoping tubes), or make manufacturing annoying, as the weld is difficult to drill through).

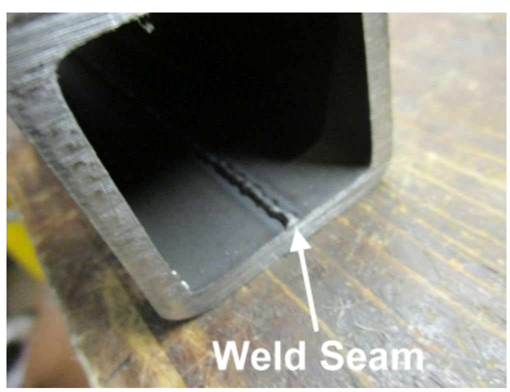


Figure 3.7: Weld Seam on Tubing

DOM (Drawn-Over-Mandrel) or *seamless* tubing further processes this tubing to remove the inner seam and produce a product as if it were extruded. It is typically used in demanding applications such as aerospace or motorsports, as well as in components which cannot have a weld seam (such as a receiver hitch, or telescoping tubes).

Other than telescoping tubes, why else is the weld seam problematic or annoying?

3.2.5 Sheet

Material that is sold as sheet rather than plate usually has little-to-no straightness tolerance (in especially thin gauges, it might even be sold as rolls).

3.3 Manufacturing Processes

Once you have a material you like in a shape you can use, you probably have to cut or form it into the final shape you want. There are nearly infinite ways of doing this, but here are the most common.

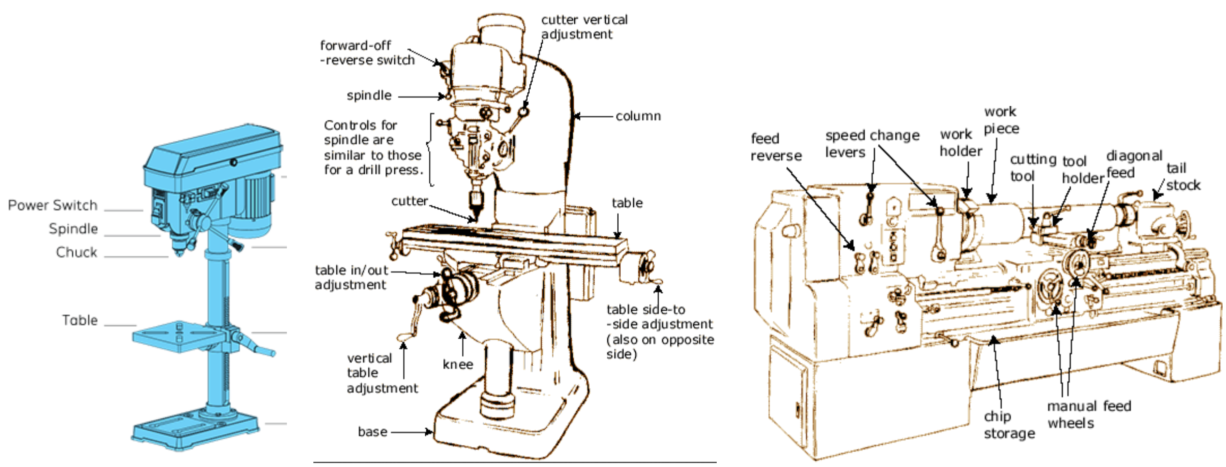
3.3.1 Hot Work

Casting, sintering, and forging are manufacturing methods which generally require a lot of tooling in order to accomplish, so are generally not suitable for quick-turnaround prototypes such as we need. Some notes, though:

- *Casting* as mentioned before, is pouring molten metal into a mold. It can produce very complex shapes (like engine blocks), but the material may end up with lots of voids.
- *Forging* is heating up a metal so that it can be more easily formed, though not liquid. It is then pressed between large dies to form it into the desired shape- essentially, industrialized blacksmithing. Forging can produce fairly complex shapes (like crankshafts), while preserving (and even enhancing) material properties.
- *Sintering* is compressing and heating powder in a mold. Also known as *powder metallurgy*. This can produce somewhat simple parts with good material properties and no draft - many small gears are made this way.

3.3.2 Machining

Machining is a broad category of processes that cut material away with a sharp tool. There are many tools that can be used to accomplish this, but there are three that are the most essential and common:



(a) Drill press (b) Milling machine (c) Lathe

Figure 3.8: The Most Common Machining Tools

a) A *drill press* has a rotating spindle and chuck where drillbits can be inserted. Workpieces are clamped to a fixed table. The spindle can then be brought down and into the work to drill holes.

b) A *milling machine* has a rotating spindle where drill bits and mill bits - end mills - can be inserted. Workpieces are secured to a table that moves along X, Y, and Z axes with respect to the spindle. *Routers* operate by the same principle, but generally refer to a tool which moves much more in the X and Y than the Z, and may not be as rigid; more suitable to cutting sheets of plywood or foam.

c) A *lathe* has a rotating spindle in which the workpiece is held securely. Cutting tools are mounted to a carriage which moves axially and radially, shaping the exterior of the work. Additionally, a tailstock can accept drill bits and other supporting devices.

There are lots of variations on these machines: combinations of these exist, and 4- and 5- axis mills where the head or table tilt on the fly also exist. They can also all be enhanced with the addition of *CNC* (Computerized Numeric Control) in order to produce even more complicated shapes and/or increase productivity.

These different machines can accept a wide variety of cutting implements. Here are a few of the most common to consider.

(a) Drillbit (b) Center drill (c) Step drill (d) Hole Saw (e) Reamer

Figure 3.9: Holemaking tools

a) *Drill bits* drill holes. The spiral flutes on the outside may be sharp, but they generally aren't sharp or hard enough to actually cut metal. They work with Jacobs chucks, which are designed to only transmit vertical force and torque.

b) *Center drills* are used to start holes. They are short and stubby, so don't deflect much.

c) *Step drills* have multiple steps in them that can be used to quickly make large holes. These can sometimes produce holes with good tolerances for slip-fits on bearings ($\approx \pm$ 0.005").

d) *Hole saws* are effective at quickly removing large disks of materials. Typical bi-metal hole saws are not very precise, but well constructed carbide-tipped hole saws can achieve tight tolerances ($\approx \pm$ 0.002").

e) *Reamers* enlarge existing holes to precise ($\approx \pm$ 0.0002") diameters. They are used by first drilling a hole about 1/32" smaller than the target diameter and then running the reamer in.

(a) End mill (b) Ball end mill (c) Lathe tooling

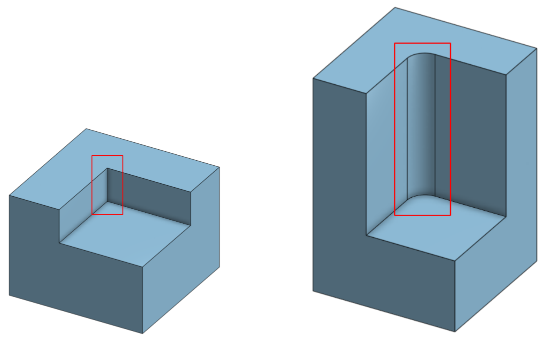
Figure 3.10: Machine Tooling

a) *End mills* cut on all surfaces - they are all ground sharp. This means they can cut on the side, and produce side loads - so they should not be put in Jacobs chucks in drill presses!

b) *Ball end mills* are an example of a more sophisticated end mill. There are many different shapes. This one enables smooth contours to be made.

c) *Lathe tooling* comes in many different shapes and sizes. This one is a simple cutting tool that gets clamped to the toolpost and shapes the outside of the work.

If you can consider briefly how these machines work, you can perhaps spot a few problems with your designs as you go along. Can you spot some issues with these parts?



(a) Sharp inside corner (b) Deep radius

Figure 3.11: Problematic geometries for machining

a) The sharp inside corner cannot be made, as it would require an infinitely small diameter tool.

b) The deep radius would require a very long end mill, which would not be very stiff. This radius is 0.25", and it is 2" tall; this is a ratio of depth-to-diameter of 4:1, which is a sub-optimal ratio. Ideally, this ratio would be no more than 3:1.

3.3.3 Broaching

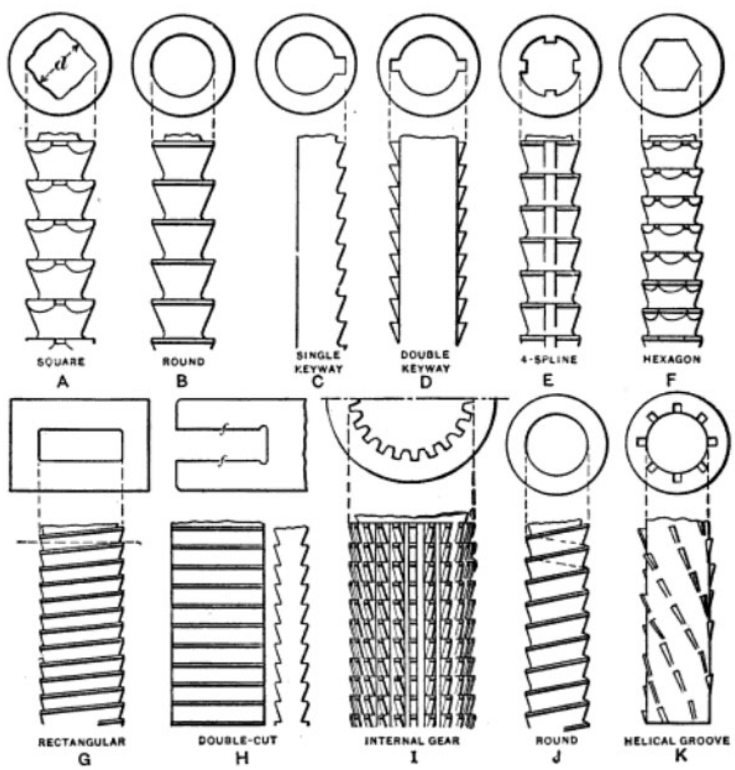


Figure 3.12: Broach Examples

But how do we make splines, keyways, and hexes in things? Those need infinitely sharp corners, so we broach them. This is done by first drilling a hole of the appropriate diameter, and then inserting a broaching tool into the hole. The tool is then pushed through with a press. Each tooth of the broach takes off gradually more material until the final shape is achieved. Broaches are typically very expensive and relatively delicate tools.

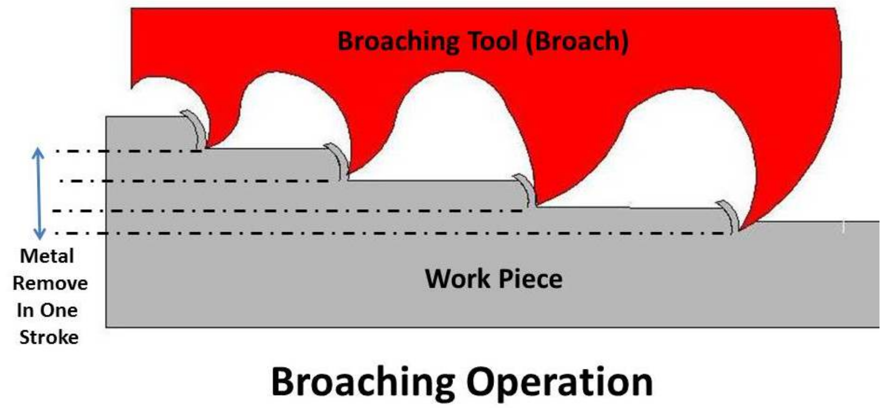


Figure 3.13: Broach Detail

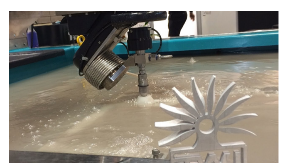
> How could you put a female hexagon into a blind hole (like on a socket head screw)?

3.3.4 Path Cutting

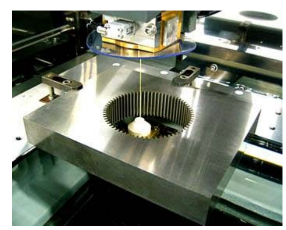
Path cutting is encompasses any sort of 2-dimensional X/Y cutting with a thin beam. It is almost always done on a CNC-capable machine.

(a) Plasma cutting

(b) Laser cutting



(c) Waterjet cutting



(d) EDM cutting

a) *Plasma cutters* use an arc to melt metal and pressurized air to blow it away. The tolerances are usually good for large shapes, but not for precision work.

b) *Laser cutters* melt material with a laser and either simply vaporize it or use pressurized air to blow it away. Hobby lasers can cut some plastics and plywood, while industrial systems can cut metal. The tolerances are usually acceptable with these machines (±0.020”*orbetter*).

c) *Waterjet cutters* mix high-pressure water with garnet sand and blast it at material, rapidly abrading it. The tolerances are usually good with this process (±0.010” or better).

d) *EDMs* (electric-discharge-machines) use an electrified wire to remove material. The wire is fed through or plunged into material. The electrification zaps away material next to the wire. The tolerances with this process can be impeccable (±0.001” or better).

These all allow machinists to overcome the depth-to-diamter ratio imposed by milling, and can sometimes be much quicker setup than traditional machining, though they all come with their own drawbacks.

The first limitation is the width of the beam. Since a finitely sized beam muse be used, infinitely sharp interior corners cannot be made.

Draft is also an issue. Laser-cutters typically have a point in the thickness where the beam is focused to. This means that the laser doesn’t cut a line in its cross-section, but rather an X. Thus the resulting shape is two-dimensional. With a waterjet or plasma cutter, the draft grows exponentially. This may be acceptable, or require further post-machining to bring it into specification.

Draft (and power) also limits how thick of material can feasibly be cut with these processes, although it should be noted that EDM can cut extremely thick materials compared to the other processes.

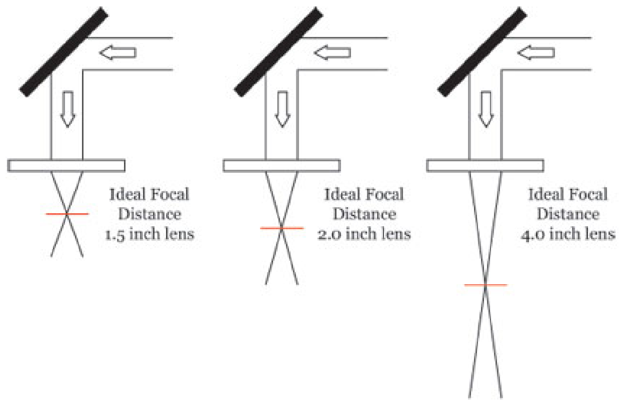


Figure 3.15: Focal properties of a laser cutter's beam.

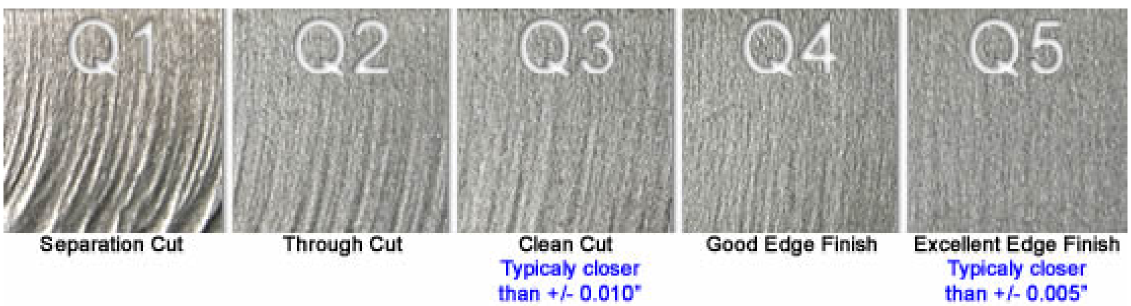
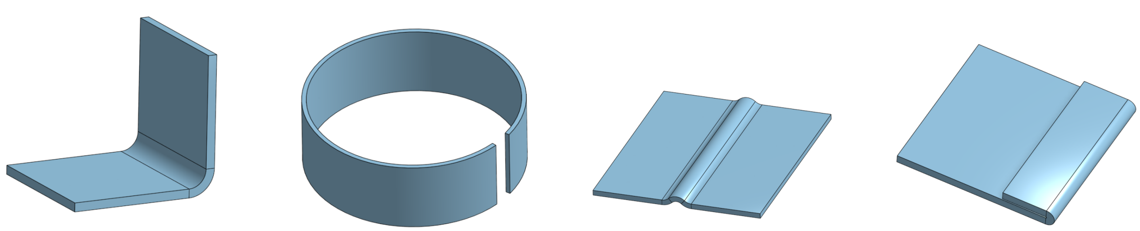


Figure 3.16: Draft and surface quality samples on a waterjet with different settings.

3.3.5 Sheet Forming

Sheet forming is a versatile process of making parts from, well, sheet. Sheet may be cut with either a stamping or path-cutting operation to form a blank. This blank can then be loaded in and undergo one of several processes.



(a) Bend (b) Rolling (c) Bead Rolling (d) Hemming

Figure 3.17: Rudimentary sheetmetal operations.

a) Simple *bends* can be made on a linear portion of the flat pattern. This can be done with a finger bender, press brake, or, in a pinch, a vise with a hammer.

b) Flat portions of material can be *rolled* into an arc, or even full circle.

c) *Bead rolling* can be done on any portion of a part to provide additional stiffness.

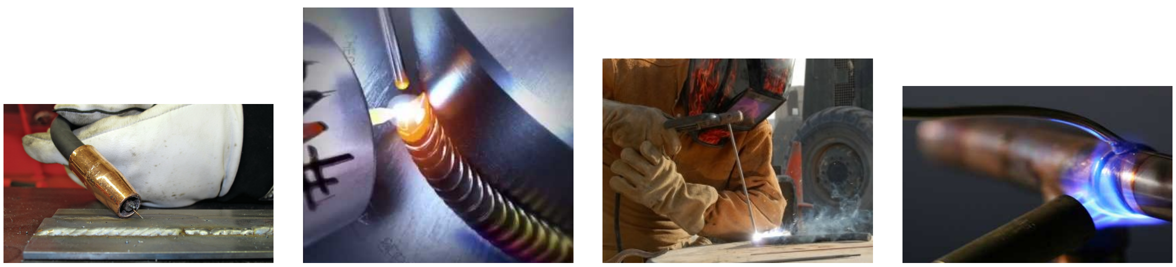
d) *Hemming* provides a smooth, radiused outer corner and some additional stiffness. First, a bend is made, and then it is bent all the way to 180 degrees. This can be done with a finger bender or press brake, and additional clamping to finish the hem.

Most CAD packages have tools to design parts made with sheet metal. You can draw up the bent part, and then the CAD package will determine how to unfold and produce a flat pattern that can be cut out.

These operations are typically done with metal, but nothing prevents them from being applied to plastic. Polycarbonate can be bent like sheet metal. Polypropylene, polycarbonate, acrylic, and PETG, among others, can be heated - heat gun or other method - and then bent by hand.

3.3.6 Welding and Brazing

Welding and brazing are very important manufacturing methods. They enable large, complex structures to be made from smaller simple ones without fasteners that might fail. However, it requires time consuming labor and creates non-serviceable structures.



(a) MIG (b) TIG (c) Stick/Arc Welding (d) Brazing

Figure 3.18: Various welding/brazing technologies.

a) *MIG* (Metal-Inert-Gas) welding uses an electric arc between filler wire and the workpiece, which melts both the wire and the workpiece. The arc is shielded by inert or semi-active gas to control chemical reactions. The wire is advanced at a constant rate into the workpiece. This is the easiest method to learn, but provides the least amount of control, and has the lowest capacity for superior results.

b) *TIG* (Tungsten-Inert-Gas) welding uses an electric arc between a fixed tungsten rod and the workpiece, melting the work but not the tungsten. The arc is shielded by inert gas to eliminate chemical reactions. Filler rod is advanced manually and separately into the molten work. This method is much harder to learn, but provides the most amount of control, with the highest capacity for superior results.

c) *Stick/Arc* welding uses an electric arc between a rod containing flux and filler metal and the workpiece, melting both the rod and the workpiece. The arc is shielded by the vaporizing flux. This method is hard to learn, but provides good control, and works best outdoors, so is quite common in the construction and pipeline industries.

d) In *brazing*, heat is generated either by a TIG or flame torch and directed at the work without melting it. Brazing material, which will melt at this surface temperature, is fed onto the work, melting and flowing across it. As it solidifies, it adheres to the base metal.

3.3.7 3D Printing

3D printing or *additive manufacturing* is a varied class of technologies that add material selectively and in a discretely controlled fashion. This allows the production of extremely complex geometries with little to no tooling costs, but is a pioneering field and has many limitations.

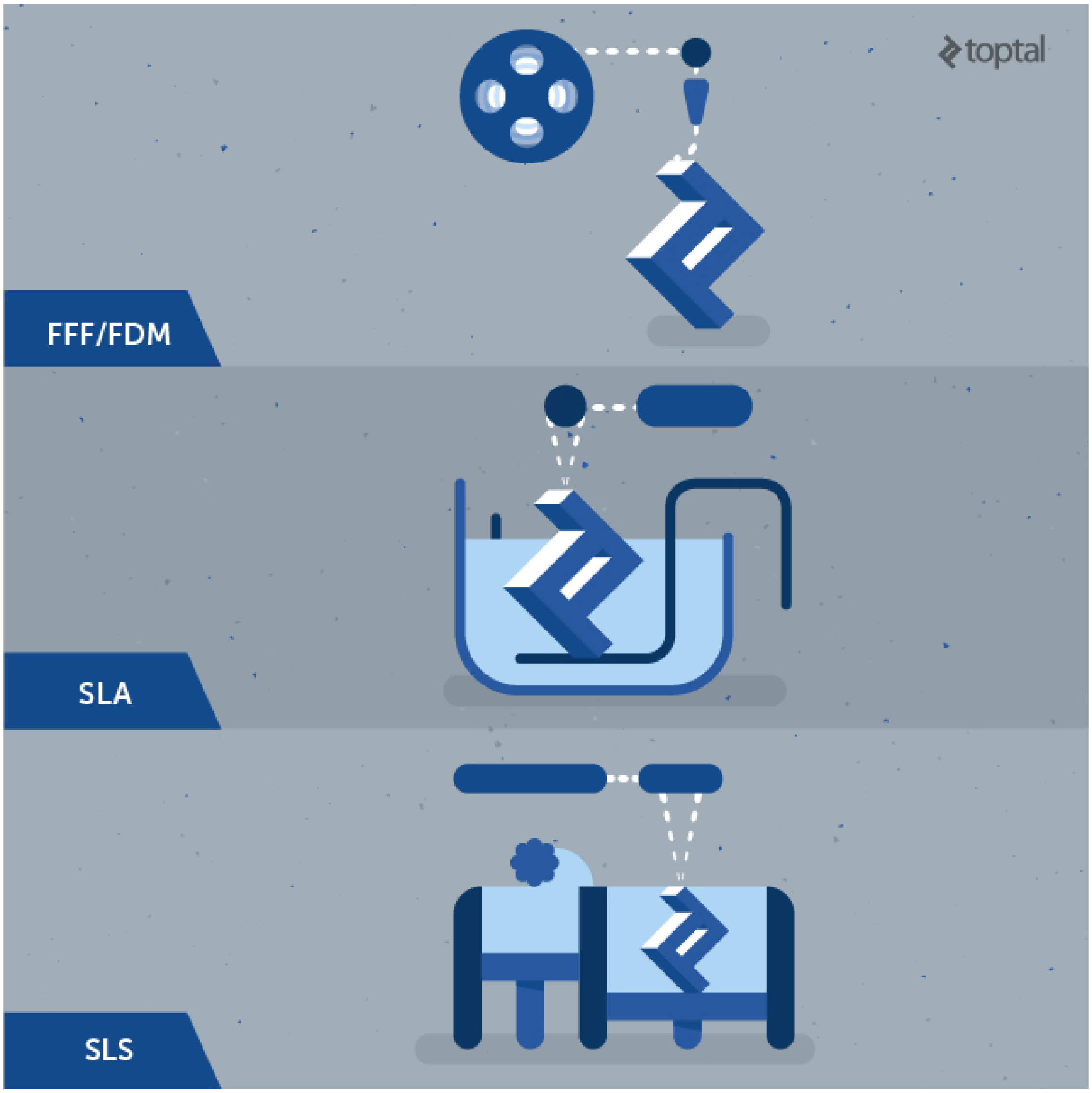


Figure 3.19: Major 3D printing technologies.

a) *Fused deposition modeling (FDM)* uses a continuous piece of plastic filament which is heated in the *hot end* before being squeezed through an *extruder* to lay down thin layers of material which melt into previous layers. This method is quite reliable and cheap, but does result in models with visible layers, and generally results in models where the strength can vary with the orientation of the layers. Because it works by melting existing material, it is limited to materials that can be melted and cooled into final form such as thermoplastics. Common materials are PLA, ABS, and to an increasing extent, PETG, Polycarbonate, and Nylon. FDM is furthermore is limited in that it cannot print steep overhangs without wasteful or surface-quality changing *support material*. Porosity and sealing can also be concerns. On the upside, it can create hollow parts, enabling high strength-to-weight ratios as material can be placed only where it is needed. *Continuous-strand reinforcement* is a new addition to this technology. As the name implies, this is the inclusion of a fibrous high-strength material such as fiberglass or carbon fiber into the filament, so that when it is extruded, the part has many strands of this reinforcing material. Markforged makes printers capable of this.

b) *Stereolithography (SLA)* uses a laser to quickly cure liquid *resin* into solid material. The print bed moves away from the laser as additional layers are added. This method is inherently limited to materials that can be made from resins, ruling out many materials. It is a quite time-consuming process but can result in parts with good sealing properties and excellent surface finish. Hollow parts cannot be created as the resin would simply be trapped inside cavities. Formlabs is a prominent manufacturer of such printers.

c) *Selective laser sintering (SLS)* uses a laser to selectively melt and *sinter* powdered material together.

After one layer is sintered, another thin layer of powder is put over top, and the process repeats. This process can achieve excellent mechanical properties which are not dependent on layer orientation, as well as stellar dimensional accuracy. However, it results in parts with a very coarse surface texture. Hollow parts cannot be created as the powder would simply be trapped inside cavities. The continuous addition of powder (of which the unsintered material can be reused) allows for the production of parts with infinitely sharp overhangs since the previous layer acts as support material.

Metal 3D printing technologies are also in the works, most being a modification of the traditional SLS method with metal powders.

3.4 Fasteners

Fasteners are a broad family of mechanical solutions to fastening parts together.

3.4.1 Pins

The simplest fastener is a pin. Pins prevent plate holes from shearing past each other by putting all of the load through the pin. There are a couple different kinds, each with different properties:

Quick pins allow users to easily adjust or reconfigure equipment. They are easily insertable/removable, usually without any special tools.

(a) Clevis pin (b) Wire-locking pin (c) Ball-detent pin

Figure 3.20: Various quick-removal pins.

a) *Clevis pins* are loose tolerance pins which have a hole for an R-shaped locking pin or wire to go through.

b) *Wire-locking pins* serve the same purpose as clevis pins, but use a spring-loaded wire to keep the pin captive.

c) *Ball-detent pins* serve the same purpose as clevis pins, but use a spring-loaded ball detent to keep the pin captive. These can be pulled/pushed in without and additional steps.

Precision pins serve a nearly opposite purpose- they are permanent installations, but provide extremely tight tolerances when used right. They allow for installation and detachment of components with high repeatability in locational positioning. It's not uncommon to see precision equipment register together with pins, and then be bolted together in addition to the pins. Pins also can provide higher load transferral because they do not have the stress concentrators that bolts do.

(a) Dowel pin (b) Spring pin (c) Hollow dowel pin (d) Taper pin (e) Shear pin

Figure 3.21: Various precision pins.

a) *Dowel pins* are tight-tolerance. They are typically pressed into one part's hole with a loose fit on another mating part.

b) *Spring pins* are formed from coiled metal and are intended to be pressed in like a dowel pin, but have some give to them so that they can be used with looser-tolerance holes.

c) *Hollow dowel pins* serve the same purpose as dowel pins but allow a bolt to pass through them as well.

d) *Taper/scotch pins* are like dowel pins, but they are slightly tapered, so they wedge into multiple parts like a nail.

e) *Shear pins* are specifically designed to fail at a specified load, preventing damage to equipment.

3.4.2 Threads

Threaded fasteners (bolts, nuts, and screws) are a ubiquitous solution. There's an age old question of the difference between a screw and a bolt and the answer is merely in application: if it goes into a nut, it's a bolt. Otherwise, it's a screw. So, anything said about screws is true of bolts and vice versa.

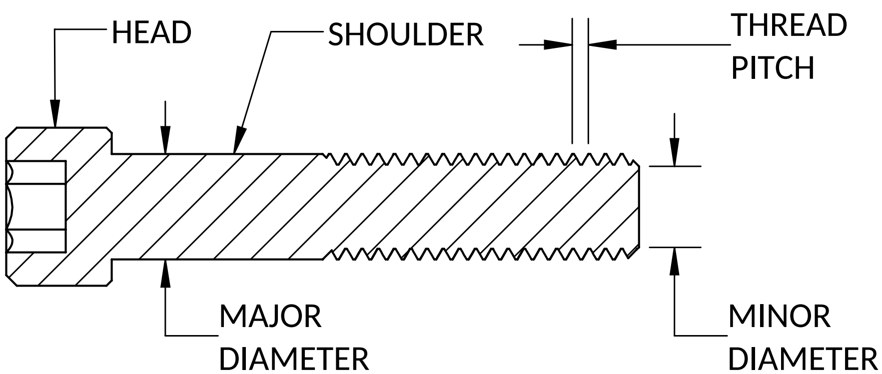


Figure 3.22: Thread nomenclature and dimensions.

Threaded fasteners are denoted by:

- The major diameter of the thread.

- The thread *pitch*, or threads-per-inch. Metric bolts are specified by the pitch (a M5x0.8 has 0.8mm between each thread crest). English bolts are specified by the number of thread crests in an inch (a 1/4"-20 has 20 threads per inch, or a pitch of $1/20 = 0.05$ inches). Even among the same diameter, bolts can have different pitches. For instance, a 1/4"-28 is fine thread, and a 1/4"-20 is coarse thread.

- The thread length - the bolt might be threaded fully, or only partially. The unthreaded portion is the shoulder and is usually the same diameter as the threads' major diameter.

- The handedness of the thread - most threads are right handed (meaning turning them in a clockwise fashion will make them move away) unless specified as left-handed.

- The grade or class - this refers to the strength of the material. English bolts are specified by *grade*, and metric bolts by *class*. Bolts usually have head markings that reflect the material. Grade and class are only for steel, though - other materials have more exotic standards.

The thread or end-features on a screw may be specialized to work better going into a particular substrate, rather than the typical 'machine threads' one would find on a nut or bolt.

(a) Wood Screw

(b) Self drilling screw

(c) Tapcon

(d) Plastite Screw

(e) Dogpoint Screw

Figure 3.23: Specialized Screws.

a) *Wood screws* have a tapered tip to help guide the screw in, much larger threads to engage with the wood, and a coarser pitch. While most screws benefit from being predrilled, some are designed to include features in the tip that perform this drilling operation (to some degree) as the fastener is installed, though this only works well for softwood (like a 2x4). *Lag Screws* are larger wood screws, generally with a hex or large-Torx head, and generally rated for some load-bearing capacity.

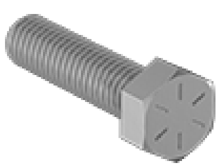
b) *Self-drilling screws* have a tip like a drillbit to perform the drilling operation and are well-suited to sheetmetal. These have the same idea as a self-drilling wood screw: the fastener can be installed with no drilling operation required.

c) *Masonry screws*, often known by the brand name *Tapcon*, allow screwing into masonry and concrete. They are hardened and coated. Proper predrilling with a masonry bit is an absolute requirement for these.

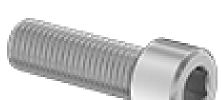
d) *Plastite screws* are specialized to go into plastic. They are generally thread-forming screws (meaning they go into a hole smaller than the threads, and shove the material out of the way as they go in). This makes for a very 'tight' connection that will not wiggle loose.

e) *Dogpoint screws* have a blunted, non-threaded tip. This tip registers into what the fastener should thread into, which eases assembly. The tip generally serves no other purpose. They are common in the automotive world.

There are many different types of bolts out there.

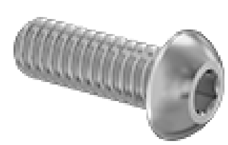


(a) External drive



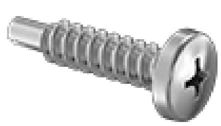
(b) Socket head

(c) Flathead

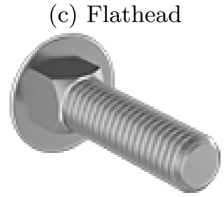


(d) Button head

(e) Shoulder screw



(f) Self-tapping screw



(g) Carriage bolt

(h) Grub or set screw

Figure 3.24: Various screws / bolts.

a) *External drive* bolts are good when only side-access is possible. The most common example is a hex-head bolt, though pentagon-, external-torx-, and square- heads exist. They are usually the most resistant to stripping out. Versions with a flange at the base also exist to help distribut load and allow sockets to push on the screw.

b) *Socket head* bolts are preferred. They can be installed in deep wells and have a compact head profile.

c) *Flat head* screws need to be installed into holes that have been countersunk to the same angle as the head of the screw. They allow for a flush, smooth installation.

d) *Button head* screws provide a smooth surface without the need to countersink the surface.

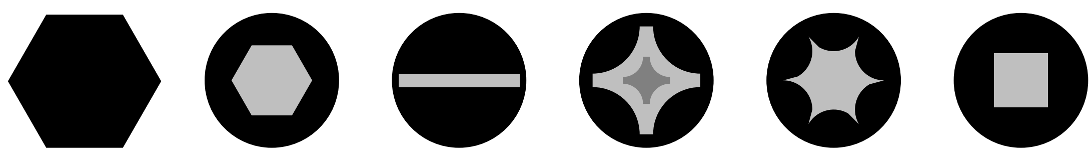
e) *Shoulder screws* are special-use screws. The shoulder (unthreaded) portion is precision ground and usually a larger diameter than the thread. This allows them to be used as pins or pivot points.

f) *Self-tapping screws* have specially formed tips based on what material they are designed to tap into. They thread into material directly; a tap is not required to form threads, and in plastic and wood, are generally stronger.

g) *Carriage bolts* have a rounded head without any means of being driven externally. Instead, the square portion sitting under the thread mates with the material it bolts together (either a plate with the corresponding female portion, or a soft material like wood conforms to the square). *Plow bolts* are the same principle, but are flat-headed.

h) *Set screws* (often called *grub screws*) are used to lock down on another piece of material. They are commonly used to secure hubs to shafts. They have very small hexes relative to their thread diameter and are notorious for stripping out.

There are a lot of different head types that can be put on these bolts as well.



(a) External hex (b) Socket hex (c) Flathead (d) Phillips (e) Torx (f) Robertson

Figure 3.25: Common drive types on engineering fasteners.

a) *External hex* is very robust, although preferred only when side access is available as it has a large profile.

b) *Socket hex* has become an industry preferred head, very easy to access from head-on or in a deep pocket.

c) *Flathead* is not a preferred drive type; it is very easy to have driver fall out while using, and the torque-transferring capacity is quite low.

d) *Phillips* heads are very much not preferred as they are very easy to cam out (in fact, they were designed to do so). When driving a Phillips screw, apply inward pressure, and make sure the proper size driver is selected (it should fit nicely).

e) *Torx* is a preferred drive method, but more expensive and the tools to use it are less common. Very difficult to strip out. When using button-head or flat-head screws, if a Torx variant is available, it can be wise to opt for it as the torque-transferring capacity is higher.

f) *Robertson* or square drive is somewhat preferred, but not common. It is usually found only in wood screws.

The drive heads on flat head, button head, and shoulder screws are necessarily smaller than those of socket head screws, and thusly strip out easier.

Why was the phillips head screw designed to cam out?

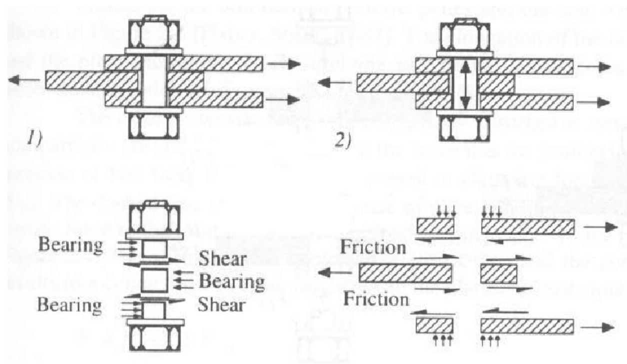


Figure 3.26: Aspects of a bolted joint.

When you tighten a screw, this not only prevents the nut from falling off, but clamps the parts together. This axial clamping force that is imparted upon installation is *preload*, which is very important in threaded joints. For shear loads as illustrated in Figure 3.26, the load is best carried by the friction inbetween plates rather than shearing the pin itself, since the load is distributed across a larger area. For joints that seal against pressures, preload is imperative as it prevents separation under pressure.

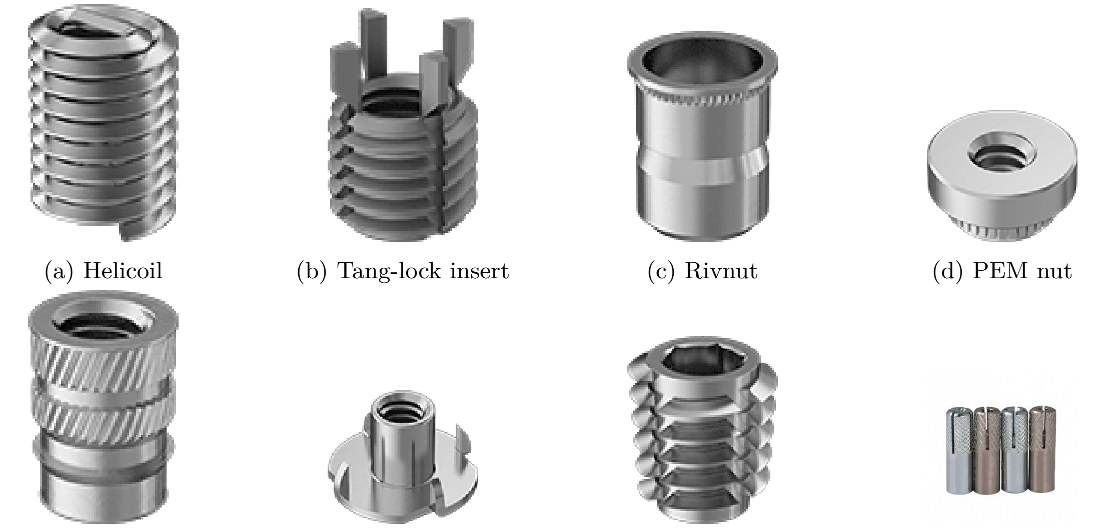
The preload depends both on how much torque is applied to the fastener, and the pitch of the thread. A finer-pitched screw will impart greater preload. Finer-pitched screws also have the benefit of an increased core (minor) diameter, so greater strength in shear. The finer threads may be more fragile and require tighter tolerance, though.

Spreading the load across the greater area increases rigidity and decreases backlash, egg-out, and strength. However, too much torque can dig the head of the bolt/screw into the underlying material, especially if it is soft (like plastic, or even aluminum). As such, care not to overtorque, or a washer may be needed.

(a) Plain washer (b) Machine washer (c) Fender washer

Figure 3.27: Plain washers of differring sizes

Bolts thread into nuts, which can be replaced if they strip out. But if the material a screw threads into strips, then that whole piece will need to be replaced or repaired- which can be even more costly. There are some considerations that can be made to ensure success when using integral threads. The first is to make sure to use coarse (not fine) threads in soft materials like aluminum or plastic. Another option is to use thread inserts.



(a) Helicoil (b) Tang-lock insert (c) Rivnut (d) PEM nut

(e) Heat-set insert (f) Tee nut (g) Wood tapping insert (h) Concrete Anchor

Figure 3.28: Various threaded inserts

a) *Helicoils* can be installed after a thread strips out, or before it does preventatively. They are a coiled piece of metal formed like threads.

b) *Tang-lock inserts* work much like helicoils, but are solid-bodied rather than coiled, and have locking tangs that can be hammered down on installation to make sure the insert doesn't back out.

c) *Rivnuts* (rivet nuts) can be installed into holes in thin metal to provide ample threads for fastening. They work much like rivets (more on those later), but need a special tool.

d) *PEM nuts* serve the same purpose as rivnuts, but are simply pressed into the sheet they are to be installed in.

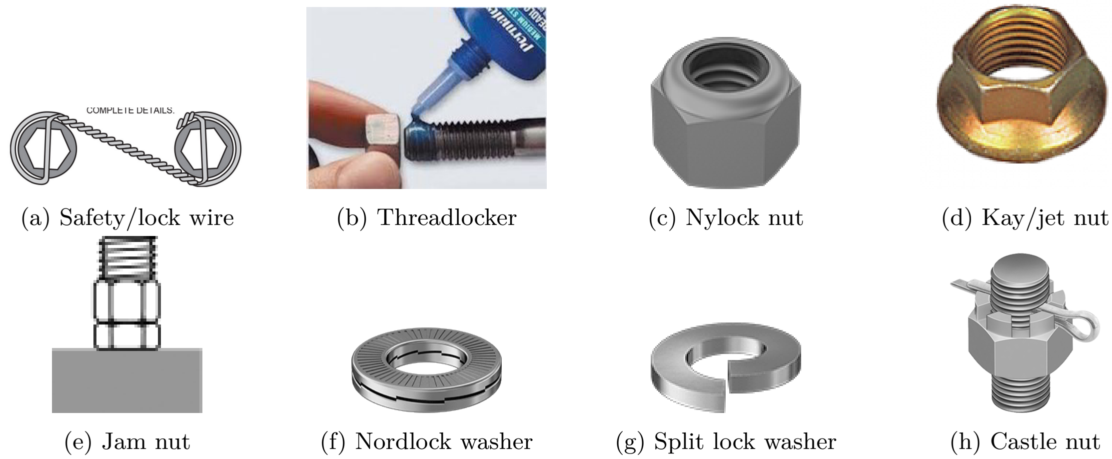
e) *Heat-set inserts* are for plastic. They are installed by heating them up with a soldering iron and pressing them into thermoplastic. An excellent addition to 3D prints.

f) *Tee nuts* are meant to be pressed into wood, much like a PEM nut. The large flange prevents tear-out and helps distribute load in soft wood.

g) *Wood tapping inserts* are much like tang-lock inserts, but with larger wings suitable for wood.

h) *Concrete anchors* come in different flavors (epoxy-in, sleeve, etc) but allow for reusable machine threads to exist in concrete or masonry. The exact type you use, as with most things, is a cost-benefit tradeoff: the more expensive options hold better, but may even require special tools to get them to work properly (especially in the epoxy-in ones).

Threaded joints have one big weakness, and that is their subsceptibility to vibration. There are many solutions to try and combat this.



(a) Safety/lock wire (b) Threadlocker (c) Nylock nut (d) Kay/jet nut

(e) Jam nut (f) Nordlock washer (g) Split lock washer (h) Castle nut

Figure 3.29: Thread locking strategies.

a) *Lock wire* requires tedious installation and bolts with cross-drilled holes to feed the stainless steel wire through. That said, when it is installed properly, it is virtually failure-proof, and as such is the standard in many aerospace and motorsport applications.

b) *Threadlocker* (sometimes referred to by the brand name Loctite) comes in various different strengths and can be used on metal-on-metal contact. It's basically long-cure, specially formulated superglue. However, it does attack many plastics, so be careful! It also requires time to cure to full strength and so is not an instant fix, but must be premeditated.

c) *Nylock nuts* have a nylon patch that deforms when the threads pass through it. The nut should be installed metal-side first, nylon-side last. These are limited use (<50 uses).

d) *Kay/Jet nuts* (metal locknuts) work on the same idea as nylock nuts, but in this case, the nut is deformed and interferes with the thread. It is quite difficult to thread into these nuts. These are extremely limited use (<5 uses) but will work in extreme temperatures, unlike nylock nuts.

e) *Jam nuts* are simply a second nut jammed up against the first nut. This enables easy adjustment, but is not a very positive way of locking something in place.

f) *Nordlock washers* are special ratcheting washers which prevent loosening when properly torqued. There are many different types of locking washers.

g) *Split lock washers* are cheap washers which arguably do not actually prevent loosening.

h) *Castle nuts* are nuts with slots through which a pin can be fed, locking the nut to the bolt it is secured to. A very robust method.

3.4.3 Rivets

Pop rivets are a light and cheap method of fastening. However, they require a special gun and are one-time use. They must be drilled out in order to remove them. They are weaker than bolts, so more must be used, but overall, they are a lighter option. Installation is also more picky than bolting. However, they can still be a time-saver over bolts when disassembly is not a factor.

Rivets are specified by diameter and *grip length* - the amount of material sandwiched together that they can grip. Rivets should be installed straight to close-fit holes with the plates already pulled together.

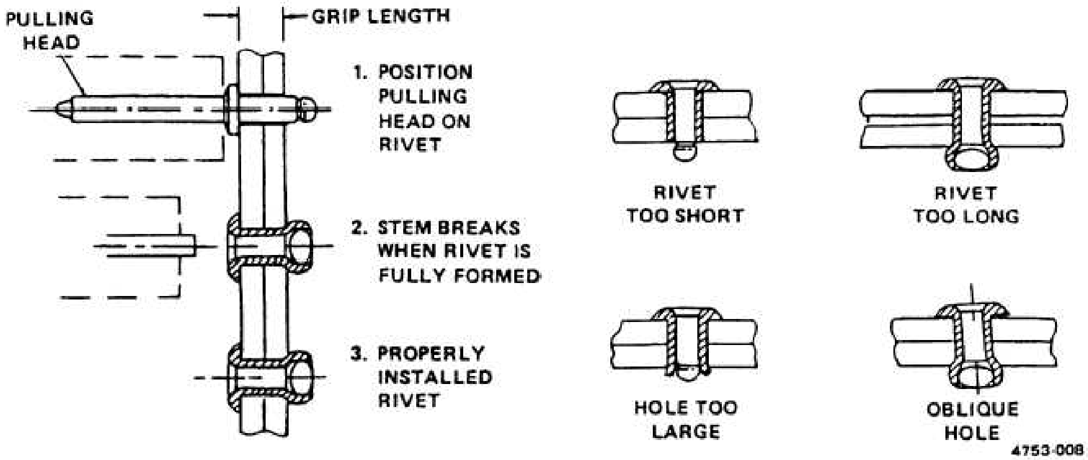


Figure 3.30: Left: Process of Rivet Installation. Right: Diagnosing rivet failures.

Hot rivets are a very different animal than pop rivets. These require very specialized equipment, and work by heating up a rivet to molten temperature, inserting it through the hole to be secured, and hammering it so it expands and mushrooms out on both sides. As the rivet cools, it shrinks further, creating an incredibly robust and secure connection.

3.4.4 Shaft Retention

Retaining rings are used to constrain objects along a shaft.

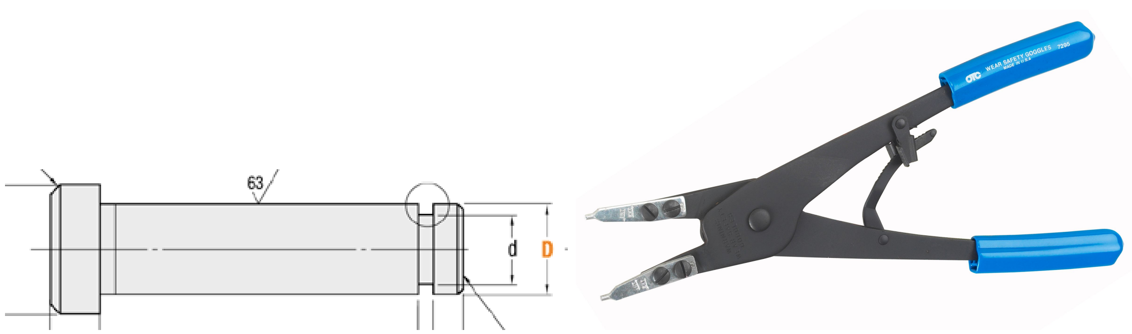


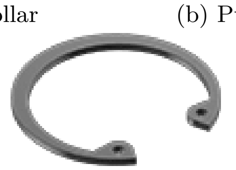
Figure 3.31: Left: Shaft with groove for retaining ring. Right: Snap ring pliers.

(a) Shaft collar

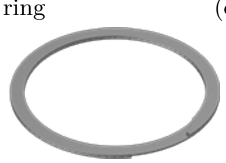
(b) Push-on ring

(c) E-clip

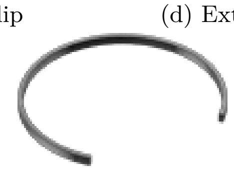
(d) External snap ring



(e) Internal snap ring



(f) Spiral ring



(g) Circlip

Figure 3.32: Shaft Retaining Technologies

a) *Shaft collars* are heavy and high-profile, but easily removable and adjustable. They come in different bore shapes (hex, round, keyed, etc) and in one or two-piece varieties.

b) *Push-on rings* are pushed onto shafts (no groove needed) and ideally ratchet on, never coming off.

c) *E-clips* can be pushed radially into a groove. They are aided by the use of a snap-ring tool to splay them apart, but it is not necessary. They can be installed without passing the clip over the end of a shaft.

d) *External snap rings* are expanded by a snap-ring tool, and installed over the groove of a shaft.

e) *Internal snap rings* are compressed by a snap-ring tool, and installed into the groove of a housing.

f) *Spiral rings* are wound into grooves. They're annoying and rare.

g) *Circlips* are very stiff, low-profile retaining clips intended for permanent installation.

When working with expanding rings, it is very important to not over-extend them on installation. It is very easy to over-extend and damage the rings -leading to successful installation, but potential for the ring to fall off later during use - if expanded much more than is necessary to feed them over the shaft.

3.4.5 Adhesives

a) *Retaining compound* such as Loctite Green is meant to bond bearings to their housings.

b) *Epoxies* are two-part adhesives that are mixed immediately prior to application. They can cure quickly.

c) *Cyanoacrylate/superglue* adhesives are good for many plastics. Loctite has a good design/test guide for different plastic/glue combinations.

d) *Tapes* can be quite useful. Good duct tape and gaffer's tape can be used for high-fidelity prototyping and quick fixes.

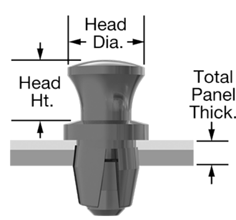
e) *Pressure-sensitive tape* such as 3M VHB can be incredibly strong. Follow the manufacturer's directions for maximum strength.

f) *Hook-and-loop tape* and dual-lock can produce easy but secure removable components.

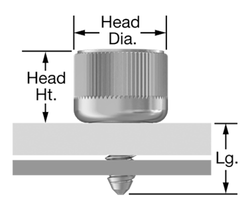
3.4.6 Panel Fasteners

Often panels need to attached to protect something, provide a clean cosmetic appearance, or smooth over a gap for aerodynamic purposes, while still providing easy service to the underlying components. There are a few solutions to this which are more robust and positive than Velcro (which may be perfectly acceptable in many cases). These solutions make sure that the fasteners are kept with the panel so there's no scrambling around to find the panel.

(a) Dzus tabs



(b) Push-pull panel pin



(c) Captive panel screw

a) *Quarter turn fasteners* such as *Dzus tabs* are an easily removable, robust solution. Some require a simple tool (flat-blade screwdriver) to remove. Often found in motorsport applications, they are permanently installed into both the frame and panel. They stick out a very small amount - the thickness of the tab.

b) *Push-pull panel pins*, like these on McMaster-Carr are a light-duty solution, but do not require any special machining to integrate, just drill holes of the right diameters. They also do not require any special tools to remove or attach, and stay captive with the panel they are attached to. However, they do stick out from the panel quite significantly.

c) *Captive panel screws* are effectively screws that are kept captive to the panel. Like any screw, they require the appropriate tool to remove.

3.4.7 The Zip Tie

I had to save the best for last: the *zip tie*, or *cable tie*. Zip ties have a slight reputation as a hackish solution, but this is more a result of people overusing them or overestimating how much they can accomplish. That being said, they can do a lot, from their intended use of holding bundles of wires together, to forming agitating flappers on ball feeding mechanisms. Zip ties come in different materials, although the most common is nylon.

Figure 3.34: The zip tie.

These have a head attached to a long strip, which can be fed into the head to form a loop. The head is ratcheting, so when the tail is pulled through, it will not loosen (until it breaks). Multiple zip ties can be chained together to form a longer one. Some special zip ties can be reused - they have a release lever.

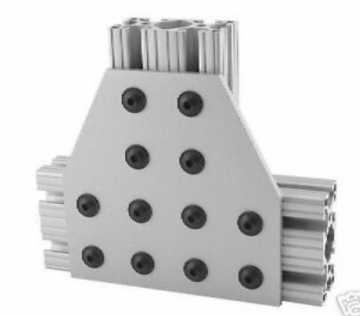
3.5 Fabrication Paradigms / Traditions

To draw an analogy to cuisine... up to this point we've talked about different ingredients - the different herbs, meats, vegetables, fruits, grains that you might use in a kitchen to make a dish with. You can combine them in a lot of different ways, but there are some combinations that make more sense than others, and some that have become traditional because of this. That isn't to say that you can't mix and match and add as you see fit - or even start your own tradition - but there are combinations of technologies that are more common than others.

3.5.1 The 80/20 Tradition

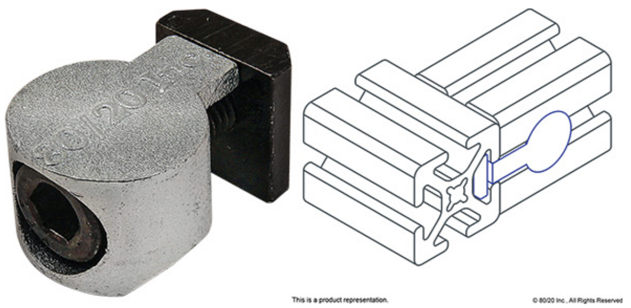
One common tradition is that of using t-slot framing as introduced in section 3.2.3. There are many different components that can be used with t-slot framing. This tradition is quite deep and even has sub-traditions.

(a) T nut



(b) Joiner plate

(c) External bracket



(d) Anchor fastener

(e) Corner block

Figure 3.35: Key components in the 80/20 tradition.

a) *T nuts* are the basic ingredient of the 80/20 tradition. They come in many flavors: some can be dropped in to a t-slot, some can be rolled in, some can only be slid in through the end. However, they all serve the same purpose: they're a nut that stays captive in the T-slot.

b) *Joiner plates* are one way of securing tubes to other tubes. They're straightforward, and come in many sizes.

c) *External brackets* are another way of securing tubes to other tubes. These come in many sizes and thicknesses, sometimes with a reinforcing strip (as shown).

d) *Anchor fasteners* (sometimes nicknamed *lollipop connectors*) are one type of end connector. There are many types of end connectors but these seem to be the most common. The framing gets milled out to accept the round portion of the connector. The connector then fits into one frame, and a bolt going through that connector gets tightened into a t nut inside another frame. The heads of the bolts can be quite frustrating to access and tighten down perfectly, and these also require that the ends of the tubes get milled perfectly square.

e) *Corner blocks* allow corners to get joined together in a very clean fashion. The ends of the extrusions must be tapped to accept a bolt. It is possible to make printed versions of these that allow extrusions to come together at odd angles.

Overall, 80/20 is a very flexible paradigm, but quite heavy and expensive, and can be prone to loosening and sliding under vibration.

3.5.2 The Sheet metal Tradition

Airplanes have pioneered this method of cut and folded sheet metal, riveted together to make complex structures. It's a somewhat like industrial origami.

Figure 3.36: An FRC (FIRST Robotics Competition) chassis made from riveted sheet metal.

Sheet metal can be extremely light, as it has the capability to put material where it is needed most. It is necessary that the sheet be bent to add out-of-plane stiffness. Sheet metal is one of the cheapest forms of metal, pound-for-pound, although the cutting required to make these frames usually produces a considerable amount of waste stock.

Sheet metal is a very scalable process in mass quantity, which is why many things are made from it, even if they aren't riveted as well.

Rivets work best in shear and with plenty of redundancy. Bolts can also be used, but they will tend to egg out the holes, so the sheet metal itself becomes the limiting factor, making the use of a higher quantity of rivets the stronger choice.

John V Neun has some examples of how to use sheetmetal.

3.5.3 The Fingerjointed Plate Tradition

What do you do if you have a way of cutting plates, but no bender? Well, cut thicker ones, and use finger joints to stick it all together! Woodworkers have long used finger joints to make nice craftwork using glue and nail. But if you want to quickly build something and maybe tear it apart, gluing or nailing aren't a good proposition.

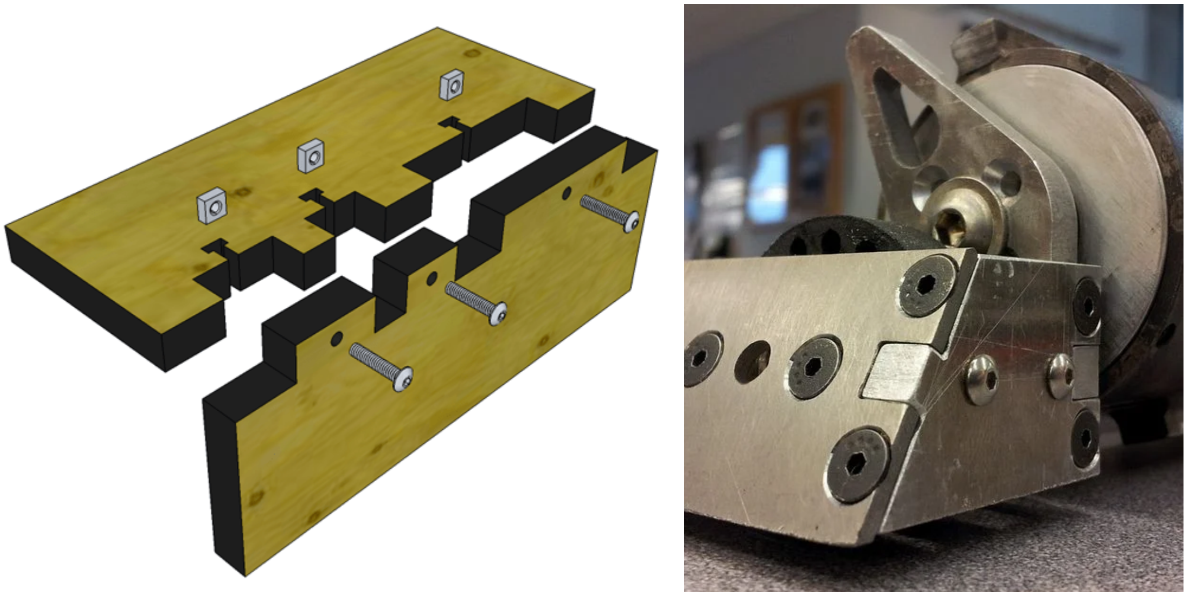


Figure 3.37: Fingerjointed and bolted assemblies.

Such joints are popular among the hobbyist community, and often feature captive nuts and bolting shown above to help keep things together. The fingers transmit shear load, while the bolts help keep things together. The joint above on the left would still flex quite a bit almost like a hinge, so putting another plate perpendicular to both - making a box or gusset - would help the structural integrity more.

These joints can also be made with metal, or at odd angles.

3.5.4 The Bracket and Tube Tradition

Sheet metal is cool, but doesn't have to be used that much. It isn't a very effective way at spanning long distances, and requires lead time since you have to get the profile cutting supplier/equipment to do it.

Figure 3.38: Tubes held together with sheet metal gussets.

Brackets can come in many shapes and sizes and purposes. They can join together tubes by sandwiching them (see the hypotenuse), join tubes by being installed to the side (see the joint of the legs), or mount extra components like bearings and motors. Brackets are cheap, often made of sheet metal and produced in large quantities, as is box tube. You can even purchase or make extrusion with regularly drilled holes, so that you don't need to bother fabricating holes into the tubes come time to build a structure.

As with sheet metal, both bolts and rivets can be used - but the use of redundant rivets rather than bolts can end up being lighter and stronger, although less serviceable.

3.5.5 The Spaceframe Tradition

Tubes are strong and light. Welds are even lighter than gussets. Welding tubes together directly and using round, rather than square tube to prevent stress concentrators creates *spaceframes* or *tubeframes*.

Figure 3.39: A spaceframe for a Formula SAE racecar.

Spaceframes are time-consuming to produce, as tubes must be cut to length and have the ends shaped so they fit together, a process known as *coping* or *notching*. Additionally, a jig or figure is required to hold all of the tubes in place before they are welded. On the upside, they allow for near-ultimate flexibility in material placement and routing.

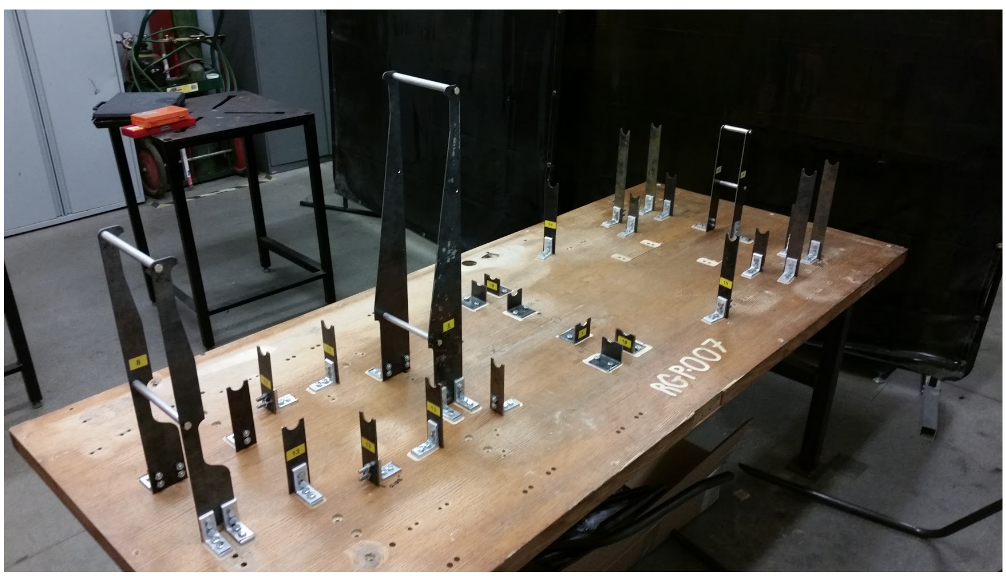


Figure 3.40: A jig for a spaceframe.

Chapter 4

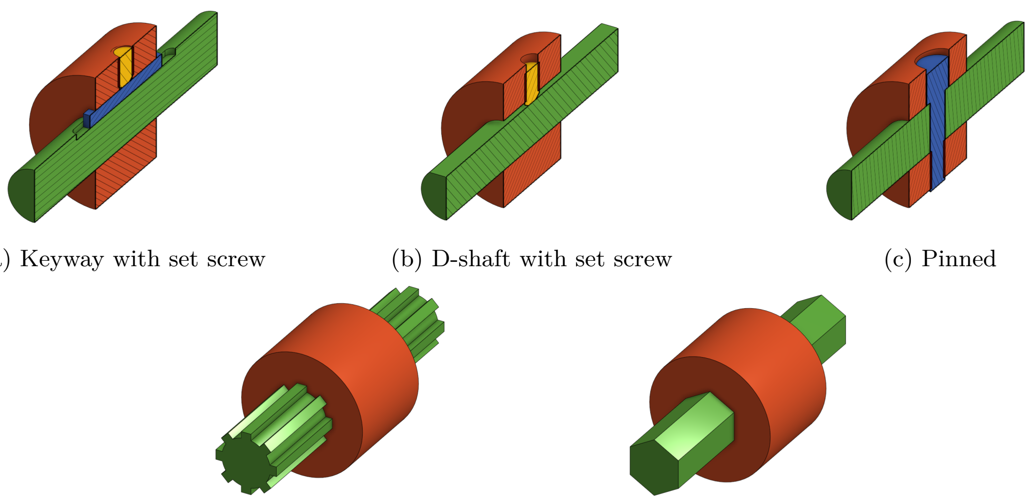
Complex Components

4.1 Axial Power Transmission

Getting power transmitted over a shaft in a straight line is not terribly difficult, but still must be done properly.

4.1.1 Shafts, Hubs, and Interfaces

Shafts or *axles* are rotating components which mate into *hubs*. *Hubs* may be used then to mount to other useful components like wheels or arms, or may be integral to said useful components.



(a) Keyway with set screw (b) D-shaft with set screw (c) Pinned

(d) Spline (e) Hex or other polygon

Figure 4.1: Shaft-hub geometries.

a) *Keyed* shafts, shown in green, have grooves into which *machine keys*, shown in blue, can be halfway inserted. The hub, shown in orange, has a groove matching the other half of the key. Set screws, shown in yellow, may be included to clamp down on the key to make sure it doesn't move, and to help secure the key from fretting. These connections are quite common in industrial applications, but their load-carrying capacity is low compared to alternatives.

b) *D-shafts* have a small flat milled into them. This allows either a hub with a D-shape to mount to it, or a hub that is internally round but has a set screw (yellow) that can tighten down onto the flat. The addition of the flat makes this a much more secure connection than simply tightening the set screw onto a plain round shaft.

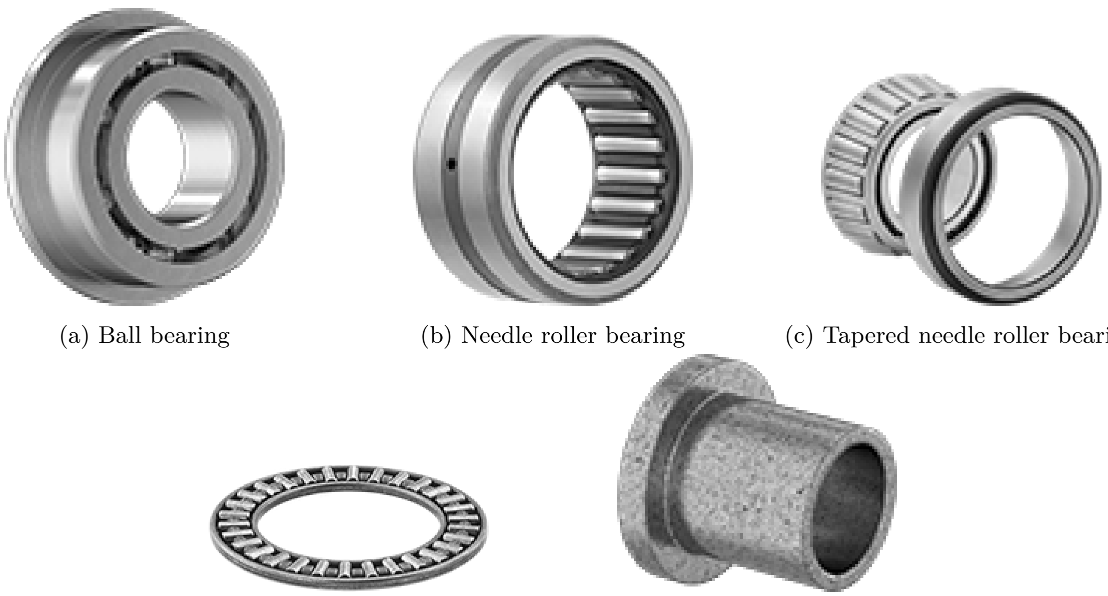
c) *Cross-pins* or bolts can be used to secure shafts. There many variations on this, but one easy to build, easy to maintain, and fairly reliable method is shown. The hub is tapped on one side, and has a hole with clearance for a bolt head on the other side. The shaft has a clearance hole for the bolt. This makes lining up the shafts easy, and the tightening action will help eliminate wobble.

d) *Splines* are complex geometric shapes with many load-bearing teeth. There are many different standards of splines. These are hard and expensive to produce, but provide the highest torque-transmitting capacity.

e) *Hex* and, in general, *polygon* shafts are a good compromise between cost and load-bearing capacity. Hex is extremely common, especially within the FRC ecosystem and agricultural equipment. Hex stock in many different materials can be readily procured to use as shafting material, and a hex broach can be used to produce the hub.

4.1.2 Bearings, Bushings

Bearings and bushings are components which help eliminate wear between moving surfaces.



(a) Ball bearing (b) Needle roller bearing (c) Tapered needle roller bearing

(d) Thrust bearing (e) Plain bushing

Figure 4.2: Bearings for rotary motion.

a) *Ball bearings* have an inner *race* and an outer race with balls in between. These balls are spread out by a cage. They come in many different varieties.

Sealed bearings have a rubber seal keeping contaminants out.

Shielded bearings have a shield that keeps shrapnel out.

Open bearings have no protection whatsoever. Seals and shields trap heat, and necessitate the use of grease rather than oil. This means that in an oily environment (like an engine), open bearings can be much more efficient.

Deep groove ball bearings are the most common (meaning the balls contact primarily radially).

Angular contact and *X-contact* bearings are better at handling thrust and combined loads.

Flanged bearings have a flange which prevents the bearing from falling through the hole into which they are installed. Not all bearings are flanged.

b) *Needle roller bearings* have an outer race, and inside that, a cage that contains multiple rollers. These bearings can ride directly on a shaft if the shaft is sufficiently hard, or a separate inner race can be used.

Needle roller bearings are very low-profile and have very high load-bearing capacities as the rollers distribute load over a larger region. However, they do nothing to retain a shaft axially.

c) *Tapered needle roller bearings* are heavy-capacity bearings good for combined loading, often used in automotive applications. These mate with a *cup*, much like a needle roller bearing mates with an inner race. These must be used in pairs in opposing directions, and axial preload is necessary for proper operation.

d) *Thrust bearings* are high-capacity bearings that take thrust (axial) loads rather than radial. This means they are often found in conjunction with needle roller bearings to make a bearing assembly that is high-capacity, compact, and light.

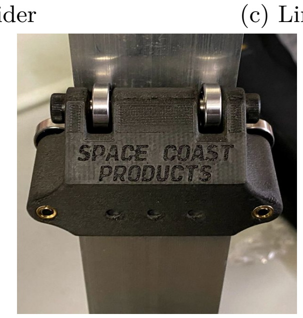
e) *Plain bushings* are high-capacity, low-RPM single-piece parts. They are made from low-friction materials like oil-impregnated bronze, or plastic. These are good because they are cheap, extremely compact, and very tolerant of improper alignment, dimensional accuracy, and shock loads (since there are no small parts to produce indents).

(a) V bearing

(b) 80/20 slider

(c) Linear ball bearing

(d) Linear bushing



(e) Elevator bearing assembly

Figure 4.3: Bearings for linear motion.

a) *V-bearings* can be used in multiples to constrain one part to a rail with appropriate mating geometry.

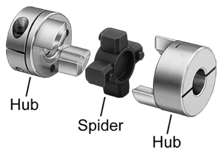
b) *Linear sliders* can be used to constrain one part to a rail, cheaply and with a low profile.

c) *Recirculating linear ball bearings* are high-precision components which are very efficient, which work in conjunction with precision ground rod. These are quite expensive, however, and sensitive to dust, dirt, and shrapnel.

d) *Linear bushings* are high-precision components which serve the same purpose as linear bearings, but are less sensitive to cleanliness, and often cheaper, although they have higher friction.

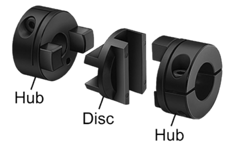
e) *Ball bearings* can be arranged in clever ways on a shaft or tube in order to produce linear guidance.

4.1.3 Drive Couplings

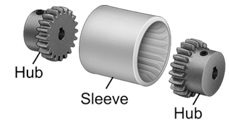


(a) Spider coupling

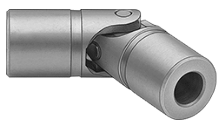

(b) Flexible coupling

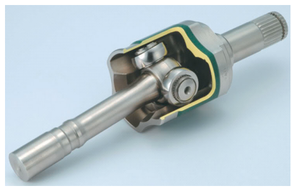


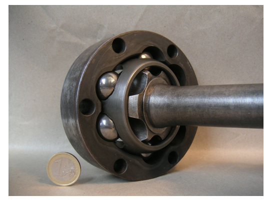
(c) Oldham coupling



(d) Gear coupling


(e) Universal joint


(f) Tripod and tulip


(g) Rzeppa joint


(h) Guibo, or flex disc

a) *Spider couplings* consist of two hubs with teeth that interface with a rubber spider. The rubber spider enables some misalignment of shafts (but does provide some support), and also dampens out vibrations.

b) *Flexible couplings* are single-body couplings with several slots machined into them in order to make them more flexible. This allows for misalignment of shafts depending on the exact design, while maintaining low backlash.

c) *Oldham couplings* consist of two hubs with slots that interface with a sliding central portion. They facilitate high shaft misplacement, but do not help with angular or axial misalignment.

d) *Gear couplings* consist of two spherical hubs with gear teeth cut into them, and a mating sleeve over the hubs. This allows the hubs to plunge inside of the sleeve in addition to being at odd angles, so allows for extreme misalignment, but is quite costly and does present some wear issues at extreme angles.

e) *Universal joints* or *u-joints* have a central cross-shaped coupling that connects the two u-shaped halves. This enables quite extreme angular misalignment (usually about 30 degrees) However, they are not constant-velocity.

f) *Tripods* are a type of *constant-velocity (CV) joint*. These consist of three bearings fixed to a hub. The bearings contact a tulip and slide back and forth on it. This joint can handle decent angular misalignment (usually about 15 degrees) and allows for axial movement, referred to as *plunging*.

g) *Rzeppa joints* are another CV joint. These joints cannot plunge, but do allow for severe angular misalignment (usually about 45 degrees). Front-wheel drive cars often use shafts where the differential side has a tripod joint and the wheel side has a rzeppa joint. This way the shaft can plunge, and the wheel can be powered and steered.

h) *Guibos* or *flex discs* are a joint (can can be considered a CV joint) which use two hubs connected by some flexible (usually rubber) coupling. This helps to absorb vibrations, and handles shaft misalignment.

> What is this ”constant velocity” behavior, and why is it important in some applications?

4.2 Nonaxial Power Transmission

We often need to transmit power from one place to another not in a line. We also often need to change the torque and speed ratios of the power. There are many ways of doing this.

4.2.1 Rope and Pulleys

Ropes, pulleys, and spools are the simplest way to transmit power from one place to another. They aren't particularly technical, but there are a few nuances which can be used to help design systems using them.

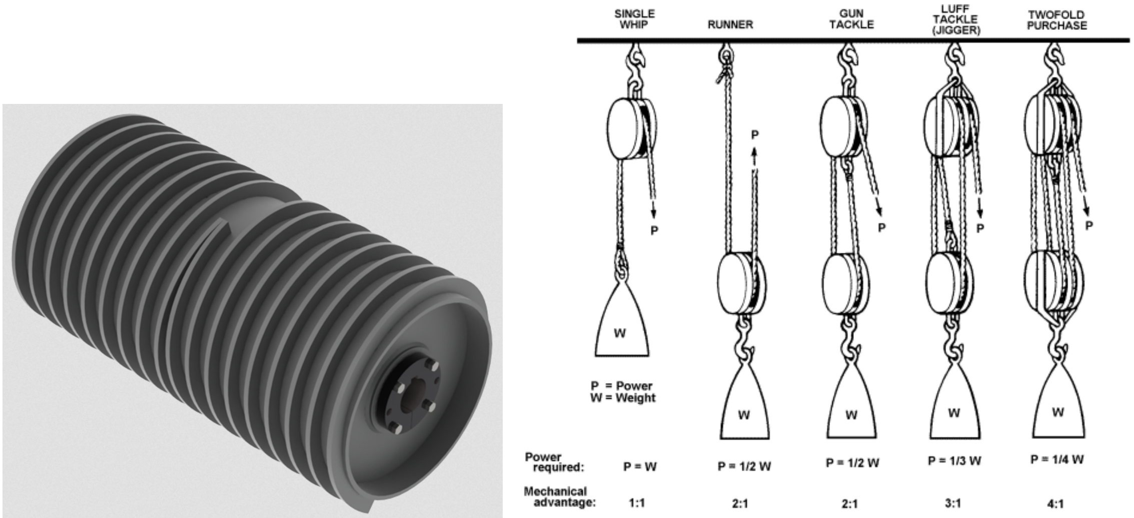


Figure 4.5: Left: helical takeup pulley. Right: various block and tackle.

Helical takeup pulleys have grooves in them which help route rope so that when it is wound, it is wound at a constant radius. This can help prevent binding or slack in closed-loop systems (like continuous rigging elevators). To help closed loop systems more, a spring inline with the rope can take up more slack than a stiff rope. Video Example (0:05)

A *block and tackle* is a system of two or more pulleys with a rope routed between them in alternating fashion as shown. This generates mechanical advantage; the rope must be pulled more to achieve the same lifting force. This also decreases the input load required to raise the load by a factor of the number of ropes.

4.2.2 Gears

A *gear* is effectively, a wheel with teeth. These teeth are specially shaped in order to *mesh* and mate nicely with other gears, so you need to be careful that you're using gears that are compatible with each other, and spacing them far enough apart.

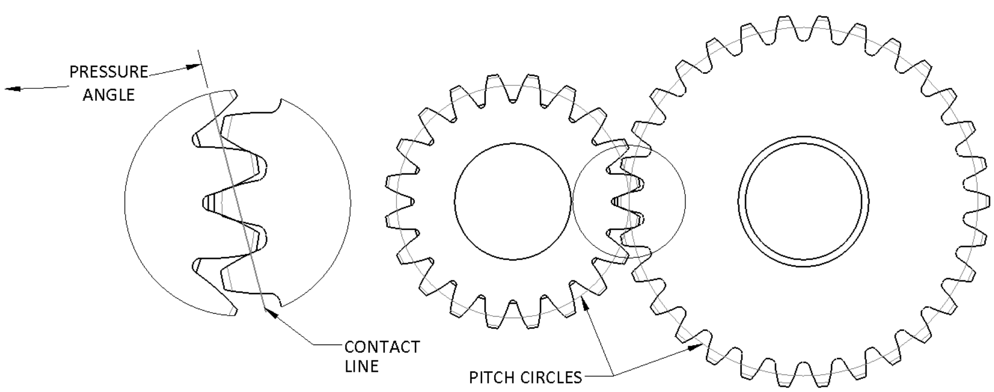


Figure 4.6: Nomenclature of different gear dimensions

Gears are specified, among other things, by the number of teeth, their *pressure angle*, and either the *diametral pitch* or *module*.

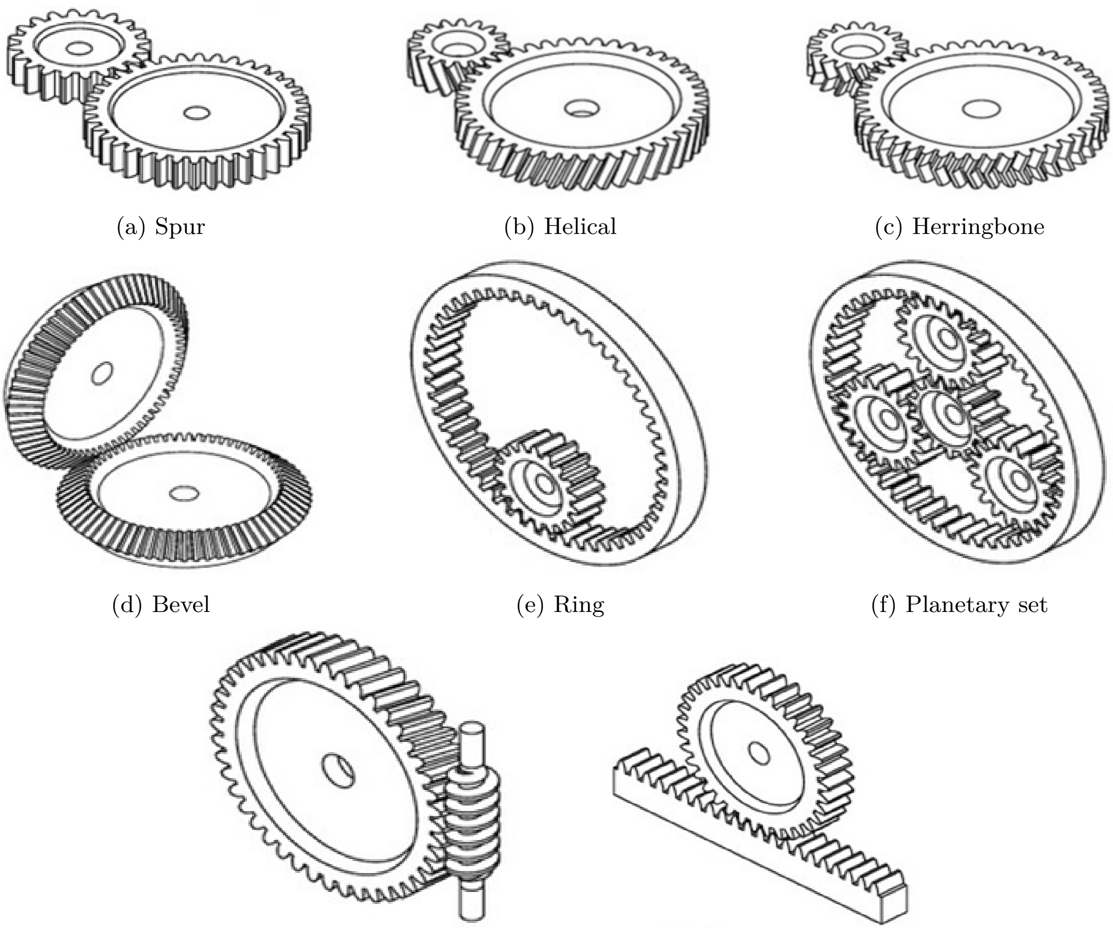
a) Gear teeth have an *involute* profile. This is a specific geometric shape that is not quite an arc, but makes sure power transmission is smooth; without excessive backlash.

b) The *pitch circle* is a rough representation of the gear as a wheel. It lies somewhere in between the overall diameter and the diameter of the root of the teeth. You can draw up a sketch containing gears' pitch circles tangent to each other, and then they will fit together.

c) A gear's *diametral pitch* (DP) is the number of teeth in a gear divided by the pitch diameter (in inches). So, if a gear has 50 teeth and is a 20DP gear, it would have a pitch circle of diameter 50 $teeth$ / 20 $DP =$ 2.5 $inches$. For two gears to be compatible and mesh, they must have the same diametral pitch, otherwise the teeth would be the wrong sizes.

d) A gear's *module* is a gear's pitch diameter (in mm) divided by the number of teeth. This measures the same thing as diametral pitch, just in a different way. If a 5 module gear has 30 teeth, its pitch diameter would be 5 $mm \times 30$ $teeth = 150$ mm.

e) A gear's *pressure angle*(PA) measures how steep the teeth are, or the angle of the contact line. This must be the same between two gears for them to be compatible. There is a lot of testing and science behind picking a good angle; higher angles are weaker and produce higher loads on the system, but do make oil flow better. Usually, though, this isn't a big concern- just make sure that you don't mix and match pressure angles. 14.5 degrees is common for greased gears.



(a) Spur (b) Helical (c) Herringbone

(d) Bevel (e) Ring (f) Planetary set

(g) Worm (h) Rack & pinion

Figure 4.7: Various different gear sets.

a) *Spur* gears have straight-cut teeth. This means they are two-dimensional and relatively simple to produce.

b) *Helical* gears have angled-cut teeth. These are harder to produce, but they create smoother power transmission since multiple teeth are in contact, creating a seamless hand off. However, the helical nature produces an axial load in addition to the radial load that gears already produce.

c) *Herringbore* gears are effectively two helical gears back-to-back. This causes the axial loads that helical gears produce to cancel out. This type of gear, though, is obviously even more complicated to produce.

d) *Bevel* gears allow power transmission along non-parallel axes. It is important to note that bevel gears are made as sets- you cannot use a 40T gear intended for use with a 20T, with a 60T, as the angles will not mesh up.

e) *Ring* gears are simply inverse spur gears.

f) *Planetary* gear sets are compact reductions that can be configured in many ways depending on which part of the set is fixed in place. Typically, the ring is held fixed, the central *sun gear* is driven, and a *carrier plate* (now shown) holding the *planet gears* is the output.

g) *Worm* gears are extremely compact reductions, but are often not very efficient. The worm wheel (right) might have one or several *leads*, or teeth. A lower number of leads will reduce the gear set's ability to be backdriven, which can be a desirable characteristic.

h) A *rack and pinion* can be used to transform rotary motion into linear motion, or vice versa.

A *gearbox* which contains multiple gears constrained with bearings must be designed to withstand the various loads produced by gears.

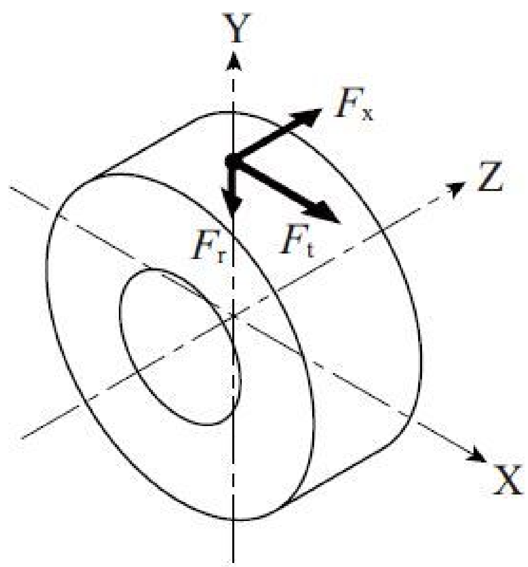


Figure 4.8: Forces on a gear tooth.

a) *Tangential force* is found simply as $F_t = T_{gear}/r_{pitch,gear}$, and is the major and obvious load that must be withstood.

b) *Radial force* is produced as a result of the pressure angle. It can be computed as $F_r = F_t \tan(\alpha)$ where α is the pressure angle. As such, higher pressure angles will produce higher radial forces, which will push gears apart.

c) *Thrust force* exists for helical gears and is computed as $F_x = F_t \tan(\beta)$ where β is the helix angle.

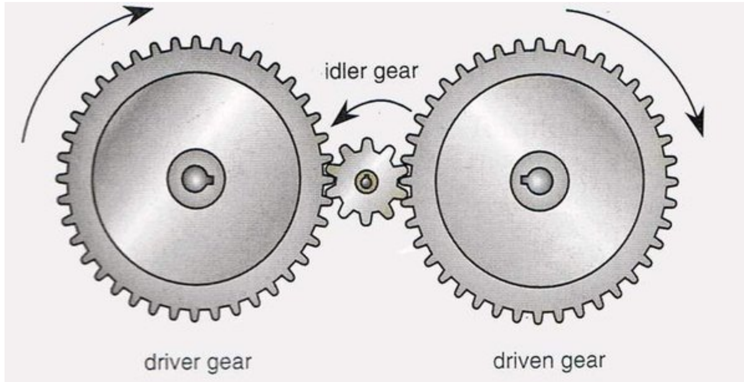


Figure 4.9: A spur gear set with a idler gear (middle).

Idlers can be introduced to a gear set to change the direction of rotation, or to bridge a large gap and transmit power from one place to another. The idler does not impact the overall gear ratio, only the direction of motion.

Differentials are a special arrangement of gears that can be used to produce differential motion

$$\omega_{input} = \frac{\omega_{left} + \omega_{right}}{2}. \tag{4.1}$$

This is desirable as a speed difference can be had between the left and right sides (for instance, a car that is turning has its wheels running at different speeds) while still sending power to both.

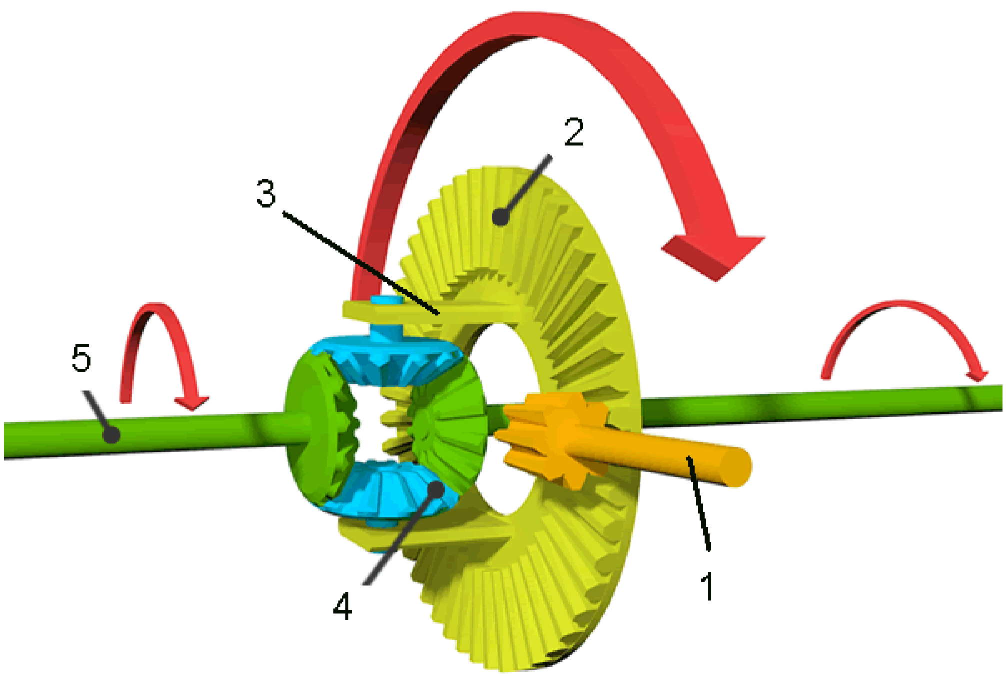


Figure 4.10: A differential.

A plain or *open* differential uses an outer casing to drive a central *spider* gear. This spider is connected to the left and right gears. Analysing the torque balance on the spider gear reveals

$$
\begin{aligned}
\Sigma T &= m\alpha = 0 \\
0 &= \frac{T_{left}}{r_{left}} r_{spider} - \frac{T_{right}}{r_{right}} r_{spider} \\
T_{left} &= T_{right} \text{ if } r_{left} = r_{right}
\end{aligned}
\tag{4.2}
$$

Analysing the torque balance on the whole differential reveals

$$
\begin{aligned}
\Sigma T &= m\alpha = 0 \\
0 &= T_{left} + T_{right} - T_{input} \\
T_{left} = T_{right} &= \frac{T_{input}}{2}
\end{aligned}
\tag{4.3}
$$

As such, the open differential makes the torque on each wheel the same. This can be problematic if one wheel loses traction, as the other wheel will have its torque capacity correspondingly reduced. *Limited-slip* differentials employ additional components or techniques such as clutch packs to limit the amount of speed difference $|\omega_{left} - \omega_{right}|$ and/or the amount of torque difference $|T_{left} - T_{right}|$ to continue delivering power in adverse conditions.

> An adder-subtractor is an arrangment of differentials and gears that can be quite useful. Why would you want to use something like it? (Look up: “differential swerve”, “differential elevator”, “adder-subtractor module”).

4.2.3 Roller Chain and Sprockets

Roller chain is a robust way of transmitting power from one place to another.

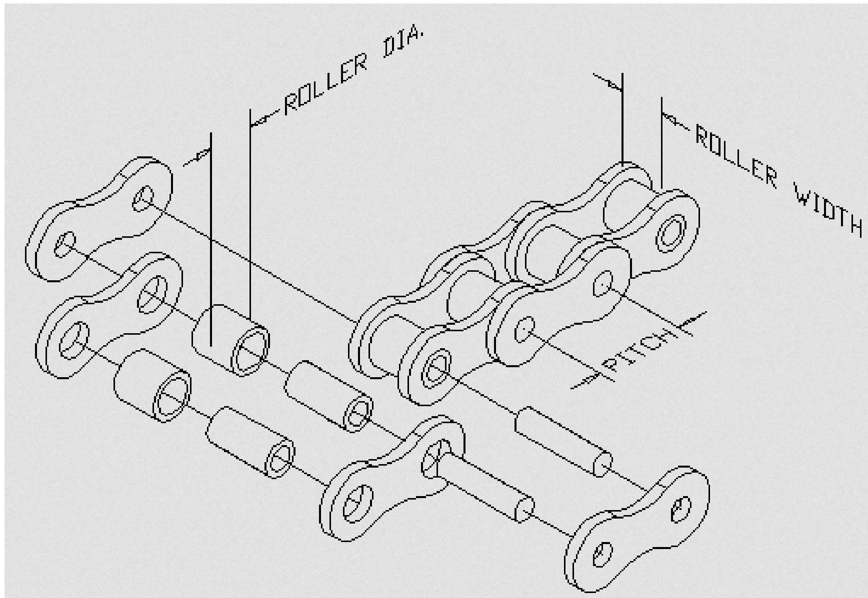


Figure 4.11: Roller chain exploded view, and dimensions

Chain is dimensioned by the *roller diameter*, *roller width*, and *chain pitch*, but may have a standard number that details all of these. Table 4.1 lists some common sizes.

Chain #	Pitch (in)	Roller Width (in)	Roller Diameter (in)
25	0.250	.125	.130
35	0.375	.188	.200
40	0.500	.312	.312
41	0.500	.250	.306

Table 4.1: Common roller chain dimensions.

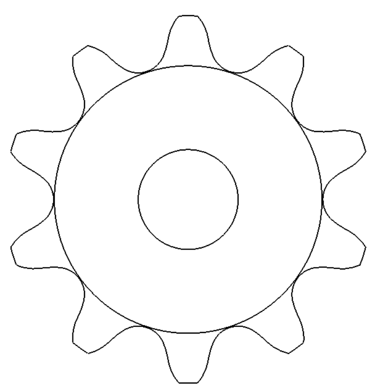
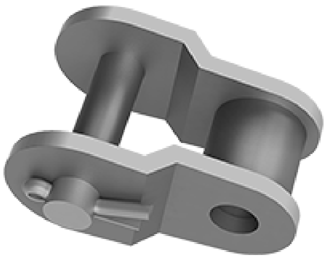


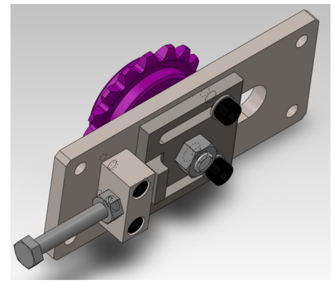
Figure 4.12: A sprocket's profile.

Sprockets are shaped specially to mesh with chain- they are not gears. *Hub* sprockets are designed to mount directly to a shaft, while *plate* sprockets mount with a bolt pattern to another mechanism, or a hub.

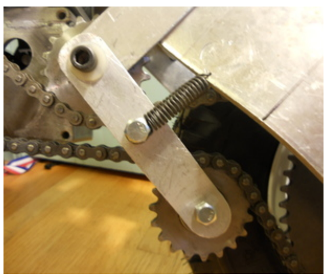


(a) Half link

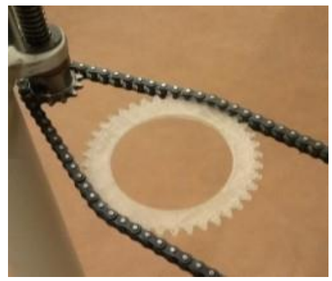
(b) Master link



(c) Axle position adjustment



(d) Idler sprocket



(e) Floater

(f) Inline tensioner

Figure 4.13: Various different adjustment methods for chain.

Chains need to be properly tensioned to make sure that they do not skip, to reduce the backlash of the system, and still run smoothly. If they are too tight, they can bind. If too lose they can skip teeth and throw the chain off the sprockets.

a) *Half links* can be used for coarse adjustment. Normally roller chain is made of connecting links and outer pin links, so adjustments can only be done in lengths of $2 \times pitch$, but half links allow adjustments of exactly the pitch. However, these half-links are often significantly weaker than

b) *Master links* are quickly removable links of a chain that use a clip to retain the pins rather than being pressed into position. This clip has a nonzero chance of falling off.

c) *Moving the distance of the axles* is an easy method of adjusting the tension. This can be accomplished in a multitude of ways. This may not be easy to accomplish, however.

d) *Idler* rollers or tensioners may be added to increase the tension by re-routing the chain. They may be spring-loaded or automatic, or fixed. These (sometimes in multiples) can also be used to increase chain wrap.

e) *Floating sprockets* can be added to increase the tension. These can be further adjusted by moving the floater away from the center and towards the ends.

f) *Inline tensioners* can be used when the chain does not make full revolutions. These are easy to integrate and are very low-profile.

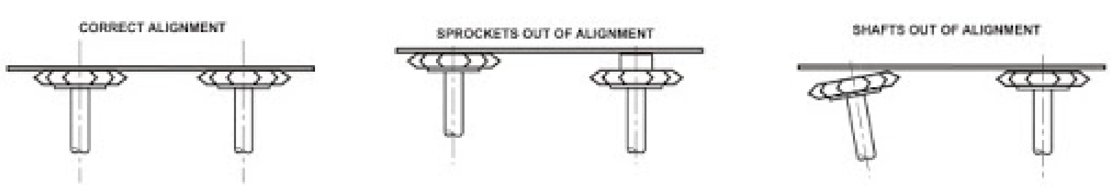


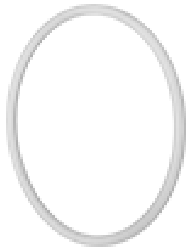
Figure 4.14: Sprocket alignment.

Sprockets and the axles they ride on must be aligned properly otherwise there is a risk of throwing the chain.

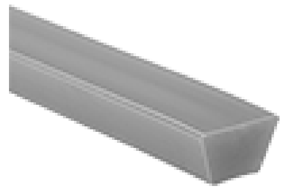
Wrap is another important consideration for chain drives. If there is not enough teeth in engagement with the sprocket, the sprocket may wear out or break, or the chain may skip.

4.2.4 Belts, Pulleys

(a) Flat belt



(b) Polycord / round belt



(c) V belt

(d) Timing belt

Figure 4.15: Various drive belts.

A *belt* is a continuous loop of a flexible material. There are many different types of belts.

a) *Flat belts* are flat in cross-section with no special features. They transmit power solely by friction. A crowned pulley, proper tensioning (about 1-3% stretch for polyurethane belts), and alignment keeps the belt from walking side-to-side excessively.

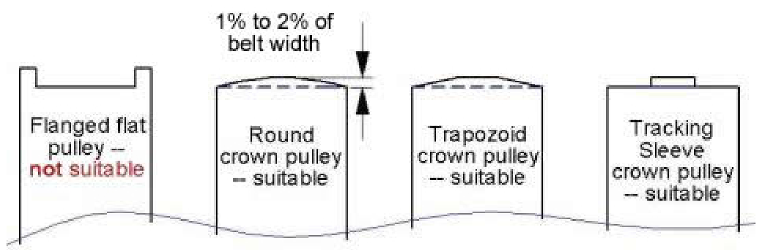


Figure 4.16: Crowning on pulleys to keep flat belts on pulleys.

b) *Polycord* or *round belt* is round in cross-section. They are somewhat forgiving in how much they can be tensioned (as long as ample stretch is provided; around 10% for polyurethane cords). They work best with pulleys that have a 60 degree (included angle) V cut into them.

c) *V-belts* have a V cross-section that digs in to pulleys. Multiple vees may be attached side-by-side for increased flexibility. They (usually) have reinforcing fibers that provide strength and stiffness much higher than pure rubber. Sometimes they have teeth in them, but these teeth are not for power transmission, they are simply to allow greater flexibility in the belt while still allowing for a tall, centering profile.

d) *Timing belt* has teeth to ensure positive transmission of motion (so it can be used to time multiple components together). It has very high load-carrying potential without need for perfect tensioning. Like v-belts, they have reinforcing fibers that provide strength and stiffness much higher than pure rubber. There are many different series of timing belts (HTD, GT2, MXL, etc.) - they are not compatible with each other. In FRC the most common are HTD and GT2 (which are, actually, semi-compatible). The pitches must also be the same in addition to the series.

Belts, like chain, must be properly tensioned and aligned. Most of the methods explained for chains also work for belts. Special considerations must be made for the back-bending capacity of the belt in question (every belt has a rated back-bending radius). Pulleys for timing belts usually require at least six (6) teeth of engagement, although this may increase or decrease based on your load case and manufacturer's recommendations. Timing belt doesn't need tensioning, just correct and precise spacing.

My EveryCalc has a calculator to determine the length of belt needed to achieve a certain center-to-center distance (or vice versa) for flat belts, polycord, and timing belts.

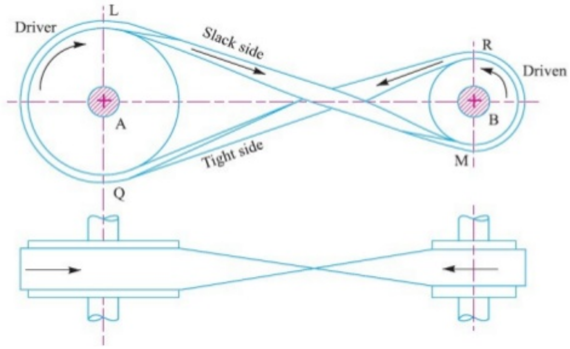


Figure 4.17: Crossed drive belt

Belts can be crossed in order to transmit power while reversing direction, or even transmit power between non-parallel axles. This generally works best with polycord, but can be accomplished with any belt.

4.3 Lead Screws

Figure 4.18: Lead screw and nut

Lead screws are specially-formed screws that are intended for power transmission. They are used in conjunction with a correspondingly threaded nut to transform rotational motion into linear motion. Like worm gears, they may have multiple *leads*, and depending on the angle, may be self-locking. The more leads and the coarser the thread pitch, the slower the nut will move, the efficiency will be decreased, and the arrangement will be more self-locking.

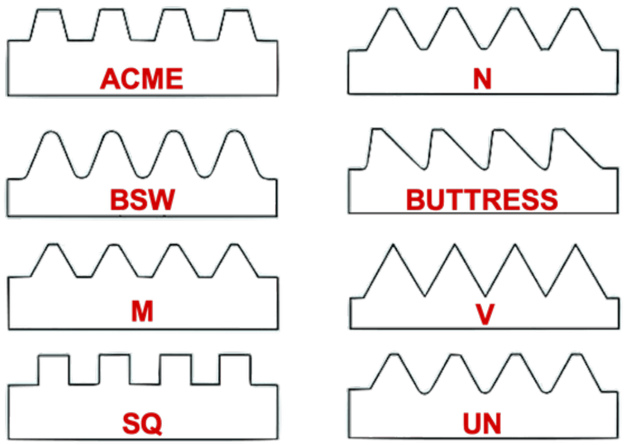


Figure 4.19: Different thread forms

While typical screws use triangular thread forms, there are more types for lead screws, and lead screws generally have a much higher surface finish since they will be screwed and unscrewed repeatedly.

a) *Square* threads offer superior performance and reduced sliding friction. However, they are much harder to produce.

b) *Acme* threads are a particular standard using trapezoidal-shaped threads. The increased size of the thread provides more strength, and they have a shallower angle than a typical thread, providing a compromise from a square thread for manufacturability sake.

c) *Buttress* threads are asymmetrical, intended to be loaded dominantly in one direction (e.g. for a lift).

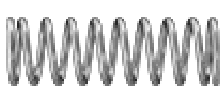
d) *Ball screws* have round cutouts intended for recirculating ball carriers. These are a class of their own, requiring the highest precision, but offerring the most efficient power transfer.

4.4 Energy Storage

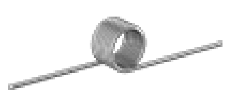
4.4.1 Springs

Springs are components designed explicitly to change shape by a great distance and store energy in the process.

(a) Extension



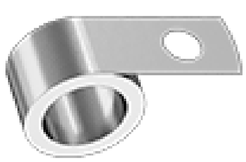
(b) Compression



(c) Torsion

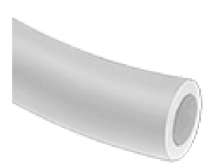
(d) Progressive

(e) Leaf

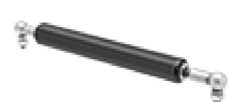


(f) Constant-force

(g) Rotor



(h) Surgical tubing



(i) Gas shock

a) *Extension* springs can be pulled on to provide tension. They have hooks or loops on either end for attachment. They provide force F proportional to the distance Δx they have been stretched from their relaxed state.

$$F_{spring} = k\Delta x \tag{4.4}$$

b) *Compression* springs can be pushed on to provide compressive resistance. There are different styles of ends (open, closed, closed and ground). Like extension springs they have a linear force ratio.

c) *Torsion* springs can be bent to provide resistance. They come in different windings and are designed to be bent in a particular way and not the other. Like extension springs they have a linear force ratio (although the units may be angular).

d) *Progressive* springs are compression springs that have variable windings. As they are compressed, the tighter wound windings bottom out, increasing the spring rate k.

$$F_{spring,\ progressive} = k(\Delta x)\Delta x \text{ where } \frac{dk(\Delta x)}{d\Delta x} > 0 \tag{4.5}$$

e) *Leaf* springs are flat strips, sometimes stacked on top of each other. Commonly used in truck suspensions as they can also act as suspension links in their stiff direction.

f) *Constant force springs* are thin strips of stainless steel that are tightly coiled. The strip can be secured to one object while the rest of the coil is secured to another object. Unlike other springs, the force does not vary much with distance, making them ideal for many scenarios.

$$F_{spring,\ constant-force} \approx F_k \tag{4.6}$$

g) *Rotor* springs can be wound many times to provide not quite constant, but close to constant force as the coils unwind.

h) *Elastic* such as *surgical tubing* can be used as a cheap and adjustable source of springiness. Surgical tubing can be easily mounted with zip ties and the insertion of a plug into the ends.

i) *Gas shocks* provide not only spring force, but damping as air is throttled through a small orifice. They also come as bolt-on units, making packaging quite clean.

4.4.2 Flywheels

Figure 4.21: A flywheel.

Flywheels are discs of material which are intended to spin at high speed to store energy for future use. This could be to even out the vibrations in an engine, or to store energy in a flywheel-based shooter. They are specified by their *moment of inertia* I.

This moment of inertia can be computed with a volume integral:

$$I = \int_{\forall} \rho r^2 d\forall, \tag{4.7}$$

where ρ is the density of the material and r is the distance from the axis of rotation. This may be confusing and not mean but much to you, but the takeaway is this: a larger (bigger r), denser (bigger ρ) flywheel has a higher moment of inertia, so can store more energy. By placing the mass of a flywheel far away from the center and hollowing out the center, the moment of inertia can be increased while minimizing mass.

4.5 Wheels

There are many different types of wheels so they're worth of their own section.

4.5.1 Hard Wheels


(a) Molded tread wheel

(b) Colson wheel


(c) Removable tread wheel

a) *Molded tread wheels* have a hard plastic center that is molded into or bonded to a grippy exterior which may be textured. These are cheap and usually quite solid options, but do wear over time.

b) *Colson* wheels are a brand name of wheel that has a firm but grippy rubber exterior. They are known for their very consistent wear and abrasion resistance.

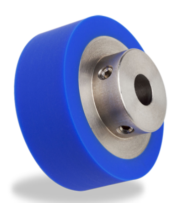
c) *Removable tread* wheels or *plaction* (plastic+traction) wheels have a solid plastic or metal center with removable tread fastened to the outside with rivets, bolts, or staples. This allows for the use of extremely grippy but quickly-wearing tread.

4.5.2 Soft Wheels


(a) Tubeless tire


(b) Tubed tire


(c) Tweel


(d) Fairlane wheel


(e) Compliant wheel

a) *Tubless tires* are simply tires mounted to a hub. The tire makes a seal on the hub allowing it to be pressurized with air. *Pneumatic tires* (tubed and tubeless alike) usually have the appropriate amount of squish to be used as shock absorbtion, and also will flatten out and dig into rough surfaces like carpet, making them quite grippy.

b) *Tubed tires* are tires mounted to a hub with a *tube* inside of them. This tube is pressurized and presses against the tire and hub. This helps prevent punctures to some degree and allows for replacement or repair of the tube rather than tire, which is significantly easier. There are techical drawbacks to these, especially at high speeds (which is why most road vehicles use tubeless tires).

c) *Tweels* or *airless tires* have spokes in them that serve the same purpose of the air in tires: allowing the wheel to squish some to gain a greater contact patch and absorb impacts.

d) *Fairlane wheels* or *drive rollers* are solid rubber rollers bonded to a slim center hub. They have a degree of squish or give and often have quite high grip and abrasion resistance.

e) *Compliant wheels* or *flex rollers* look like tweels, but are much, much softer. Compliant wheels are usually made out of very soft urethane, enabling extreme amounts of compression. This allows them to conform to objects, especially irregular geometries.

4.5.3 Casters

Any wheel can be placed on an offset pivot to create a *swivel caster*. This a cheap solution, useful in permitting unpowered motion in any direction. However, casters do pose potential problems since their direction is uncontrolled.

One issue you may have encountered is instability at high speeds. The caster is like a weathervane- it reorients as a result of the movement of the ground underneath it. If the distance from the offset to the contact point on the ground is improperly sized, the caster may overshoot the correct position, or not come to it fast enough.

Another issue posed by this re-orienting nature is that casters impart a *steering torque* when they are re-oriented. You may have noticed this if you try reversing a shopping cart after going forwards, as the casters will push the cart slightly to one side or another while they swivel around and change direction. This can produce inconsistent behavior in cases where precise motion is necessary.

Casters are also ill-suited to uneven terrain, as the side-forces which occur as a result of travelling sideways across an incline will steer the caster away from the direction of movement rather than towards it.

4.5.4 Omni Wheels

(a) Omni wheel

(b) Mecanum wheel

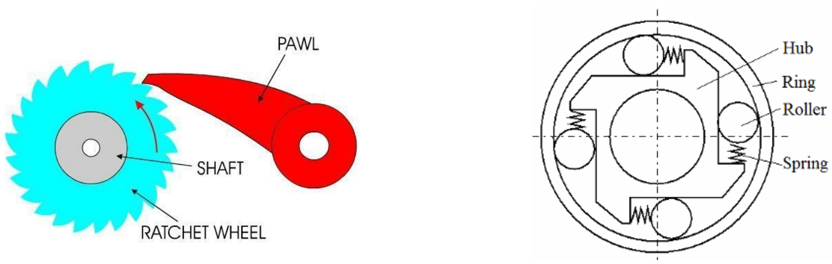
a) *Omni wheels* have rollers on them that are perpindicular to the axis of rotation. This allows them to transmit power back like a normal wheel, but they have no resistance to being pushed sideways. This can be desirable in drivetrains (see section 8.5). They are also good as casters, as they do not have a swivel stem that needs to reorient before moving in a new direction.

b) *Mecanum wheels* have rollers on them that are oriented 45 degrees to the axis of rotation. This allows them to transmit power at a 45 degree angle, while being able to be pushed at -45 degrees. This makes them useful in drivetrains and intake systems (see sections 8.5 and 8.1).

4.6 Engagement and Disengagement

4.6.1 Ratchets and Brakes

Often we want to make sure something stays in place once we set it to a certain spot (or make it stop in the first place). Ratchets and brakes let us do this.

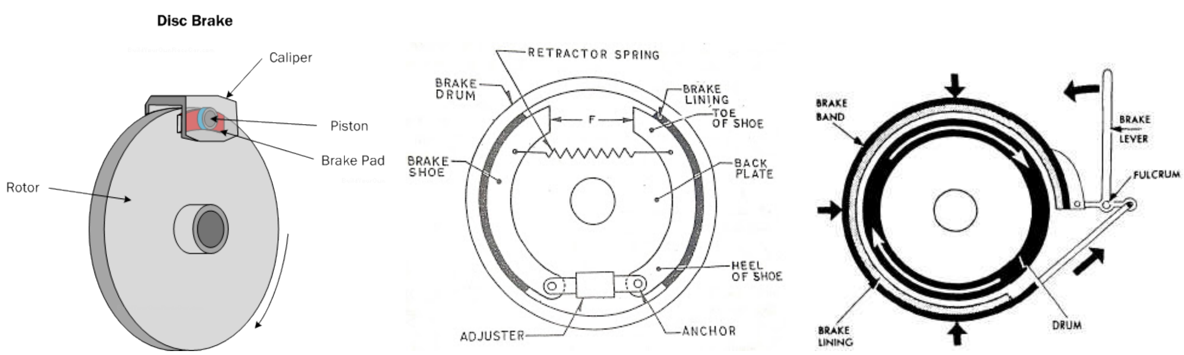


(a) Ratchet and pawl (b) One-way clutch/bearing

Figure 4.25: Ratcheting mechanisms.

a) *Ratchets* have a ratchet wheel with angled teeth on it which push up on a spring-loaded arm, or *pawl*. This arm falls down after each tooth, preventing backwards motion. This arm can be actuated by another mechanism in order to intermittently allow backwards motion.

b) *One-way clutches* or *one-way bearings* have rollers that in one direction, roll freely, but when rolled in the other direction, lock up against the outer ring. These are much smoother, efficient, and quieter mechanisms, and can be much smaller. However, they are quite expensive, have relatively lower load-bearing capacity, and cannot be externally disengaged.



(a) Disc brake (b) Drum brake (c) Band brake

Figure 4.26: Braking mechanisms.

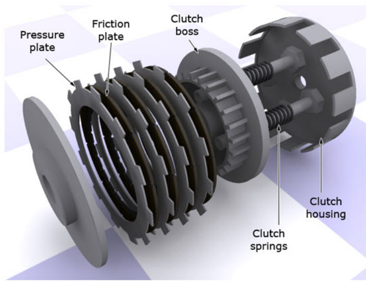
a) *Disc brakes* have a *disc* which is grabbed by the *brake pads* of a *caliper*. These are simple to find and reasonably simple to integrate into a system. They are also good at rejecting heat and providing consistent performance, which is why they are the standard in motorsport applications.

b) *Drum brakes* have *shoes* which are actuated outwards and grab onto the *brake drum*. This action causes the shoes to dig-in, increasing the braking capacity. These are lower-cost in large quantities and integrate nicely into wheels, but can be finicky to set up.

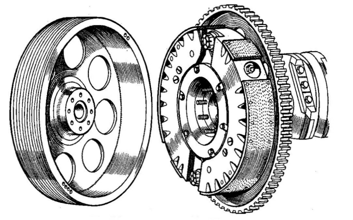
c) *Band brakes* have a *band* which is pulled down tightly around the *brake drum*. This is a fairly simple mechanism to make and actuate.

4.6.2 Clutches and PTOs

Sometimes we want to couple and uncouple rotating components on the fly (sometimes called a *PTO*, or Power-Take-Off).

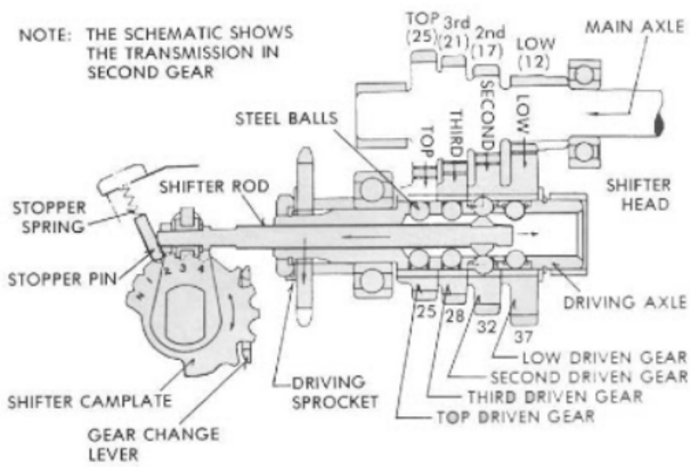


(a) Multi-plate clutch



(b) Centrifugal clutch

(c) Dog



(d) Ball shifter

Figure 4.27: Clutching and shifting mechanisms

a) *Plate clutches* have several friction plates stacked on top of each other in an alternating fashion. Every other one is fixed to one shaft/housing, and the others are fixed to the other shaft/housing. By applying a pressure to compress all of the plates, friction couples the plates together. By using multiple plates, the same frictional force can be applied redundantly to all of the plates, creating mechanical advantage.

b) *Centrifugal clutches* have swinging arms mounted to the input housing, which when spun up, swing out and latch onto an outer output housing. This is useful for cheap gas engine powered devices, where the throttle both controls the speed of the engine and its engagement to the rest of the system. At low RPM, the engine is allowed to idle without the load of the rest of the system.

c) *Dogs* are teeth that protrude axially. Rings with dogs on them an an internal spline (hex or true spline) can slide on a mating shaft, and into other components (such as gears) on the shaft that also have dog teeth, but are fixed to the shaft with bearings so would otherwise be free-spinning. This allows gears on the shaft to be engaged and disengaged.

d) While dogs engage idle components on a shaft axially, *ball shifters* engage them radially. The driving axle in this case has holes drilled into it radially, in which balls can be placed. These balls bottom out against a shifter rod that slides back and forth inside the driving axle. The shifter rod has a bumped portion in it which can push the balls out and into idled components. This method of shifting can be smoother and more compact (especially for picking between more than two states), but is a little more difficult to pull off.

Chapter 5

Pneumatics

"All things share the same breath - the beast, the tree, the man [, the machine]... the air shares its spirit with all the life it supports." - Chief Seattle

Pneumatic systems are one way of turning electrical energy into mechanical energy. They are not particularly efficient, however, they can be easily integrated and scaled. The Official FRC Pneumatics Manual is a good resource for actually setting up and walking through the specific components seen in an FRC pneumatics system.

5.1 Pneumatic Anatomy

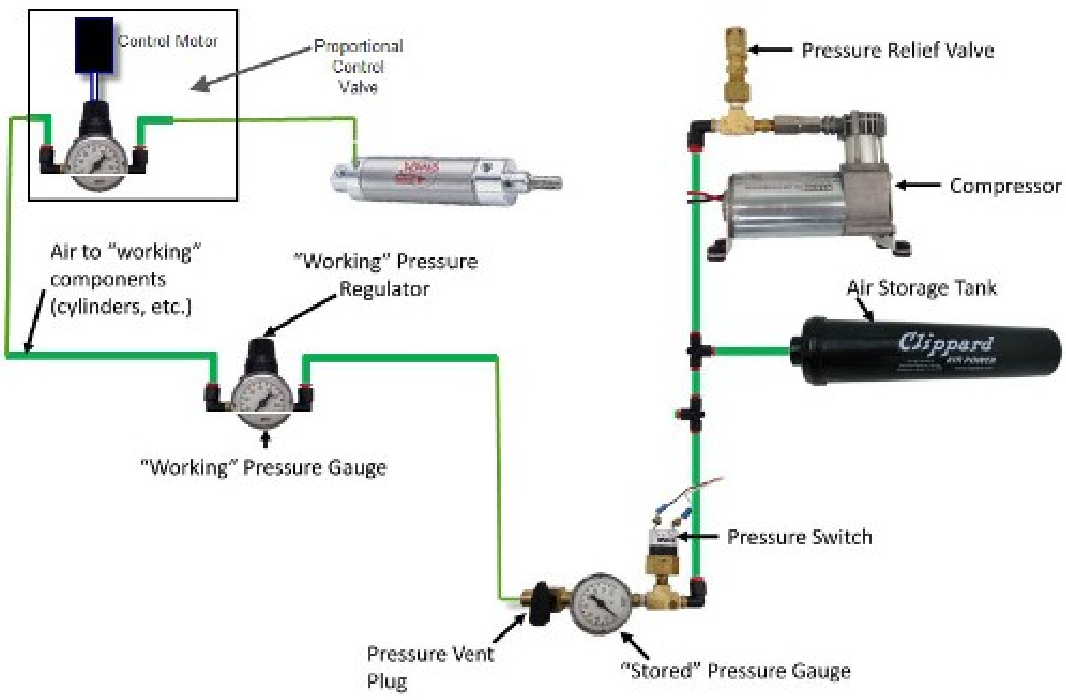


Figure 5.1: Overview of a typical pneumatics system

a) A *compressor* takes ambient air and compresses it to a higher pressure. The compressor is turned on and off by some logic system and a *pressure switch* that determines when the system is at maximum pressure.

b) The *pressure relief valve* is a safety mechanism that releases excess pressure, preventing explosions as a result of excessive pressure.

c) High pressure air is stored in a *tank*.

d) A *pressure regulator* steps the high storage pressure to a lower, working pressure. This provides predictable operation as the storage pressure will fluctuate with usage.

e) A *solenoid valve* allows air to enter and exit various pneumatic devices, typically *pneumatic cylinders*.

Flow of air can be restricted (for better or worse) by nearly any portion of the pneumatic system- the tubing, the pressure regulator, the valves, and even pneumatic fittings themselves.

Figure 5.2: Throttling valve.

Intentional flow restriction can be provided by throttling valves. These usually only throttle in one direction, so can be installed on both inlets of a pneumatic piston to control its extension and retraction rates. Speaking of fittings and valves, there are a few different types of fittings you'll typically see: threaded, and push-to-connect (although there are many, many more out there).

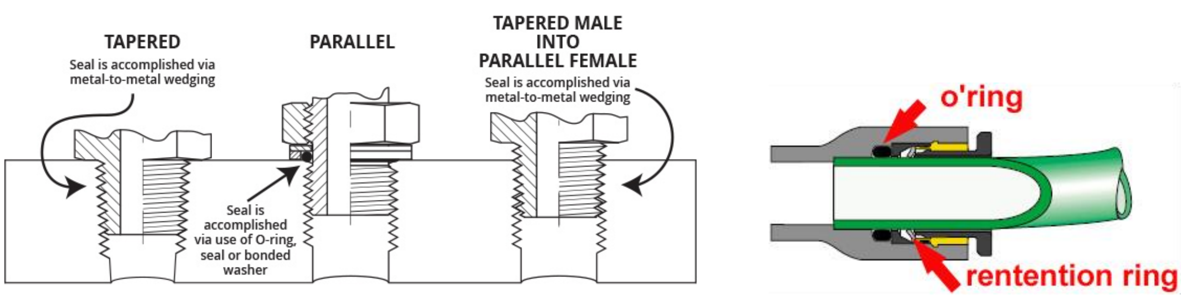


Figure 5.3: Left: threaded joints. Right: a push-to-connect fitting.

a) *Tapered threads* are threads that increase in diameter. This causes a wedging action as they are inserted. They should be used with pipe sealant or PTFE tape to help form the seal. NPT (National Pipe Thread) and BSPT (British Standard Pipe Tapered) are common standards.

b) *Parallel threads* do not seal on their own, so need some sort of seal (usually a0 rubber *o-ring*) to prevent leaks.

c) *Tapered threads* can be installed into parallel threads, although it isn't as preferred. The thread standards still need to match (There exist straight threads NPS and BSPP).

d) *Push-to-connect* or PTC fittings consist of a gripping ring or collet that grips firm tube as it is inserted into an o-ring. Once inserted, the ring has a ratcheting effect, preventing removal of the hose unless the ring is pressed in. These allow for easy and reliable connection of firm tubing to other components.

5.2 Compressors

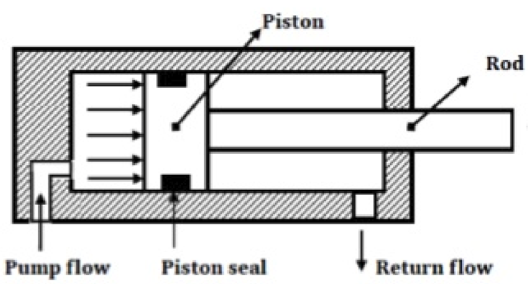
Air compressors come in many different styles. They are generally rated by the volume of air they can compress in a given amount of time to a specific pressure. When operating below this pressure, they may be able to pump even greater amounts of air- and when above it, they will pump less, or maybe even none at all.

Due to the ideal gas law,

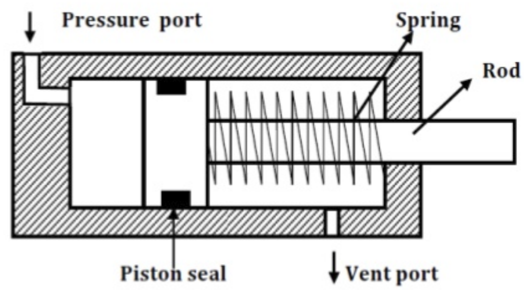
$$P\forall = mRT \tag{5.1}$$

When compressing air (higher P), the volume necessarily decreases, but the temperature also rises. Couple this with the fact that air compression is not the most efficient process, and compressors can get extremely hot, which is why they usually have heat-sinking fins and may have active cooling.

5.3 Pneumatic Cylinders



(a) Double-acting

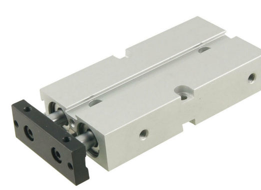


(b) Single-acting

(c) Nose-mount

(d) Universal-mount

(e) Tie-rod



(f) Guided

Figure 5.4: Varieties of cylinders.

a) *Double-acting* cylinders have two inlet ports. Air can enter and exhaust from either side so that they can push and pull on objects.

b) *Single-acting* cylinders have only one inlet port. Air can enter and exhaust from this port. When air is released, a spring cylinders the piston back to its relaxed state. These exist in both spring retract and spring extend varieties. These can reduce circuit complexity and weight when the action required only needs to exert force in one direction.

c) *Nose-mount* cylinders are mounted only by their nose, where the rod extends/retracts from. Nose mounting a piston should be done carefully- it is easy to end up putting a bending moment on the rod and bend the rod. The rods of cylinders are generally not designed to withstand loads from the side.

d) *Universal-mount* cylinders feature both a nose mount and a rear pivot point. This rear pivot point helps make sure the rod does not get side-loaded and bend.

e) *Tie-rod* cylinders have many mounting features, typically tapped holes, making them often easy to integrate. This comes with the same caveat as nose-mount cylinders- care must be taken to not sideload these.

f) *Stage* or *guided* cylinders have additional guiding features or linear stages built in that allow them to withstand side loads. This also has the added benefit of preventing the end from twisting, making them useful in many applications, albeit quite expensive.

Pneumatic cylinders have four key dimensions.

a) *Stroke* is how much the rod of the cylinder extends from its contracted state.

b) *Overall length* is the overall length of the cylinder when it is contracted.

c) *Bore* is the inner diameter of the cylinder.

d) *Rod diameter* is the diameter of the cylinder rod.

These are important considerations that help you determine what sort of cylinder you need. While the lengths may be fairly well-understood, determining the bore is a little more difficult, and based around the force of the cylinder.

5.4 Basic Cylinder Analysis

To size a cylinder's bore, let's examine the physics a little bit. Pressure is simply force spread out over an area. That is to say,

$$P = \frac{F}{A} \rightarrow F = P \cdot A \tag{5.2}$$

For a cylinder being extended, the area is simply the cross-sectional area of the cylinder (the bore).

$$F_{extend} = P\frac{\pi}{4}d_{bore}^2 \tag{5.3}$$

For a cylinder being retracted, the pressure doesn't act on the entire bore, but is obstructed by the rod running through the center. This means the area is the bore minus the area of the rod.

$$F_{retract} = P\frac{\pi}{4}[d_{bore}^2 - d_{rod}^2] \tag{5.4}$$

A simple way to get a rough estimate of required piston size is to solve the pushing equation for bore diameter.

$$d_{bore} = \sqrt{\frac{4F}{\pi P}} \tag{5.5}$$

My EveryCalc tool contains calculators to analyze pistons- including some analysis for fast-acting pistons (using much more complicated math than these equations).

Chapter 6

Motors

"No one [motor] should have all that power" - Kanye West when asked about the Falcon 500 powered by Talon FX

Motors are one of the fundamental aspects of mechatronic systems - they're where power is transformed from electrical into mechanical. There are many, many different types of motors, and some of these (like servomotors) are actually complex systems built on top of motors.

6.1 DC Motors: Brushed and Brushless

To begin with, let's talk about the most essential types of motors: Brushed DC motors.

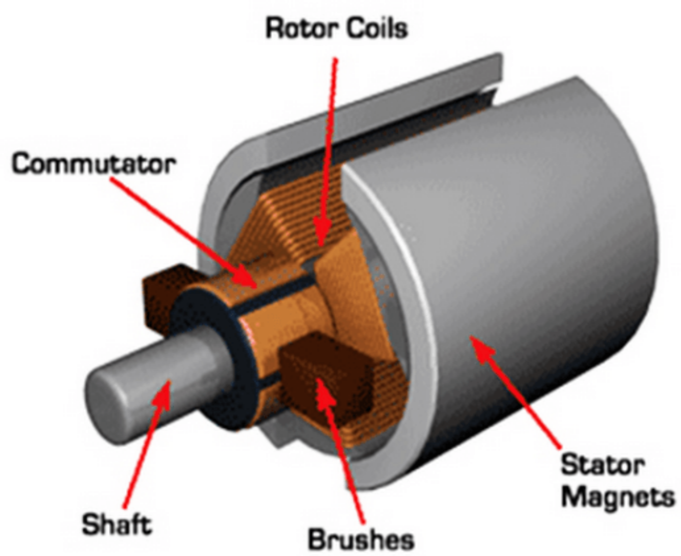


Figure 6.1: Brushed motor anatomy

Brushed DC motors have two electrical leads on them - power in, and power out. Current is directed first through carbon *brushes*. These brushes rub against a *commutator*, forming a rotary switch. This switch determines which coil(s) on the rotor fire, and which direction they fire in. When a coil turns on, it pushes/pulls against the permanent magnets, which creates a torque, thus turning the rotor. When the rotor turns, the commutator redirects power into a new set of coils. This process repeats, syncing the firing of the coils with the position of the rotor in order to produce torque.

This setup is very cheap, as it does not require any complex electronics. However, such motors are not particularly robust, as these brushes can be a source of friction and wear. Can we eliminate these problematic brushes?

Brushless DC motors, as per the name implies, do exactly that. Let's flip things around so that the rotor contains the permanent magnets, and the electromagnets are fixed in place.

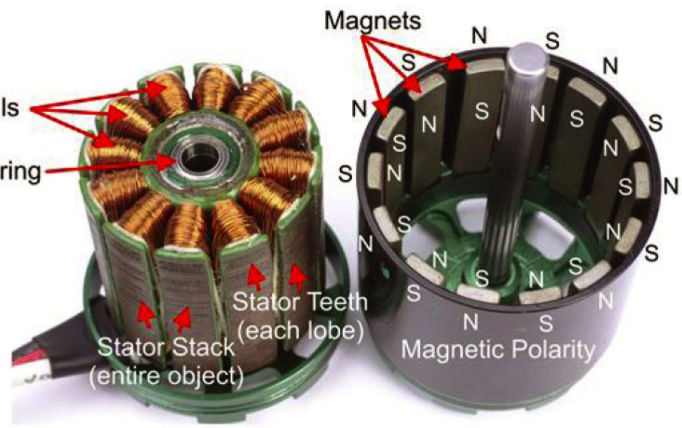


Figure 6.2: Brushless motor anatomy

An *Electronic Speed Controller (ESC)* creates three AC waveforms. These waveforms are fed into the motor. The motor can be either a *delta* or *wye* configuration. This alternating current creates alternating forces, which rotate the rotor.

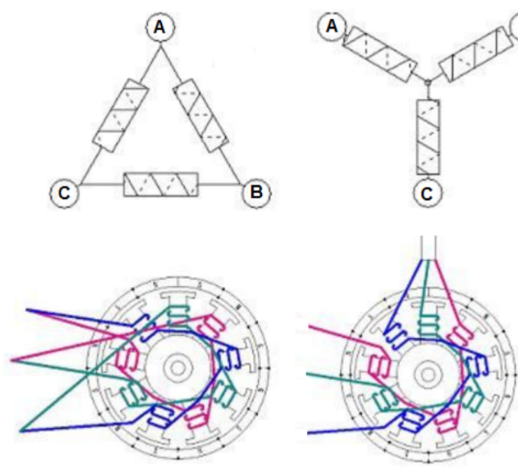


Figure 6.3: Delta and wye winding configurations

Whether a motor is wired as delta or wye does not impact the fundamental behavior, but does change its performance characteristics.

Why do delta and wye windings behave differently? Are there advantages and disadvantages?

The hard electrical connections are more robust, but does add some cost and complexity as the ESC is required in order for this motor to work. However, there is one major issue with this setup: what happens when the AC waveform is no longer in sync with the rotation of the rotor? Well, a loss of torque occurs. These motors are not very well-equipped to handle high torques, and so are better equipped for high-RPM, low-load applications, such as propellers on hobby aircraft.

However, we could employ an encoder to read the rotor's position, and feed that information back into the ESC. If the ESC can be programmed to read this signal, it can keep the waveform in sync with the rotor's movement, creating higher torque. Another strategy to get around this problem involves reading the *back-emf* that the motor windings produce in order to roughly back out information about the motor's position and velocity. This is not as robust a method, however.

Brushless motors have a few other subtle advantages.

Since the waveform is electronically controlled, it can be finer tuned to achieve peak performance (mechanical power output or efficiency). The elimination of brushes also eliminates one source of friction, so their efficiency is generally higher.

The coils of brushed motors, being fixed to the rotor, have very little surface area by which to dissipate heat-the heat has to dissipate out primarily through the shaft. Brushless motors' coils are fixed to the case, which has a much higher surface area, and so they can reject heat better, keeping the motor cool and efficient.

6.2 Empirical DC Motor Behavior

Like many complex systems, analysis is good for design, but for application, gathering empirical test data is a much more practical approach. It turns out that the test data (almost) always follows a general shape, with different numbers. This shape is often called a *motor curve*. Motor manufacturers typically provide some of these specs in some form. motors.vex.com is a very good site as well for FRC, as they conduct third-party testing using the same procedure on each motor, so the results are an apples-to-apples comparison.

The first portion of the motor model we'll look at is torque, varying with operating speed, while all parameters are held constant (generally, at the maximum rated voltage). The data typically looks like so:

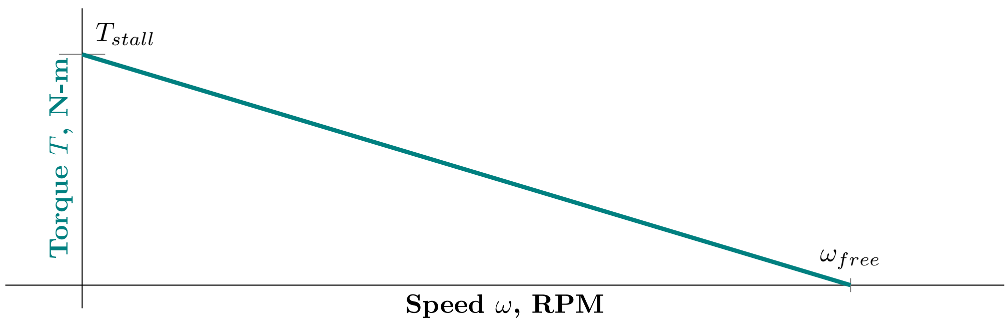


Figure 6.4: Torque varies linearly with speed.

This could be expressed as an equation for a line,

$$T = T_{stall} \frac{\omega - \omega_{free}}{\omega_{free}} \tag{6.1}$$

With the torque and velocity data, we can compute the power; the rate at which torque is done, or

$$P = T \cdot \omega \tag{6.2}$$

Substituting Equation 6.1 into 6.2 yields the following equation for the power curve.

$$P = T_{stall} \frac{(\omega_{free} - \omega)\omega}{\omega_{free}} \tag{6.3}$$

Note: ω must be in rad/s, not RPM.

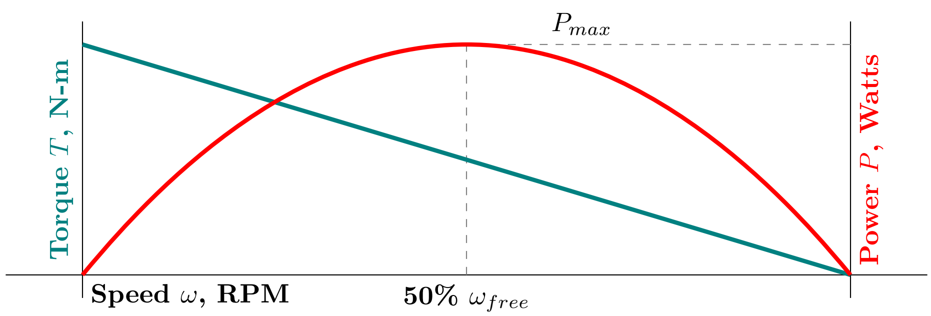


Figure 6.5: Power forms a parabolic curve with speed.

From this we can see that the peak power is produced at half of free speed. This is also half of torque.

Current (I) is how much electricity is drawn. It varies proportionally to torque, so

$$I = CT$$
$$I = CT_{stall}\frac{\omega_{free} - \omega}{\omega_{free}} \tag{6.4}$$

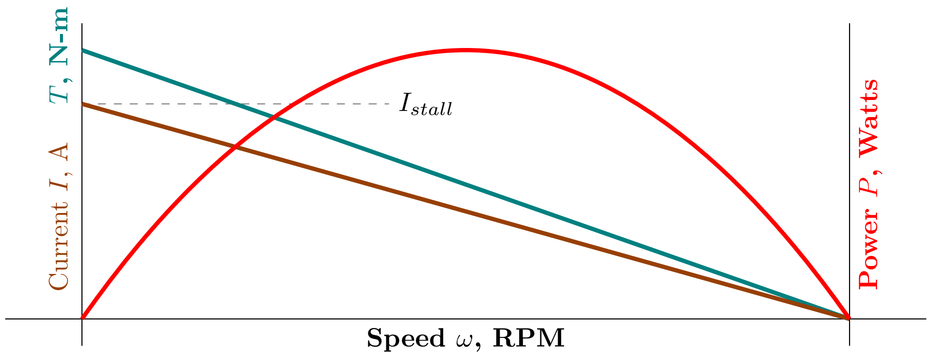


Figure 6.6: Current varies with torque.

Efficiency (η) is a ratio of how much mechanical energy is produced per electrical energy spent.

$$\eta = \frac{P_{mech}}{P_{elec}} = \frac{T - M_{friction}\omega}{VI} = \frac{[T_{stall}\,\frac{(\omega_{free}-\omega)}{\omega_{free}} - M_f]\omega}{V\ C\ T_{stall}\frac{(\omega_{free}-\omega)}{\omega_{free}}}$$

Indeed an ugly equation, let's just plot it with some semi-realistic values.

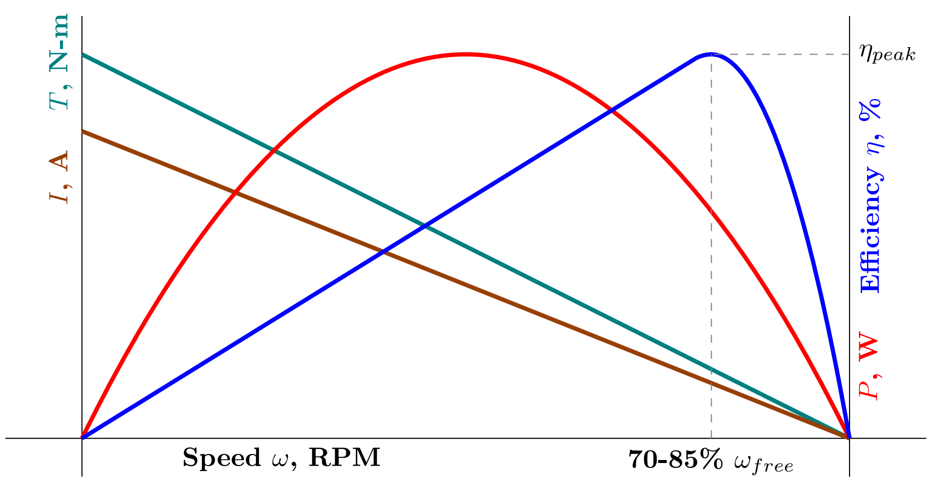


Figure 6.7: Complete motor curve.

In summary:

Motors produce less and less torque as they spin up.

No power is produced when the motor is at maximum speed or maximum torque.

Maximum power is produced at 50% of maximum speed, which is also at 50% of maximum torque.

Maximum efficiency occurs somewhere between 75% and 90% of free speed.

6.3 Comparing Motor Types

	Brushed DC	*Brushless DC*
Efficiency	Low	High
Mechanical Robustness	Medium	High
Electronic Complexity	Low	High
Position Control	Not inherent	May have integrated encoder
Cost	Low	Medium

Table 6.1: Motor types at a glance

Chapter 7

Electrical

7.1 Power Electronics

7.1.1 Batteries

Power sources are a critical component of electrical systems. For mobile ones, a battery is the obvious choice- the question is, what battery? Batteries may be rated by many parameters.

1. *Chemistry* refers to the type of chemicals and technologies being used in the battery. Spillable Lead-Acid, Sealed AGM, LiPo, NiCd are all different types of chemistries on the market each with their pros and cons. Some work better at cold temperatures, some cannot be used in extremely high temperatures, and some have much higher flammability hazards. Some require maintenance and watering, some do not.

2. *Nominal voltage* is the approximate voltage that a battery will sit at. This will fluctuate throughout operation both due to internal resistance and chemical changes- over time the battery will drain and the voltage may sink. A 12 volt nominal AGM battery may be fully charged at 13.5 volts, but be depleted at 11.

3. *Amp-hours* is a measure of how much energy can be stored by the battery, specifically, how many hours it could run for if one amp was constantly being used.

4. *Cold Cranking Amps (CCA)* is a performance characteristic often found in car batteries, which must pull extremely high amounts of current in order to start an engine. As temperature negatively impacts the current-supplying ability of lead-acid batteries, the cranking capacity is usually measured at a representative worst-case temperature. The CCA rating is found by the number of amps a battery can support for 30 seconds at 0 Farenheit before the battery voltage drops to 1.2 volts per cell (7.2 volts for a 12V battery).

5. Other measures like *Pulse Cranking Amps (PCA)*, *Marine Cranking Amps (MCA)*, and *Hot Cranking Amps (HCA)* also exist.

6. *Internal resistance* is a key performance characteristic that is often not rated. This is a measurement that is found by realizing the battery is not an ideal voltage source, and instead modeling it as such:

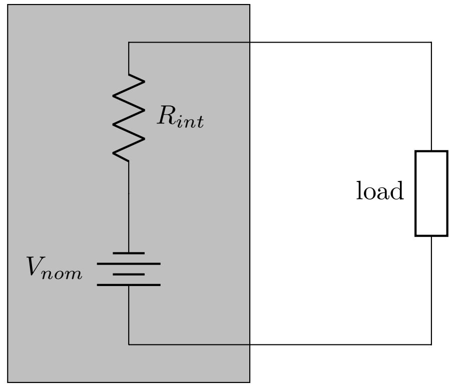


Figure 7.1: Battery with internal resistance driving a load.

$$V_{nom} - I_{load}R_{int} = V_{load} = V_{apparent} \tag{7.1}$$

This behavior is fairly accurate: when more current is drawn, the apparent voltage of the battery will drop as well.

7.1.2 Regulators

Voltage regulators help even out fluctuations in voltage, or convert between different voltage levels.

1. *Linear regulators* take excess voltage and waste it as heat. They cannot step up a voltage, only decrease it. This makes them extremely inefficient, but quite cheap.

2. *Buck converters* are a type of switching converter that has much greater efficiency, and can reduce voltage levels.

3. *Boost converters* are a type of switching converter that has much greater efficiency, and can increase voltage levels.

4. *Buck-Boost converters* are a combination of a buck and boost converter that has high efficiency, and can transform a voltage to a level either less than or higher than the input.

7.1.3 Breakers and Fuses

1. *Fuses* are components which only permit a certain amount of current through them. Once this current is exceeded, the fuse ‘blows’; destroying the path where current could flow through.

2. *Slow-blow* or *time-delay* fuses require this amount of current to be passed for a sustained period of time before blowing; permitting quick surge currents to pass without interruption.

3. *Breakers* serve the same role as fuses, except that they accomplish this by disconnecting the path (called ‘tripping’) for current to flow, like a switch, rather than destroying it. They are good for applications where repeated tripping is to be expected. Normal breakers must be manually reset.

4. *Thermal breakers* will trip if abnormally high current is seen for an extended period of time, or if extremely high current (i.e. a short) is seen momentarially. This behavior makes them useful for many applications such as protecting equipment that can handle high load, but only for so long.

5. *Auto-resetting breakers* will reset on their own after allowed to cool down. This makes them useful for protecting mission-critical circuits and enabling ’retries’.

6. *Software current limits and monitoring* can be used to avoid power disruption to a circuit while still enabling safe behavior. They may be employed alongside or in lieu of fuses and breakers to provide safety functionality.

7.1.4 Wires

Wires seem fairly straight forward, but have their nuances.

1. Wire may be *stranded* or *solid*. Solid wire is often cheaper and holds its shape well, but is very difficult to form and is not good for applications where it must be flexed. For these reasons, it is relatively rare except for building wiring. Stranded wire comes in different strand counts- more strands means more flexibility (and arguably, higher current carrying ability).

2. Wires exist with different *jacketing*. The jacketing can impact flexibility as well as insulation resistance (in high voltage applications) and temperature resistance.

3. Color is important in wires. There are different conventions which exist for different regions, industries, and companies.

4. Wire *gague* is the amount of cross-sectional area available to carry current. In the American Wire Gague (AWG) system, a lower gague number has a higher cross-sectional area. The gague should be sufficient to carry the current per safety standards, and also to minimize voltage drop. The higher the cross-sectional area, the lower the voltage drop.

$$\Delta V = IR_{wire} \tag{7.2}$$

The voltage drop can be calculated with this tool at calculator.net.

7.2 Sensors

7.2.1 On/Off Position Sensors

(a) Limit Switch (b) Inductive Proximity Switch (c) IR Photoeye

a) *Limit switches* are basic switches. They mechanically switch power between different positions- so do not require power to operate them (just signal).

b) *Inductive proximity switches* send out a magnetic field and detect interference in this field caused by metallic objects (*ferrous* metals usually work best). This allows them to sense if an object is in position without risking dangerous mechanical contact. They require appropriate power to operate (refer to their datasheet for requirements). These sensors come in different packages, although the screw-body style shown is the most common. They are also rated by their minimum and maximum sensing distances.

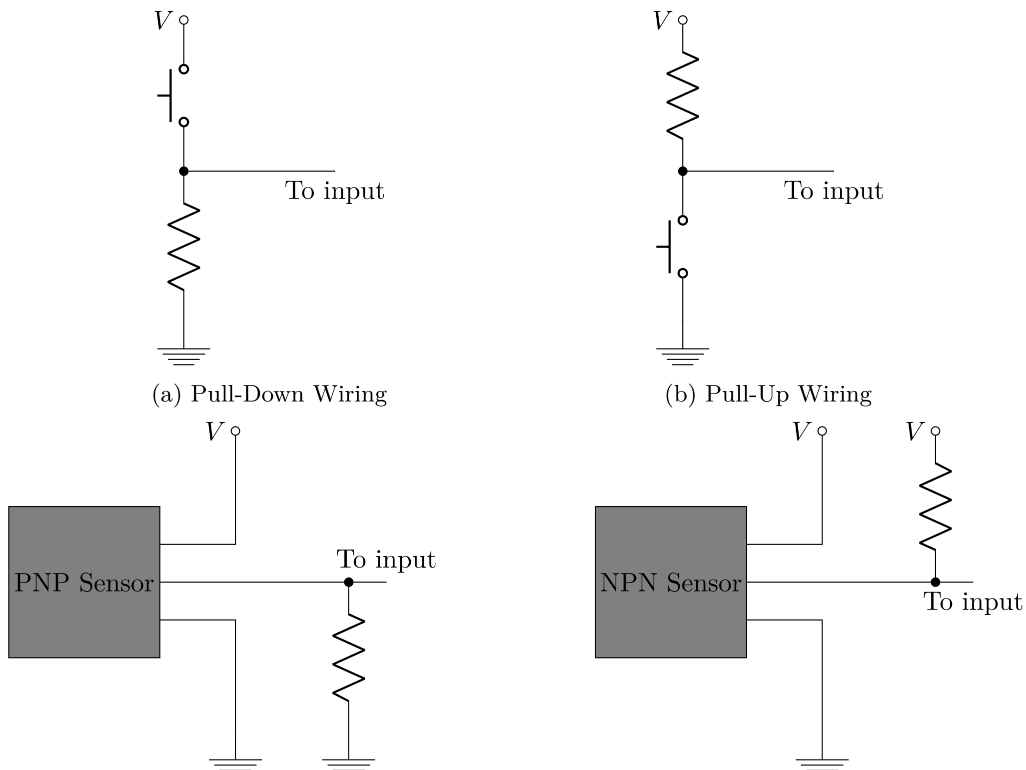
c) *IR photoeyes* emit infrared radiation and measure how much is reflected back. This allows any object to be detected if it is within the sensing range. They require power to operate (refer to their datasheet for requirements).

d) *Beam breaks* emit infrared lasers and collect them on the opposite side. If an object blocks the path, the beam is broken, causing a change in signal.

Switches and sensors may be denoted as [x]P[y]T to indicate how they may be wired. For example, a *SPDT*, or *Single-Pole Double-Throw* switch has a single contactor which can be switched between two positions. A *DPST* may only alternatve the switch between a connected and unconnected state (single pole) but has a second electrically isolated version of the switch (double-throw).

Switches also may be *momentary*, reverting state as soon as they are unpressed, or *toggle*, staying put until actively switched back (like a lightswitch, or a pushbutton pen). If the switch is momentary, it may be either *normally open (NO)* or *normally closed (NC)*, referring to if the switch is open or closed by default. If the switch has two poles, the poles may be referred to as NO and NC as one will be normally opened, and one normally closed.

Sensors can be wired in various ways.



(a) Pull-Down Wiring

(b) Pull-Up Wiring

(c) PNP Sensor Wiring

(d) NPN Sensor Wiring

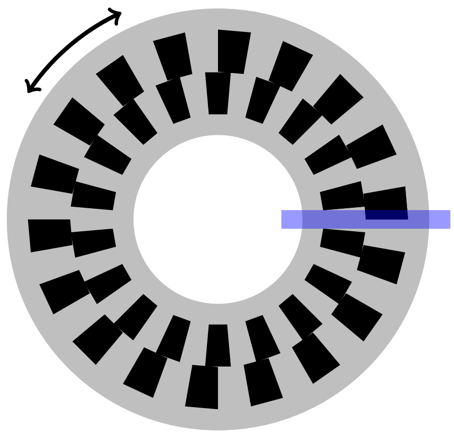
Figure 7.3: Sensor wiring diagrams.

a) *Pull down resistors* make the inputs of a microprocessor rest naturally at ground level. When the connected switch is closed, the resistance of the switch is much much less than the pulldown resistor, so the voltage of the input will rise to the logic voltage. The resistor is sized so as not to consume too much current (usually R = 5 to 20 kΩ). A microprocessor may have such a resistor built-in to the circuitry, although the resistor may need to be enabled.

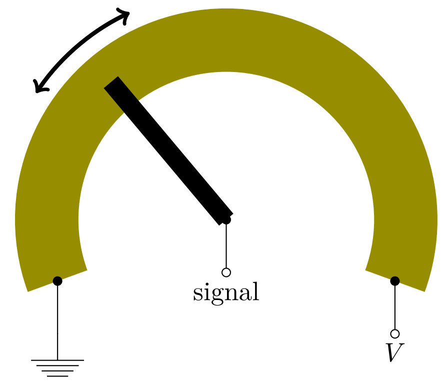
b) *Pull up resistors* work on the same principle as pull down resistors but with reversed voltages. On the RoboRIO, 2.2 kΩ pull-up resistors are on all DIO pins when in input mode.

c) *NPN* and *PNP* sensors are to be wired as shown. You may note that the wiring looks the same as for a pull-up or pull-down, respectively; match the type of pulling resistor in your microprocessor to the type of sensor you intend to use, otherwise external pulling resistors may be necessary.

7.2.2 Variable Position Sensors



(a) Encoder



(b) Potentiometer

Figure 7.4: Position sensors.

a) *Encoders* use rotating discs with multiple on/off positions in them to determine position. The on/off mechanism could be optical, magnetic, or something else entirely. A microprocessor running fast enough can watch the waveform produced by the encoder and determine how much the position has changed. Some encoders have builtin microprocessors, which can feed back more complex signals, while others may simply feed back *quadrature* data from the two channels that are monitored. This data takes the form of a square wave.

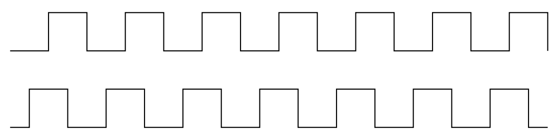


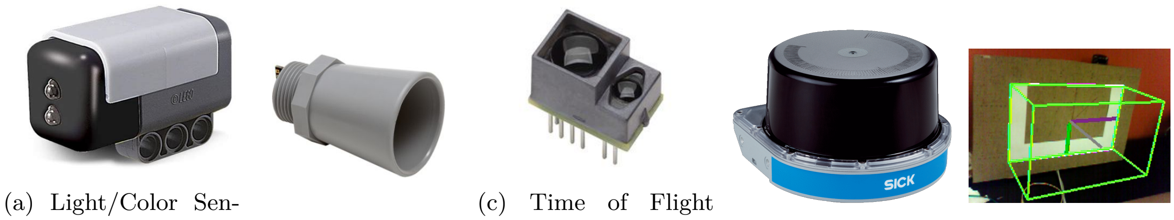
Figure 7.5: Encoder waveform

If the encoder spins one direction, the waveform for A will lead that of B. If it goes the other direction, B will lead A. Unless specified as an *absolute* encoder, encoders are *relative* devices, meaning that they can only keep track of changes, so will not maintain state when power is cycled. *Homing*, the process of moving a mechanism until a hard stop or limit switch is hit, is required to establish a known position upon startup.

If only speed data is need (i.e. for the tachometer of a car, where the engine never reverses direction), a single channel can be used.

b) *Potentiometers* have a resistive element, with the moving wiper making contact somewhere in the middle of it. When the wiper moves, the resistance between the wiper and the ends changes, which allows the voltage to be read. These are inherently absolute sensors- power cycling does not affect the resistance values. *Multi-turn* potentiometers allow the shaft to be rotated multiple times by running the wiper through a helical spiral. Linear potentiometers also exist- they often come in a piston-style package that can be mounted with rod ends.

7.2.3 Vision



(a) Light/Color Sensor (b) Ultrasonic Sensor (c) Time of Flight Sensor (d) LIDAR (e) Computer Vision

Figure 7.6: Sensors for giving a sense of vision.

a) *Light and color sensors* have a simple photoreciever which picks up light. This light may either be *ambient* or produced by the sensor itself and reflected back. Calibration of color sensors is very important to gaining consistent readings, as unlike full-blown computer vision, shape and context are not (inherently) available.

b) *Ultrasonic sensors* send out high-pitched sound waves and measure how long it takes for them to return. These can be finnicky, and do not work to detect objects that absorb, rather than reflect sound.

c) *Time of flight* sensors work on the same principle as ultrasonic sensors, but with light. Light travels much, much faster- so these devices are more sophisticated and expensive.

d) *LIDAR* systems employ a moving time of flight sensor to build a 3D map of the surroundings.

e) *Computer Vision (CV)* can be used to pick up targets visually and determine their distance and relative position. It's particularly easy when the targets are a specialized color and shape that is distinct from everything else. CV systems can operate on even the simplest of hardware such as a smartphone, but the latency and image quality may suffer. Specialized sensors exist to improve the key performance parameters when using a camera in a real-time system.

7.2.4 Inertial Measurement

Measurement of position in 3D space can be established alternatively by measuring accelerations and magnetic fields.

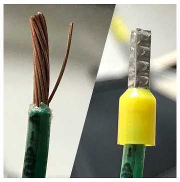
a) *Gyroscopes* measure the rate of rotational acceleration. They can be used to find rotational velocity and position by performing numeric integration with a computer. As the rotational acceleration/velocity on a rigid body is constant, it does not matter where they are mounted so long as it is of sufficient rigidity and vibration isolation.

b) *Accelerometers* measure linear acceleration. They can be used to find linear velocity and position by performing numeric integration with a computer.

c) *Magnetometers* or *digital compasses* pick up magnetic fields (such as the earth's). This allows them to determine absolute orientation, although magnetic fields can be greatly disturbed by metallic structures and buildings.

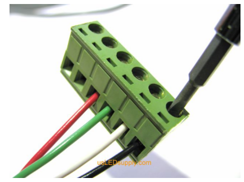
d) *Integrated Motion Units* combine several of these sensors into one system, complete with an onboard microprocessor to perform aforementioned numerical integration. This dedicated processing allows them to acheive high integration accuracy.

7.3 Terminals and Connectors



(a) Ferrule

(b) WAGO Connector



(c) Screw-Down Terminal

Figure 7.7: Simple wire connections.

a) *Ferrules* are crimped onto the ends of stranded wire to prevent fraying.

b) *WAGO connectors* are spring loaded, with the user being able to insert a wire by use of a prying tool to open the jaws and inserting the wire before removing the tool. By their spring-loaded nature, they are very resistant to vibration. These can be somewhat annoying to use, especially in tight spaces.

c) *Screw-down terminals* are common for industrial use, although they are not as resistant to vibrations, but are quite easy to use.

(a) Screw-down terminal with bare wire

(b) Fork Terminal

(c) Ring Terminal

Figure 7.8: Screw terminal connections.

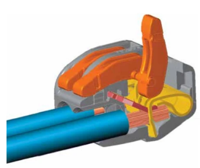
a) *Screw terminals* can accept hooked solid-core wire as shown. Make sure you hook the wire in the direction indicated to make sure the wire will tighten on installation instead of straightening.

b) *Fork terminals* crimp around a wire, and are well-suited to such screw terminals as they do not require full removal of the screw in order to be installed.

c) *Ring terminals* crimp around a wire, and work with screw terminals or even with bolt-and-hole applications. They are positive- they cannot be tugged off as a fork terminal might be.

All screw based terminals, however, are subject to loosening under vibration, making them suboptimal for automotive or other mobile applications.

(a) Wire Nut



(b) Lever Nut

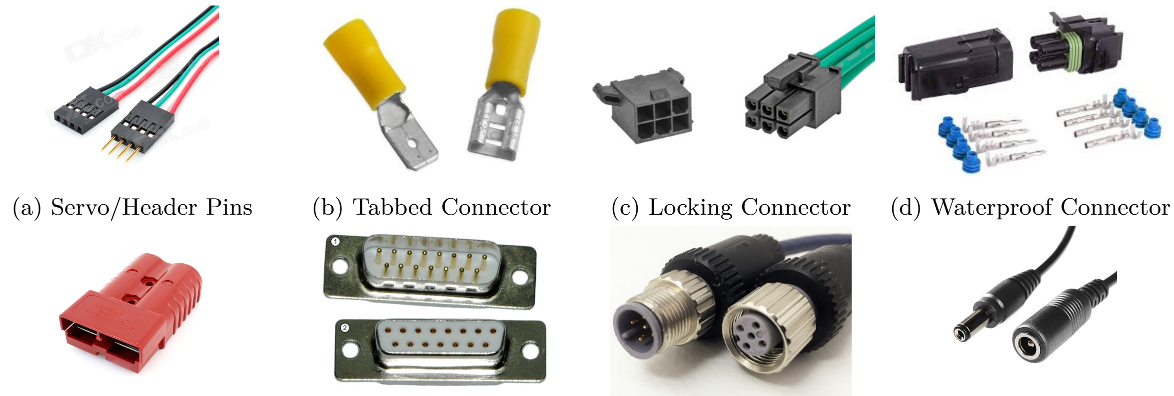
(c) Butt Splice

Figure 7.9: Wire-to-wire connectors.

a) *Wire nuts* go over top of twisted pairs of wires to connect them more securely than simply taping them together. Very common in building wiring, but not good for anything that would see vibrations.

b) *Lever nuts* allow wires to be separately joined together and quite easily. The installation process is as easy as opening a lever, inserting a wire, and closing the lever. Of course since they are multiple parts, they can be quite expensive.

c) *Butt splices* are crimped over two wires to join them together.



(a) Servo/Header Pins (b) Tabbed Connector (c) Locking Connector (d) Waterproof Connector

(e) Anderson Connector (f) D-sub Connector (g) Screw on Connector (h) Barrel Jack

Figure 7.10: Quick disconnect connectors.

a) *Header pin connectors* or *servo connectors* are simple, cheap connectors. They are commonly found on hobby servos. They don't have any locking features, though, so loosening is a major concern.

b) *Tabbed connectors* are simple crimp-on connectors. There are male and female sides which connect together. Shrouded versions which prevent shorting also exist.

c) *Locking connectors* come in many brands and styles. They feature a locking tab for quick and easy assembly, with positive latching.

d) *Waterproof connectors* are like locking connectors, but feature gaskets to keep moisture out from the wires and pins.

e) *Anderson connectors* are a type of *hermaphroditic connector*- meaning there is no male or female side, so only one version of the connector is needed. These connectors have a snap feature, so they can be easily connected and disconnected, but there is nothing to positively keep them from coming apart. They can be zip tied together, however.

f) *D-sub connectors* are commonly associated with antiquiated serial ports, but their application is not limited to this. They can be screwed positively together, making them quite common on industrial equipment to this day.

g) *Screw on connectors* are circular, multiconductor connectors that can screw together to prevent them from coming apart.

h) *Barrel jacks* are very simple, easy to connect and disconnect, two-conductor connectors. While they are cheap, there is no good way to secure them, making them ill-suited to mobile use.

7.4 Communication Protocols

7.4.1 Dumb signals

a) Simple high and low signals can convey whether something is active or inactive at a particular point in time.

b) Analog signals can convey a particular variable value rather than a high or low. However, they require complex circuits to encode and decode from digital devices

c) *Pulse-width modulation (PWM)* allows for the unidirectional trasmittal of variables over one signal wire without the need for analog circuitry. A square wave of fixed *frequency* is generated and the variable to be sent is encoded in the *pulse width* or *duty cycle*. Typical "servo style" PWM uses a frequency of 50 Hz (or a period of 20 ms), with a pulse width of 1 ms corresponding to the minimum value (full reverse, or 0 degrees), and 2 ms corresponding to the maximum value (full forwards, or 180 degrees). This is a reasonably safe signal to send safety critical functions on as any interruptions to the signal would result in clearly invalid data.

7.4.2 Serial links

Serial encoding of data takes a binary signal and serializes it. For example, the ASCII character 'A' is represented in binary as 01000001. So, one device would send a low signal, then a high signal, followed by five low signals, and a final high signal in order to transmit an 'A'. Serial transfer is essential unidirectional, so if two devices want to communicate back and forth, two signal wires (along with a ground) will be needed.

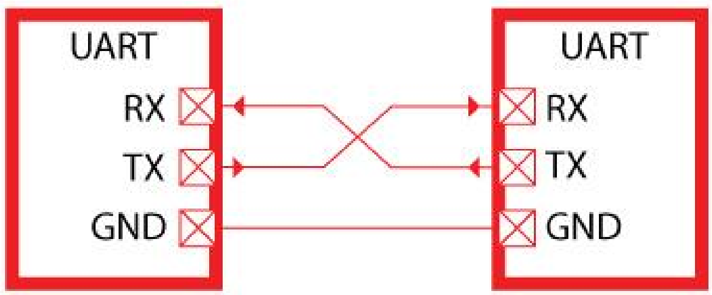


Figure 7.11: Basic serial wiring for bidirectional communication.

It isn't quite this simple, though- and so first-time users of raw serial protocols can often get quite frustrated as to why their devices won't connect.

To begin with, data is not always going to be transmitted over the line. The line will be a constant value before the data to be transmitted is sent. The sending device must first send a *start bit* to denote the beginning of a transmission. Additionally, a *stop bit* may be sent to denote the end of the transmission.

The devices need to agree in how many bits will be sent in a frame. Usually this is 8 bits, but 7 is possible (as is theoretically any number).

The two communicating devices must also be on the same frequency. There are many standard frequencies, or *baud rates*.

All signals also bear the possibility that they are degraded or contain errors. Use of *parity* may be used to check for corruption. Parity is established by counting the number of high bits in the transmission, and then adding another bit at the end of the transmission to bring the count of high bits to an even number of bits (known as *even parity*). The receiving device can then check if it recieved a transmission with an even number of bits- if the number was odd, the data got corrupted. If it is even, there's still a chance it was corrupted (maybe two bits flipped, cancelling the effect out), but a reduced one. *Odd parity* also exists, working on the same principle, but with the aim of sending an odd number of bits.

The voltage levels are also important. The RS232 standard is for a logic low to be +9 to +25 volts, and a logic high to be -9 to -25 volts (note that this is inverse from what you might think!). This can fry a UART chip, which uses transistor-level voltages (usually either 5 or 3.3 volts), with 0 volts being a low and the transistor-level voltage being high.

USB is another standard that builds on the idea of a serial link- although its wiring and protocol is much more complex.

7.4.3 Bus signals

Let's say, though, you want to build a network of devices. One topology to do this with would be a *data bus*. This works by stringing all the devices together on a common set of wires.

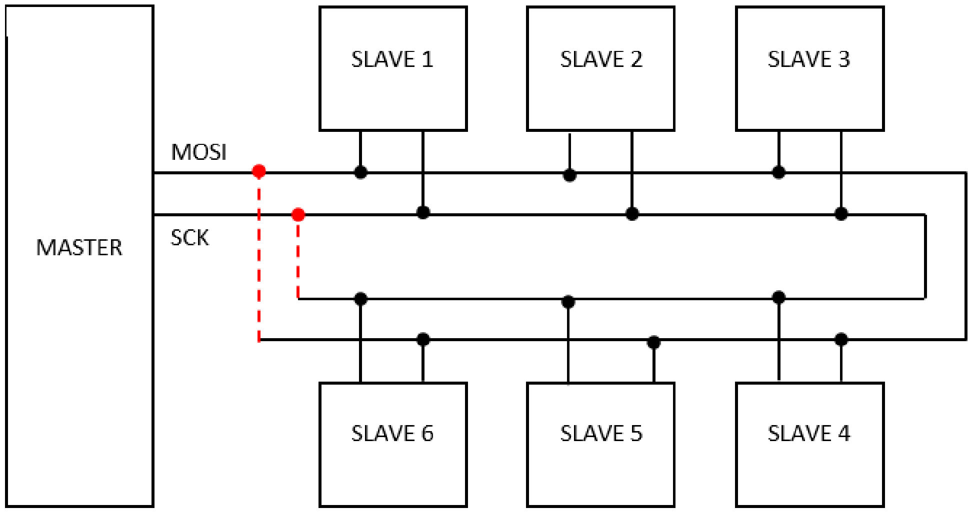


Figure 7.12: SPI bus

To send a communication, a device would put out a packet containing an intent to send information and its intended recipient, before sending the data. During this time, no other device can send data. The wiring of such a system is very simple and allows for the transmittal of sophisticated data, but does have bandwidth limitations and devices cannot simply hog the bus for extended periods of time.

There are many technical details and reasons to pick a particular bus technology or standard. The most prevalent are *I2C*, *SPI*, and *CAN (Controller-Area-Network)*

CAN can be used in various topologies, or even a mix of them.

A In *ring* or *loop* topology, the devices are wired fully together, forming a loop. A *terminating resistor* of 120 Ω is needed to connect the two lines of the bus together.

B In *bus* topology, the devices are wired one to another, forming a line. Terminating resistors should be connected at either end of the bus.

C In *star* topology, one master device or node is connected to all other devices, which would have their own terminating resistors. This may require more wire, but can be advantageous in that if one device becomes disconnected, the bus is not rendered inoperable to the other devices.

Chapter 8

Basic Systems

"Complex is better than complicated." - The Zen of Python

There is often no need to reinvent the wheel. Many problems already have a solution, or at least some sort of prior art. Familiarity with this can help you quickly identify a design for a problem in a pinch, or at least have a jumping off point. Even these systems are building blocks that need put together. You will probably need to mix and match many of these together to make a machine.

8.1 Grabbing

8.1.1 Jaws

Figure 8.1: Jaw-based grippers.

Jaws grab components that are in a relatively stationary state. They are many beginning designers' go-to thought of how to grab something, and are well-suited in many tasks, but begin showing their weaknesses when tasked with controlling objects that are not in an established position.

Multiple jaws can be used to more reliably hold an object, such as a three-jaw chuck of a lathe.

Jaws can also be oriented such that they pick the inside of an object rather than the outside.

8.1.2 Latches

Figure 8.2: Gate latch, which is naturally gravity-closed.

Latches are claws that are mechanically actuated to snap shut automatically on an object, like a trap. This provides a major improvement over a claw in many circumstances, although the trapping action may require more sophisticated action to reset if multiple uses are desired. If they are not, though, they can be ideal for many tasks such as grabbing onto end-game items.

Pole Latch Video Example (3:27) Grappling Hook Video Example (0:45)

Intakes grab uncontrolled components in a continuous, indiscriminate fashion. This makes them preferable to claws in many cases. A properly designed intake is often described as "touch it, own it."

8.1.3 Beater bars

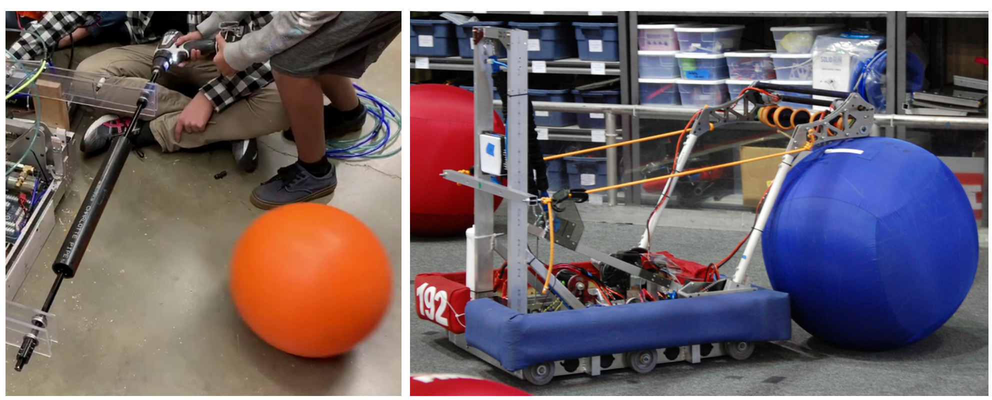


Figure 8.3: Beater bars.

A *beater bar* or *horizontal intake axle* has a rotating, grippy element that is horizontal and makes contact with an object, pulling it in. These usually work best with parts that can roll as they enter.

Video Example

8.1.4 Side wheels

Side wheels are rotating, grippy elements on a vertical shaft which make contact with an object, pulling it in. These are often spring-loaded to help deal with misalignment as they require somewhat precise positioning (at least more than a beater bar). Because of this, they are typically used where a beater bar is not as viable (like to intake an object that cannot roll).

8.1.5 Centering intakes

Centering intakes bring objects in to a particular point.

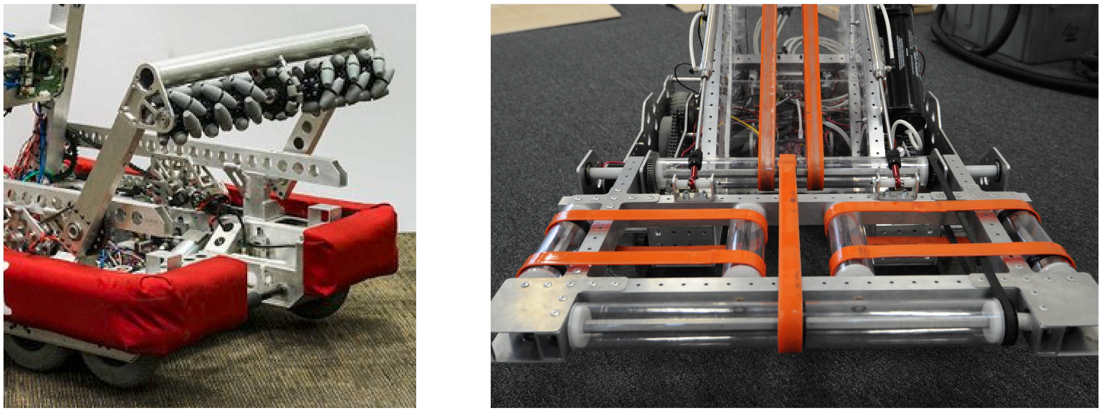


Figure 8.4: Left: Vectored intake wheels. Right: Centering intake with belts.

a) A simple way of accomplishing this is by creating a beater bar with *Mecanum wheels* or *vectored intake wheels*, which have rollers at a 45 degree angle. They provide a centering action when properly implemented, as the rollers will cause a force vector 45 degrees to the axis of rotation, rather than perpindicular. Video Example

a) Multiple belts feeding into each other can also produce the centering effect. Video Example (1:48)

8.1.6 Scoops

Figure 8.5: Left: scoop picking up frisbees. Right: scoop with additional beater bar (in red).

A *scoop* simply wedges under an object, picking it off the ground. Scoops can be useful if the object to be picked up has a tapered bottom that is conducive to this and has much higher friction on the surface it is being picked up from versus the surface of the scoop. Video Example (0:38) Scoops can also be combined with beater bars to provide positive latching of the object to be grabbed.

8.1.7 Vacuums

Figure 8.6: Vacuum gripper on a robot arm lifting a cardboard box.

Vacuum pumps can be used to acquire objects that can form a sufficiently good seal. They are a little difficult to set up properly, and are also notably inefficient and loud, but can be used properly and effectively. Video Example

8.2 Indexers

An *indexer* is any mechanism that takes one or more already-controlled objects and moves them to somewhere else where it can be used.

8.2.1 Gravity Hoppers

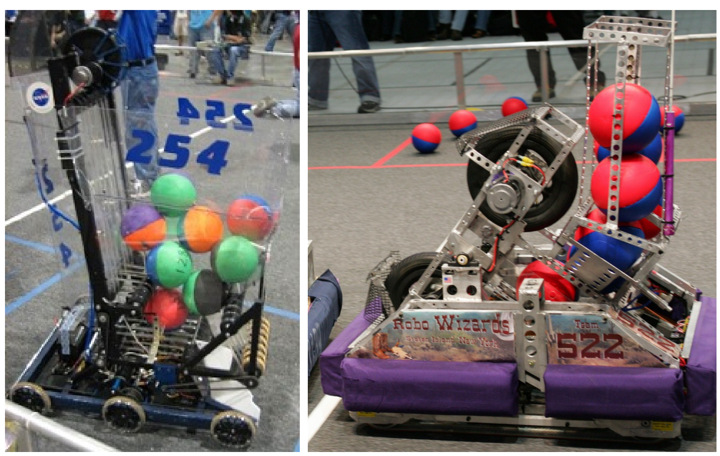


Figure 8.7: Gravity hoppers for foam balls.

Gravity-fed, metered hoppers are the simplest form of indexing. A hopper holds objects, and a wheel or gate controls their exit. Hoppers can jam easily depending on the object, and for high-speed applications, may not feed fast enough on their own.

8.2.2 Conveyors

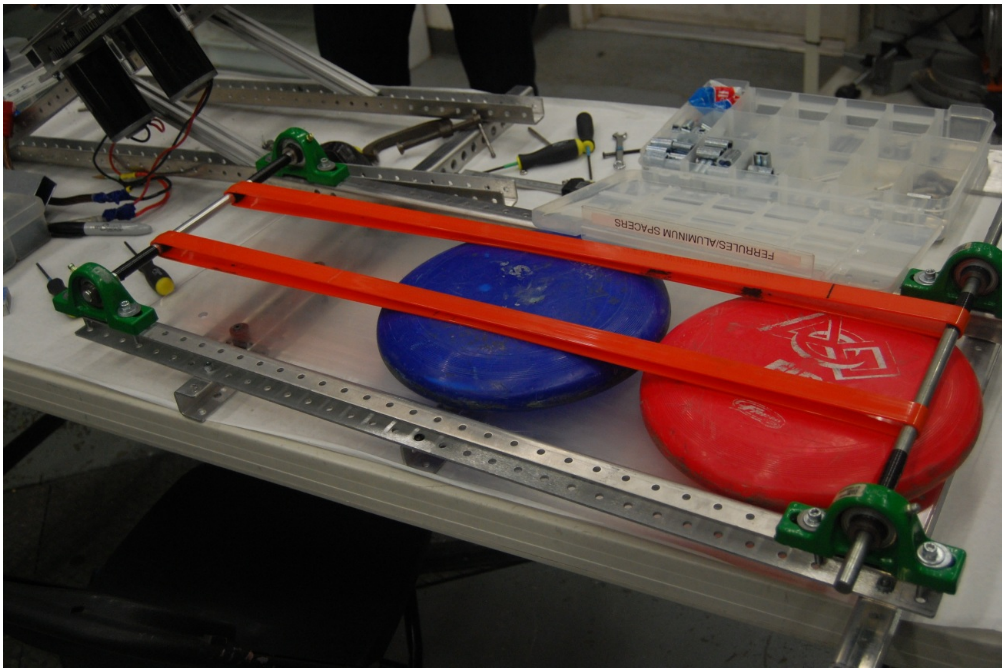


Figure 8.8: A single conveyor belt feeding frisbees from the top.

Conveyors are the most common type of indexer. Objects are fed single file from one place to another using continuous belts. Variants of this exist, such as dual-conveyors (where objects are passed between two conveyors, so they do not need to roll or slide, but are still well-constrained). Video Example

8.2.3 Rotary Hoppers

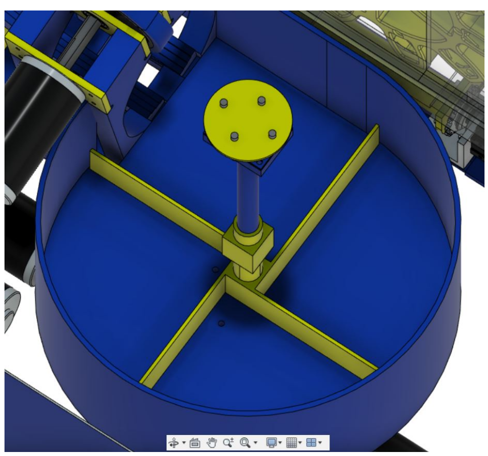


Figure 8.9: Rotary hopper or spindexer

Rotary hoppers or *spindexers* are like gravity hoppers, but use some sort of rotating piece at the bottom to both agitate objects in the hopper and forcefully feed them to the next place. These allow for high capacity and control. The base can either have positive interaction with the objects, or frictional interaction (i.e. flat).

Video Example (0:12)

8.2.4 Agitated Hoppers

Figure 8.10: Agitated hoppers.

Agitated hoppers are slightly angled hoppers which also feature moving sidewalls or rollers that help agitate objects and may even influence them to move faster than gravity would normally allow for. These can be simple to design and integrate while allowing for greater throughput and less jamming than a gravity hopper.

Video Example

8.3 Connected Motion

8.3.1 Elevators, Cascade and Continuous

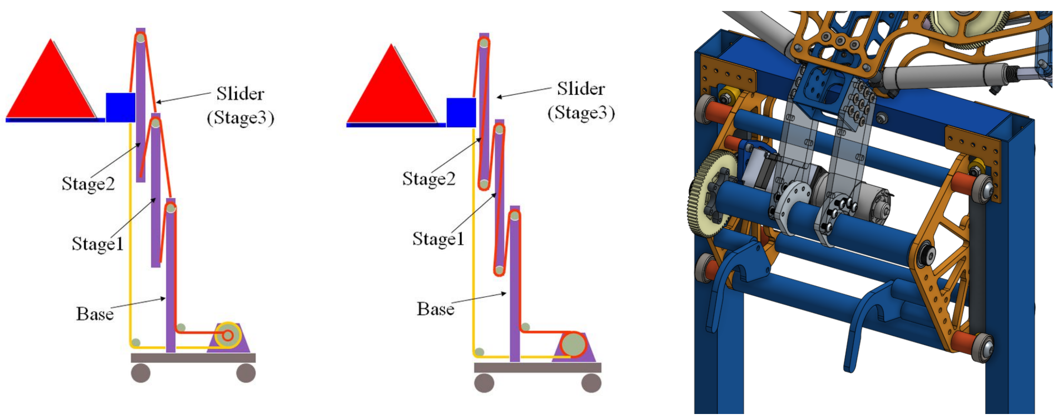


Figure 8.11: Elevators- cascade (left) and continuous (middle). Example construction detail on right.

An *elevator* is a mechanism that moves back and forth in a straight line. The multiple *stages* are held together with bearings or slides to reduce friction. *Cascade* and *Continous* elevators are able to reach further than their initial size without additional degrees of freedom by using special rigging of string to pull multiple stages that are nested in each other.

Cascade elevators have multiple strings to consider. They also have mechanical disadvantage by a factor of the number of stages in the lift. Continuous elevators do not have this mechanical disadvantage and only have one string to worry about.

Video Example (0:37)

8.3.2 Gantries

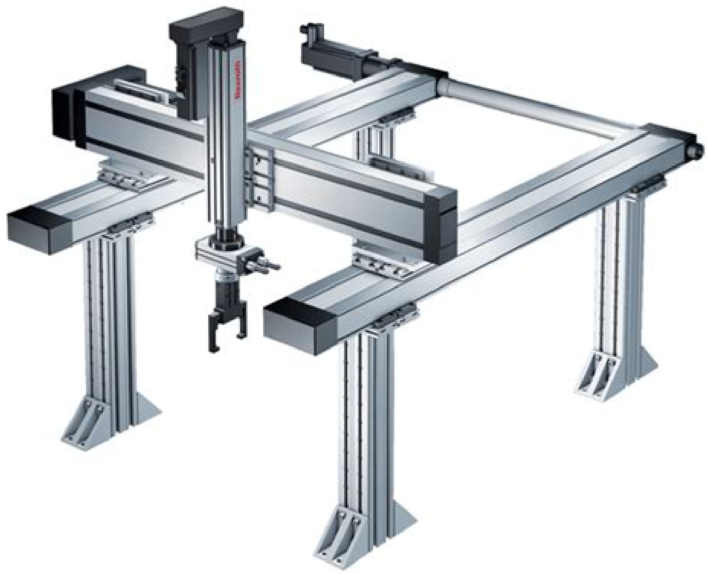


Figure 8.12: Gantry platform.

A *gantry* consists of multiple elevators or linear stages stacked orthagonally and in series, enabling motion in multiple axes. This is a common confiuration for many CNC routers, as it provides a sturdy base and control that is easy to accomplish and optimize.

8.3.3 Scissor Lifts

Figure 8.13: Scissor lifts

Scissor lifts are linkages that can achieve incredible extension from a compact initial size. However, they can be quite problematic in practice, as the parts count to create the several stages can be quite high, and because there are so many parts, so is the backlash. They also have incredibly poor mechanical advantage, meaning the force required to drive them is very significant.

Video Example (0:18)

8.3.4 Parallel 4 Bar

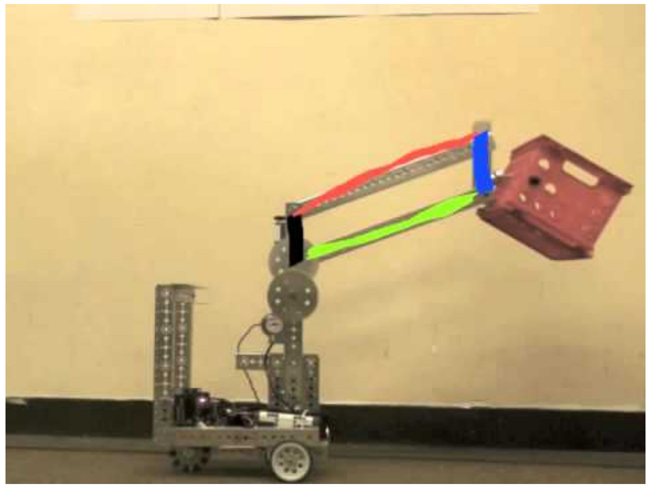


Figure 8.14: Parallel 4 bar mechanism

8.3.5 Pivoting Arms

Figure 8.15: A simple pivoting arm.

Fixed arms are the simplest lifting mechanism, consisting of a beam which is driven about a pivot point. This means whatever is fixed to the end will rotate with the entire arm.

Parallel 4 bar linkages have four links forming a parallelogram, where two opposing sides are the input and output. These are simple to make but do not lift straight up and down- they will move outwards in an arc as they rise. This may be a desirable trait. Video Example 1 Video Example 2 (0:36)

8.3.6 Virtual 4 Bar

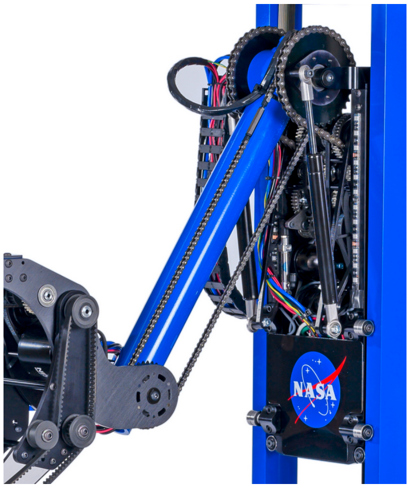


Figure 8.16: Virtual 4 bar mechanism

Virtual 4 bars achieve similar motion to parallel 4 bars, but overcome the major issue regarding the *singularity* that occurs when the links come to a straight line. At this singularity, the mechanism is no longer fully defined and may invert, causing undesired behavior. Virtual 4 bars, on the other hand, can rotate continuously. They are built by using a single linkage, two sprockets, and chain binding the sprockets together. The sprockets are fixed on either end.

Video Example

8.3.7 2N Bar

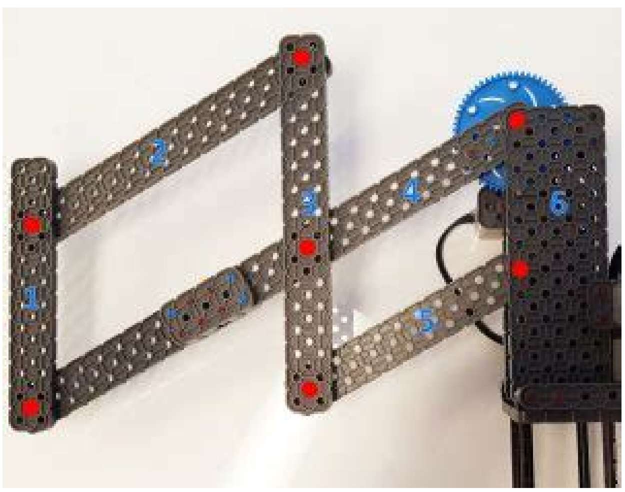


Figure 8.17: 6 bar linkage.

4 bars take up a lot of dead space. They can be made to extend further by staging multiple of them together. These may be called *6 bars*, *8 bars*, and so forth- there is no theoretical upper limit, but increasing the number of stages will pose the same issues as a scissor lift will (you may note, that the underlying linkages are nearly identical, they are just used differently).

Video Example

8.3.8 Double Reverse 4 Bar

Figure 8.18: Double-reverse 4 bar.

Double reverse 4 bars sound complicated, and they are to some degree. These are two 4 bar mechanisms stacked on top of each other, reversed, and linked together (either with gears or a link). This allows them to fold up flat but reach tall heights, and move in a straight line (as any inward motion by the lower 4-bar is counteracted by the outward motion of the upper 4-bar).

Video Example

8.3.9 Compound Arms

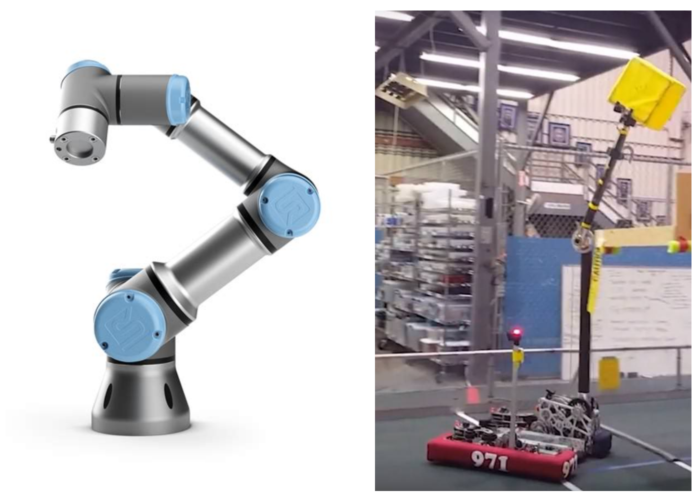
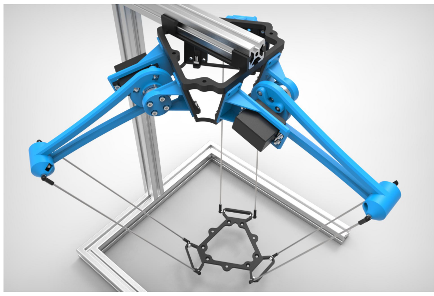


Figure 8.19: Compound arms.

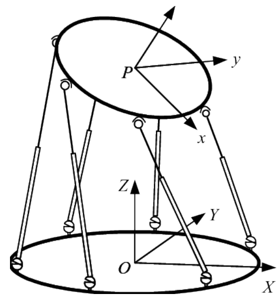
Compound arms consist of multiple fixed arms affixed to each other in *series*. With sophisticated software, complex motions can be performed in one or more planes.

Video Example

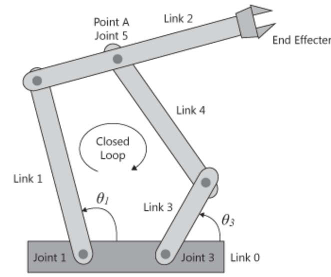
8.3.10 Parallel Manipulators



(a) Delta



(b) Stewart



(c) 5-Bar

Parallel manipulators are a very sophisticated class of mechanisms. Their name comes from the fact that instead of actuators being stacked on top of each other to produce the desired motion, the actuators are placed side-by-side and connected to the same base and mobile object. Although this requires much more complex software which is not intuitive to understand, the results can be quite astounding since the absence of stacking reduces compliance and power requirements to move actuators on the later stages.

a) *Delta* platforms use three actuators, either rotary arms or linear stages, each connected to a mobile platform by two parallel linkages. These linkages keep the platform parallel to the base, and at a constant distance to each stage. This enables the mobile structure to be extremely light and fast, making them quite common on robots used for rapid pick-and-place operations. Video Example

b) *Stewart* platforms use six linear actuators which can be controlled to control all six degrees of freedom of the mobile platform. They are commonly seen on flight simulators. Video Example

c) *Five-bar* platforms use two rotary actuators to drive parts of a five bar mechanism. Video Example

8.3.11 Counterbalancing

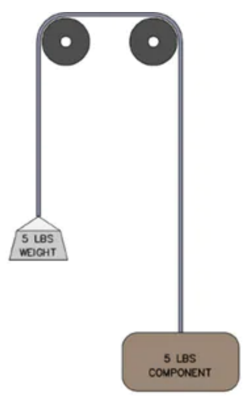


Figure 8.21: A counterbalance.

Most lifts may be improved by the use of a *counterbalance*. The purpose of a counterbalance is to provide load that counteracts the normally seen load or weight. This way force exerted on the lift is used not to fight gravity, but to accelerate the mass of the system. Because weight is usually a concern (and adding mass would increase the inertial loads of the system), a *counterspring* may be used to offset the load without much added mass. Constant-force springs are particularly equipped for this task as they can extend a great distance and provide constant force rather than counterweight that varies with position.

8.4 Shooters

Shooters take objects and propel them great distances.

8.4.1 Flywheel-Based Shooter

Flywheel based launchers store energy in *flywheels* spinning at high velocity. Objects can then be introduced to the flywheels, and the energy is transferred via friction to the objects. This makes flywheel based launchers good for high-throughput applications.

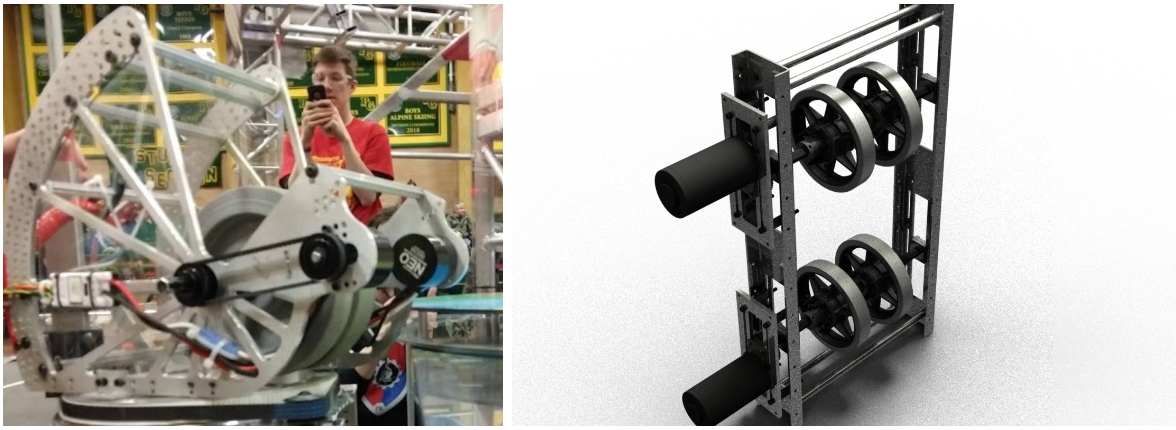


Figure 8.22: Wheeled shooters. Left: hooded. Right: dual-wheel.

Hooded shooters use a singular set of wheels and a fixed *hood* to contact the ball. This produces a high amount of backspin, which may be desirable due to the *Magnus effect* which generates lift (or drop) on spinning objects.

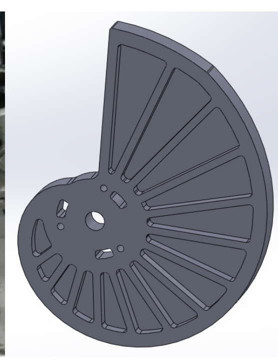
Opposed wheel shooters use mutiple sets of wheels to contact the ball. This allows for control over backspin, and may be easier to package. Example Video (In Slow-Mo!) (1:07)

Flywheel based shooters sometimes have multiple stages of flywheels in order to accelerate the ball over a longer period of time. Belts can also be used to achieve the same principle.

8.4.2 Catapults and Punches

Catapults and *punches* store energy in by pulling back springs or compressing air. Catapults work as a lever arm while punches work linearly, but both use this stored energy to accelerate a sled or cradle containing the object to be launched.

(a) Choo-choo



(b) Snail cam

a) A *choo-choo* uses a rotating plate with a pin, a link, and another link or string. As the plate is rotated, the pin makes contact with the link. Eventually the second link/string gets pulled back and goes over-center from this pin, so that the pin no longer supports the link. At this point the spring pulls the mechanism forwards as it fires. Video Example

b) *Snail cams* can be used to pull back the sled/cradle, and as the cam continues moving, it eventually returns to its starting point, causing the sled/cradle to fly forth.

c) In a *winch and release* a winch pulls back the sled/cradle. When firing is desired, a release mechanism (like those discussed in section 4.6) allows the sled/cradle to fly forth. Video Example

d) *Pneumatic cylinders* are very simple ways of creating sudden bursts of energy. Video Example (1:21)

8.4.3 Cannons

Cannons use rapidly expanding gas to propel projectiles. This gas could be in the form of gases from combustion, or could be simply the release of compressed air.

8.5 Drivetrains

Drivetrains allow for movement across surfaces. Drivetrains have many considerations which depend on the use case.

a) The type of *microterrain* that must be traversed has to be considered- is it squishy? Is it solid? Is it slippery or icy? What materials will generate grip?

b) The type of *macroterrain* that must be traversed has to be considered- is it flat? Is it bumpy? What is the geometry of the bumps that must be traversed- will the drivetrain *bottom out* or *high-center*?

c) There may be a *target velocity* that must be reached.

d) The *ride quality* is important so as not to damage cargo, electronics, or passengers.

e) The *cycle time* or *lap time* is a factor for sport applications.

f) The *efficiency* or *energy consumption* may be a factor.

g) The required *degrees of freedom* are often important- is straight line movement OK? Is steered drive enough? Do you need to turn on a dime? Do you need to move *omnidirectionally* (in any direction without a change in pose)?

h) *Traction*, whether to climb a steep hill, push objects, or remain in place, is a very important consideration.

8.5.1 Car Steering

Figure 8.24: Drivetrain of a car

The key aspects of a conventional car's drivetrain are:

1. Either the front or rear axle is powered. The left and right tires are powered by the same degree of freedom.

2. The front wheels are steered, usually up to 60 degrees.

This means that the car has 1.5 degrees of freedom. The car can move forwards and backwards (one degree of freedom), and while it is moving forwards and backwards, it can change its direction by steering (a half degree of freedom). This may sound limited, but the simplicity of the setup makes it conducive to designing in other complexities that are more important in many scenarios, such as a suspension to achieve superior ride quality.

8.5.2 Differential Drives

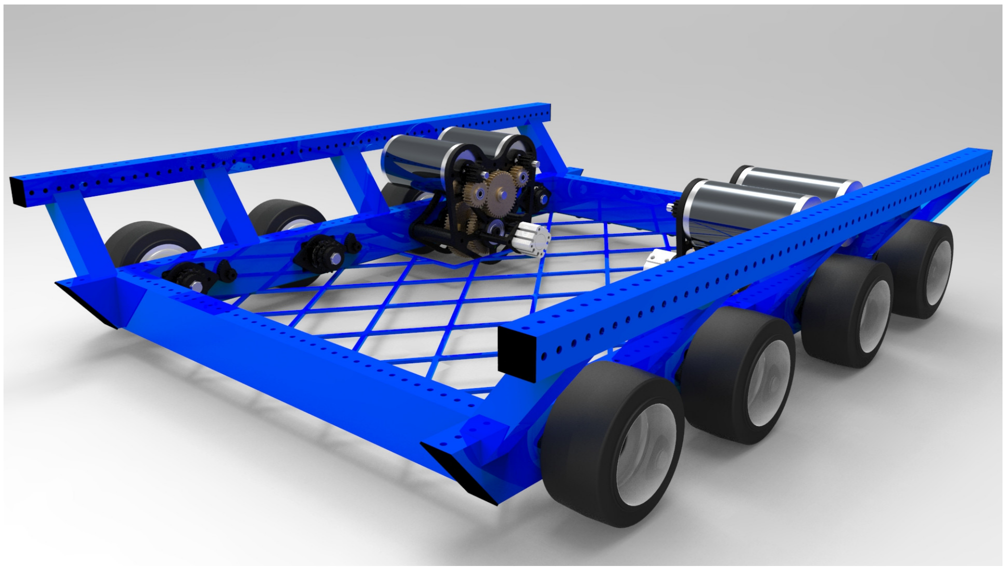


Figure 8.25: Differential drive.

Differential drives (which do not necessarially have *differential gearsets*), often called *tank drives* (even if they don't have tank-style treads) have two sets of wheels (or treads) that are controlled to move independent of each other.

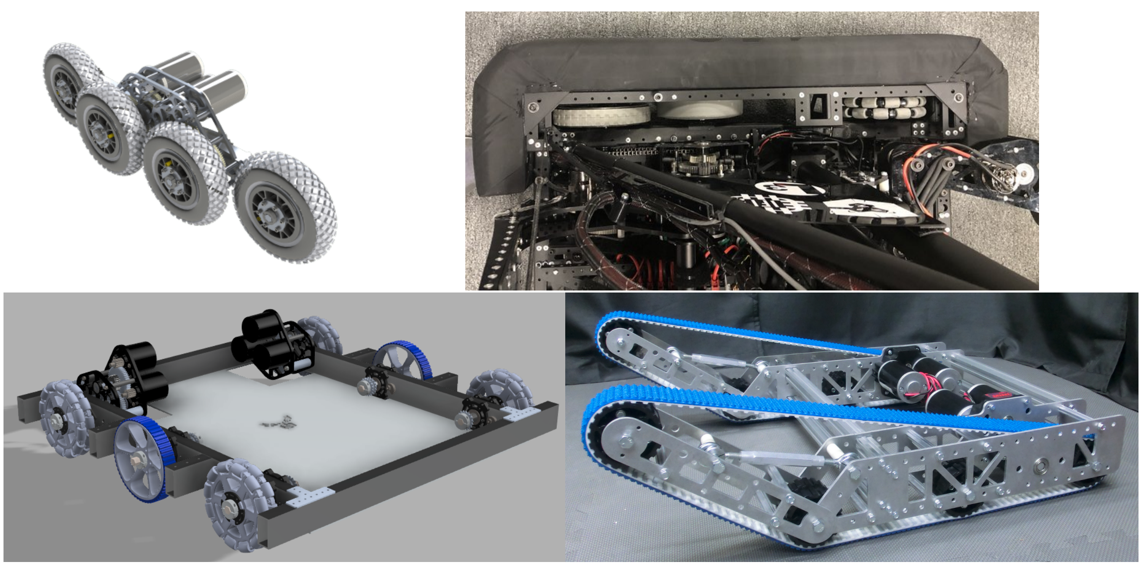


Figure 8.26: Various differential drives.

Sizes, types, amounts, and positioning may be mixed and matched to achieve different goals like climbing obstacles or additional maneuverability.

One parameter that isn't obviously shown is the *center drop* . All differential drives have *turning scrub* or *wheel slip* that happens when the wheels scrub against the ground sideways.

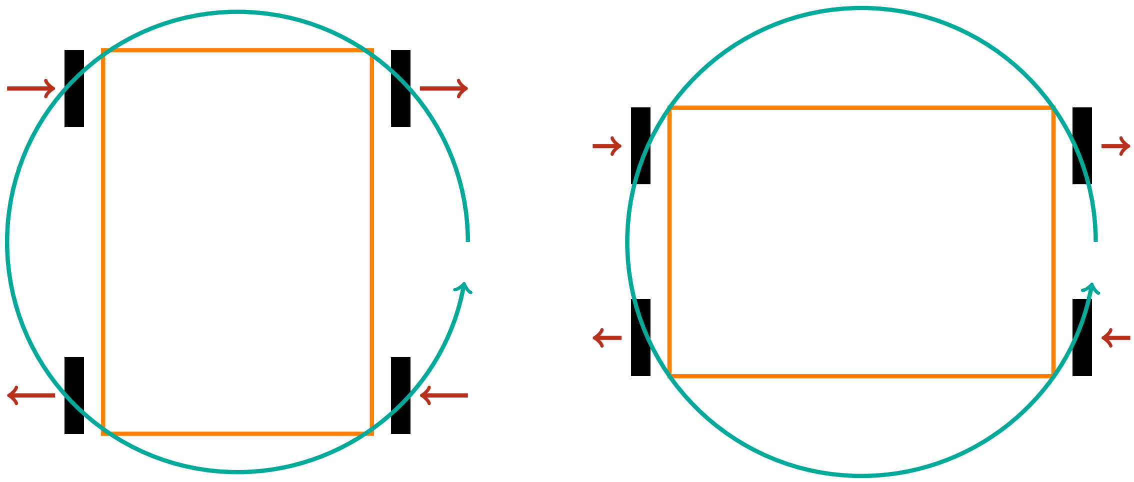


Figure 8.27: Top view of turning scrub (red arrows) of two drivetrains while turning.

When the aspect ratio of the differential drive is wider than longer, the turning scrub is reduced, making turning much easier. However, this causes the drivetrain to be more prone to tipping in the fore-aft direction. If we drop the center wheel(s) of a drivetrain, we can cause the drivetrain to have the full potential set of wheels it would need to be stable while giving it an aspect ratio conducive to turning.

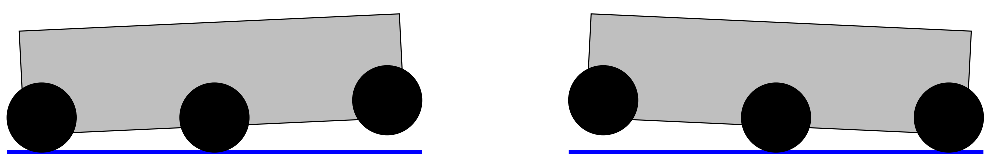


Figure 8.28: Side view of dropped-center drivetrain rocking fore-aft. Center drop is exaggerated.

Center drops are usually somewhere between 1/16"-1/8" per 10 inches of drivetrain length, depending on the exact surfaces and wheels being used.

But there's one thing we're leaving out of the picture, and that's the *center of gravity* (CG) . This is the point of the machine where mass is evenly distributed about, and is the 'natural' rotation point. Rotating about this point requires the least amount of effort- rotating about any other point would cause additional acceleration.

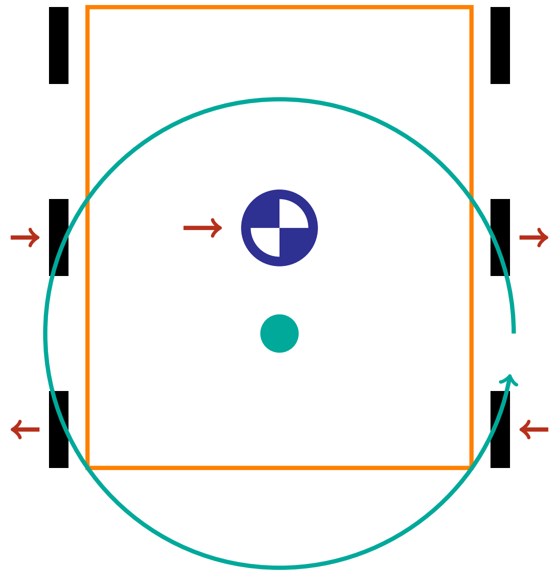


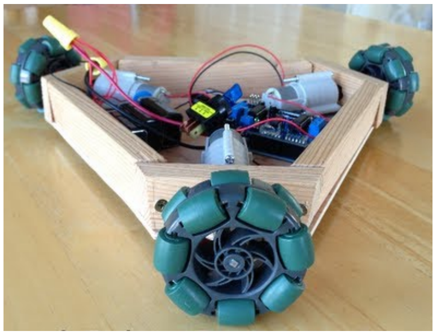
Figure 8.29: Turning of a drivetrain with center drop. The CG is marked in blue with a standard symbol for CG. The center of rotation is noted with a green dot.

Our drop-center drivetrain will alternate between these two suboptimal centers of rotation. Some people don't like this, and thusly opt for an *eight-wheel drive* (8WD). This way the center 4 wheels are normally in contact with the floor, so the center of gravity is very close to the center of rotation.

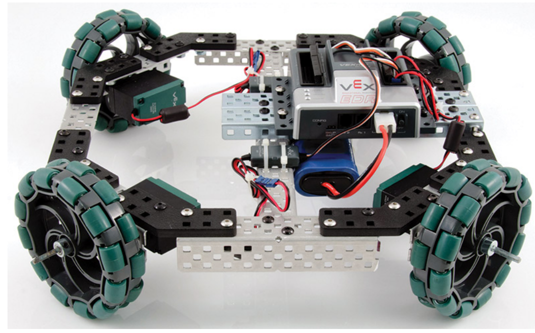
An alternative (or additional remedy) to adding center drop is to use *corner omnis* . Instead of the outside wheels being traction wheels, they are omni wheels. These have minimal resistance to turning scrub, so eliminate scrub entirely. Some designers opt to replace all of the wheels with omnis to make *4 omni drivetrains*. These can produce very agile drifting maneuvers, but have minimal resistance to being pushed sideways.

8.5.3 Omnidrives

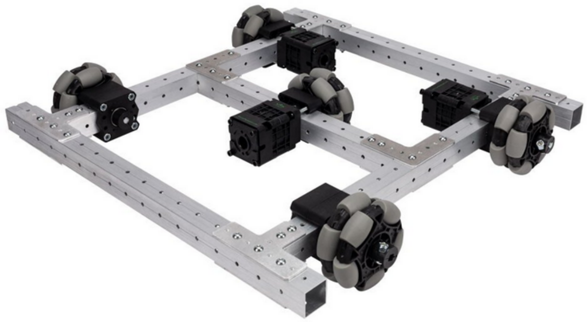
Omnidrives use wheels with rollers like those described in section 4.5 to achieve simultaneous forwards-backwards, left-right, and rotational motion. The wheels limit their use to relatively clean, firm floors, and also limit the materials that can be used on the rollers and thusly their maximum traction.



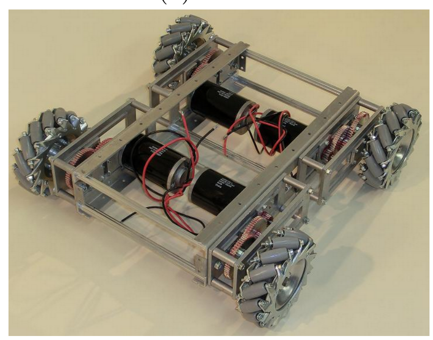
(a) Kiwi



(b) X-drive



(c) Slide



(d) Mecanum

Figure 8.30: Omnidirectional drivetrains.

a) *Kiwi drives* are the simplest omnidirectional drivetrain, comprised of 3 omnidirectional wheels at angles to each other. By varying the power to each wheel, movement in any axis can be produced. They are somewhat inefficient as there is a lot of slip on the rollers. Video Example

b) *X-drives* (not to be confused with 4 omni drivetrains) are like kiwi drives, but a little easier to package on rectangular frames. They benefit from a slight suspension, or at least a frame that is compliant enough to distribute weight between each wheel.

c) *H-drives* or *slide drives* are like differential drives but have a central omni wheel that enables side-to-side motion. This means that they may behave different in the side-to-side direction, but this may be an acceptable tradeoff for their higher efficiency and controllability. However, this central wheel requires a suspension system.

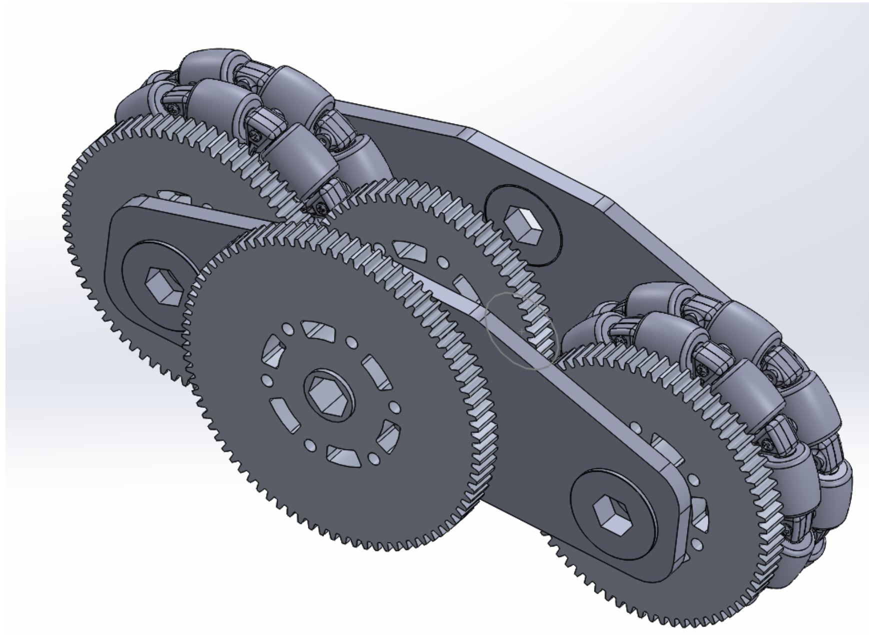


Figure 8.31: Rocker pod for a slide drive.

One novel suspension technique is to use not one but two wheels in a *rocker pod*. This uses the torque from the driving motor to engage the wheel with the ground, and from there, the force the wheel generates with the ground further digs the wheel into the ground. Properly setting the gear ratios can generate the proper amount of dig. Video Example

d) *Mecanum drives* use four *mecanum wheels*. They operate just like X-drives, but are even easier to package into rectangular frames. They are even more inefficient than x-drives, though, and have quite different behavior while strafing than moving forwards.

8.5.4 Transformers

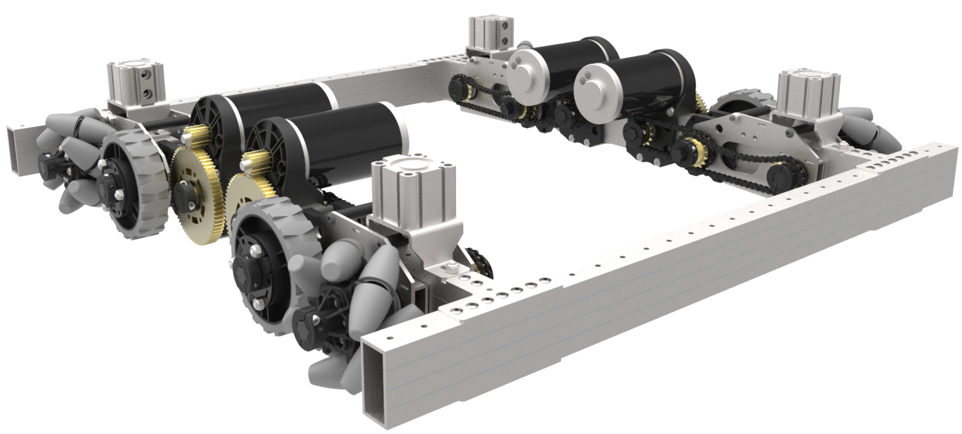


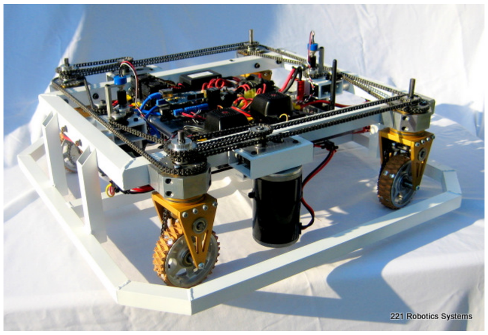
Figure 8.32: Octocanum drivetrain, an example of a jump drive.

Transforming or *jump* drives combine traditional differential drives with omni drives by taking an omni drive and chaining additional regular wheels to them which are actuated up and down. Nearly any combination can exist. but there are two general goals. First and most obvious is to enable omnidirectional motion with the choice of high-traction pushing power. The less obvious is to shift between high and low speeds since the jumped wheels can be geared at a different speed.

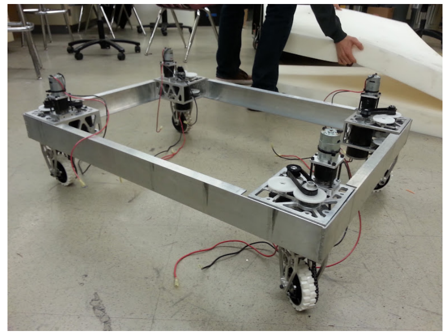
A jump-drive version of a mecanum drive is sometimes called an *octocanum*. A jump-drive version of a slide drive is sometimes called a *jump slide*. A jump-drive version of a 4 omni drivetrain (which isn't omnidirectional, just highly agile) is sometimes called a *butterfly drive*.

8.5.5 Fully-Steered Wheel Drives

Swerve and *crab* drives use traditional traction wheels, but steer them a full 360 degrees. This allows for simultaneous forwards-backwards, left-right, and rotational motion, but without sacrificing traction or object traversal capability like omnidrives. This comes, however, at the cost of higher mechanical and programattic complexity.



(a) Swerve

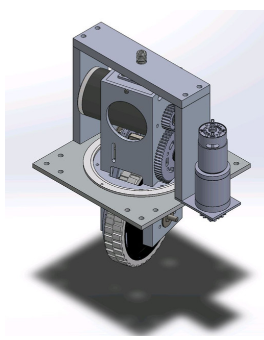


(b) Crab

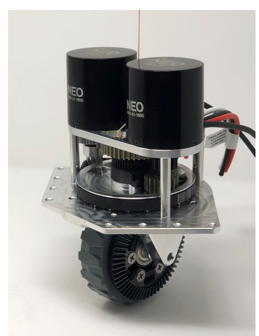
Figure 8.33: Swerve and crab drivetrains.

a) The wheels of *crab* drives are not fully independently steered and powered. Sets of two may be steered together and then centrally powered, or some other obscure combination. This means that some wheels will not be operating at peak, and turning scrub will occur.

b) The wheels of *swerve* drives are fully independently steered and powered. This means that they can all be operated at peak, but means that additional motors and sensoring is needed.



(a) Distributed (motor-in) module



(b) Coaxial module

Figure 8.34: Swerve/crab module types.

a) *Distributed* modules are steered by an external motor, and have a motor in the module that spins with the module. This makes the module in some ways simpler as it does not need a bevel gear or other means to change the direction of rotation, but it does make the module quite large, and the motor's electrical wires limit the rotation of the module.

b) *Coaxial* modules are both steered and powered by an external motor.

$$T_{steering} = T_{motor,1} - T_{motor,2} \tag{8.1}$$
$$T_{thrust} = T_{motor,1} + T_{motor,2} \tag{8.2}$$

Many more gears are required to achieve this, but in the end, higher performance can be developed from the same number of motors/motor controllers.

8.5.6 Addons

Many add-on features can be added to any of these drivetrains to achieve special behavior.

Vacuum pumps or fans can be used to forcibly remove air from the underside of a drivetrain, creating additional normal force with the ground and thusly increased grip. Notable examples are the Brabham BT46 Fan Car, and FRC 95's 2020 vacuum- both of which were extremely powerful features, but ultimately ruled illegal.

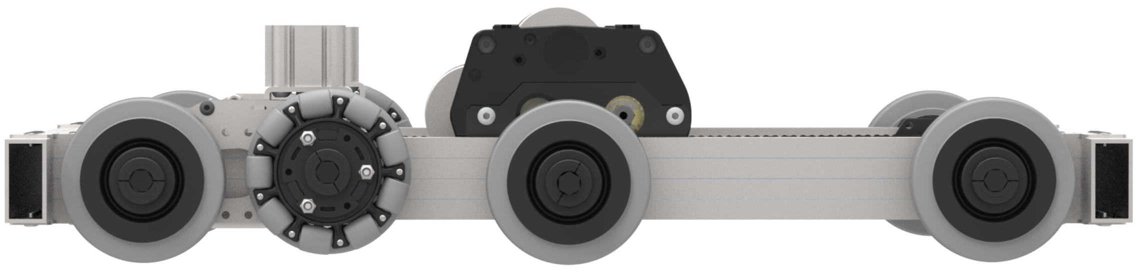


Figure 8.35: Pop-down wheel on a drivetrain

Pop-down wheels are not jump drives, though they may look and behave like it at first sight. The wheel may be idle or powered, and can serve multple purposes. The first is to lift up the front wheels, enabling the drivetrain to crawl over terrain it would normally be unable to.

Pop down wheels can facilitate quick turns as illustrated in this Video Example (0:37).

One of the driving purposes behind pop down wheels is to help get out of *friction pins*. Watch the 2011 FRC Championship Semi-Final 1 Match 1 (match begins at 1:51, pinning begins at 2:13). 973 (in blue) is able to keep 217 (in red) from moving by pushing them in a t-bone configuration. As 217 moves sideways, their wheels lose static friction and so lose their ability to move except in an arc, which isn't an issue for 973.

Pop down wheels with omni wheels installed shift the rotation point from being in the middle of the robot (which is good for handling otherwise as the center of rotation matches the center of gravity) to being in the rear. At this point, the t-boning robot would simply push past, breaking the friction pin.

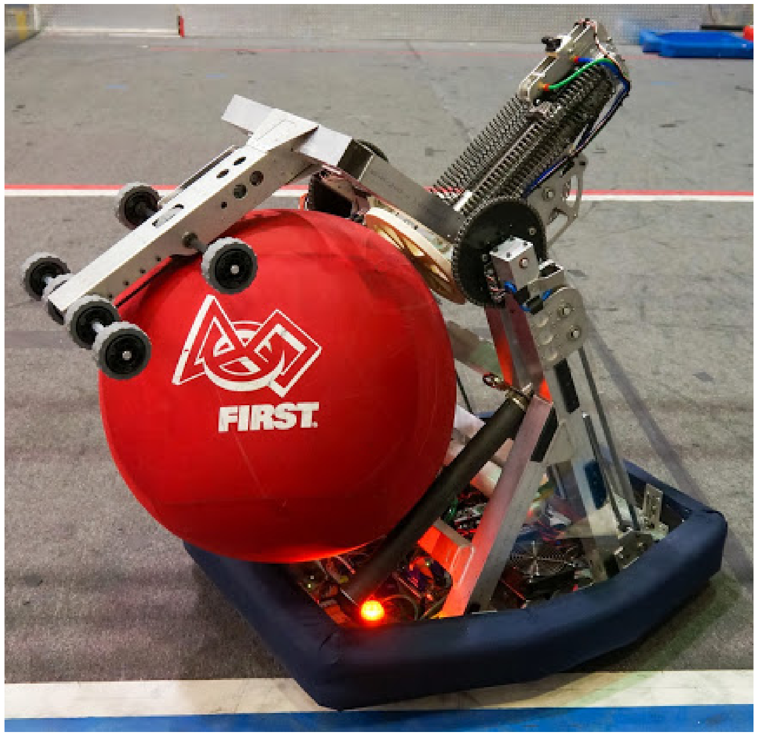


Figure 8.36: A robot with an octagonal frame.

Curved frames or *multi-faceted frames* can also help with getting out of friction pins. These allow the pinned robot some ability to turn so they can leave the pin.

Figure 8.37: A battlebot with a skirt.

Wedge plates or *skirts* are angular plates on the exterior of a frame which can be used to get underneath other machines, stealing their normal force much like a vacuum would, and giving an advantage in pushing.

Chapter 9

High-Level Design Principles

"Everything should be made simple, but no simpler." - Albert Einstein

Welcome to the opinionated part of this text. Like many opinions, they're held for particular reasons, and made by a human rather than divine intervention. The best you can hope is that I've been divinely inspired, so ask yourself constantly, "does this make sense?"

A lot of this first chapter in design will be thinking about the design process itself, rather than the actual objects being designed. This may sound like it falls under the pervue of philosophy (which may drive you to boredom or an existential crisis), and it does! But it is practical philosophy.

9.1 Designing a Project

I'll say project, and not team because some projects are done by individuals, and projects are bigger than teams. There's a lot of adages about project management. This is not a project management book and doesn't set out to be, but the fact of the matter is that project management influences technical design, to the chagrin of many engineers. Management is wed to engineering, and the divorce is always an ugly one. May as well be good bedfellows, and make a happy marriage.

What you can do in a project should always be considered. There are a number of mantras which dwell on this:

- "Good, fast, or cheap: choose two." (The delusional will realize "none" is also an option.)
- "A robot with 1 mechanism at 100% is better than 10 working at 10%"
- "The first 80% of the task can be accomplished with 20% of the work."

There's a lot of bad management out there. I'm not going to profess to know everything. I'm compiling from lots of stories, observations, and lived experiences. Above all, what I've noticed is this:

Theorem 1 *Good management works. If your management isn't adding value, it's bad and you should stop it.*

This sounds... obvious, but I've watched many teams led into processes on the basis of "this is the way we do it." Good management working doesn't mean you're winning and succeeding all of the time- it just means that it's increasing the likelihood. Do not be afraid to re-assess mid-stream and change course. Management is continuous development, not divine revelation.

9.2 Designing Metrics

A lot of my thoughts on high level design and metrics are grafted from the world of software. Gary Bernd-hart's Boundaries is a particularly good example of this because it highlights what so many engineers do wrong in their testing and design. The essential problem is that they get locked into a particular set of units which must exist, and so metrics are formed based around these units rather than end results.

Let's look at a few sets of metrics that a team partaking in competitive robotics might generate after recieving their challenge.

1) Score as many points (at least 150) as possible during a match
2) Be easily resettable after a match

This first set of metrics is... well it's pretty shallow. It doesn't give engineers any meaningful guidance, and it doesn't allow you to test the results incrementally (more on this later). There's no way of knowing you're going to achieve your overarching goal of 150 points until you build everything and play some matches.

Theorem 2 *Metrics should be unit-testable, to help gain confidence in your design.*

The second metric also has a problem of measurement- how easy is "easy"? Do we quantify it with time, with tools required, with amount of swears uttered by the pit crew?

Theorem 3 *Metrics should be measurable.*

OK, let's try being more detailed with our metrics!

1) 200 Watts of shooter power
2) Drivetrain free-speed of 15 ft/s
3) Total machine weight under 90 pounds
4) Intake spins at 30 ft/s
5) Drivetrain shifter spread of 1.5
6) Drivetrain uses 4 CIM Motors
7) ...

This is much more helpful for engineers in terms of getting work done; you could definitely build a machine to achieve these results. You could even build a machine that validates these results (by inspection, you could easily tell how many motors it uses!). But the end behavior may not be desirable. These requirements could be useful to develop at later stages beyond initial development but initially, it already boxes in the design. It's easy to get into "requirements hell" as you develop an exhaustive list of requirements you think you'll need, but prototyping might reveal are not so.

Theorem 4 *Metrics should not try to box in a design until they need to.*

To make this more clear, let's look at a last set of metrics that is much better.

1) Score 5 balls into a goal in under 10 seconds
   a) Collect 5 balls from ground in 5 seconds
   b) Shoot 5 balls into goal in 2 seconds
   c) Shooting accuracy of 90%
2) Play defense
   a) Push with 120 pounds of force
   b) Not get caught in friction pins
   c) Move 10 feet in 1.5 seconds
   d) Does not brown out under stall
3) Able to be reset by field crew with standard toolkit in under 10 minutes
4) ...

These metrics refer to particular subsystems and behaviors, are measurable, and do not box in one particular design. They would be crafted with some care and strategic analysis.

Notice how this is a nested list! Recursion can be used to help discern a useful set of requirements that tie directly back to the overarching ones.

Of course, sometimes you get suprises. Maybe one of your metrics cannot be accomplished. Maybe one of your metrics can be accomplished even better. By creating this heirarchy of metrics, you can walk back up the tree, and make changes to the overall design to compensate. Maybe now that you can only shoot with 80% accuracy, you need to shoot in 1.5 seconds. Maybe now that you can collect all balls in only 2 seconds, you can take more time shooting to improve accuracy. Your metrics shouldn't box in a design, they should be there to help draw boundaries, and will move with your design as well.

9.3 Design for Testing

It is well to design something so that it *could* achieve the desired metrics, but *tuning* it so that it does and *testing* it to confirm it does, are different stories.

Modularity, breaking a system down into modules which have clearly defined inputs and outputs, helps to perform *unit testing*, where an individual portion is tested in isolation before being inserted to the rest of the system. Especially in the mechanical world, unit tests are not perfect, but they reduce overall testing effort. How does adding additional tests reduce testing effort?

This is due to *combinatorial explosion.* A machine may be subject to lots of variance in the inputs. Take a machine with three modules A, B, and C. If input to A has 3 possibilities, B has 4 possibilities, and C has 8 possibilities, then there are $3 \times 4 \times 8 = 96$ different possibilities which the machine would need to be tested under. If, however, each unit were tested individually at all possibilities, only $3 + 4 + 8 = 15$ tests would be needed. Additionally, these tests could be conducted in parallel, so only 8 tests worth of time would be needed.

This of course assumes that there are no complications and the interactions between A, B, and C are fully understood. Some degree of *integration testing* is still needed. Perhaps unit tests could be repeated many times on these units in isolation, then when they are combined, they are only ran once, since all acted as they should have.

Designing for unit testing has an additional advantage for the upfront design phase in that a module does not depend upon the others for testing and iteration. It also is advantageous in that the inputs and outputs of units can be better understood through observation.

Theorem 5 *Modular testing with good fakes helps understanding, prototyping, and final testing.*

How does one go about designing such that testing is easy? Well, it goes back to metrics! Metrics must be established for a unit to be tested. The inputs and outputs must be understood. The unit can then be designed as intended, and *fakes* can be made for missing or dependent components (a full electrical system may be replaced by, say, a battery and a switch... a drivetrain may be replaced by a dolly). The fakes should be as close to the real components as possible in order to minimize mis-testing.

> There are a lot of terms other than *fake. Dummies, spies, mocks, and stubs* are all aspects of software testing. Why so many different terms?

9.4 Pick the Right Methods

Finding the right level to solve a problem on is often a problem. I lump this into high-level design because oftentimes, one must step back to their metrics and ask: "am I solving the right problem?"

For instance, one might need to grab an item. If one locks into a particular end effector design like a claw, they may start down a path of adding a computer vision system and additional sensing to increase process reliability or speed. However, a more simple mechanical solution may often be the solution: use funnelling, wider grip range, or even powered rollers to quickly acquire the item. Stepping back and re-assessing what will make the overall system better, rather than improving the system as it exists, can be beneficial.

Often this manifests in the idea of "don't solve a hardware problem with software", but it does sometimes work in the reverse. If multiple target positions on an arm are required, creating pneumatic hard stops which the arm would run against may not be the easiest. Simply developing a control system with closed-loop control may prove to be the simpler and more robust solution.

Chapter 10

Low-Level Design Principles

"Learn the rules like a pro, so you can break them like an artist." - Pablo Picasso

Design is tough. Before we get in the weeds I want to acknowledge that it isn't for the faint of heart, and it isn't a straightforward linear process. Often when you finish solving one problem, you'll find you've introduced another in the process. Design is iterative. Design is also play. If everything we did just simply worked no better than anything else, we wouldn't need to design things and wouldn't get anything from us, so we should be thankful that it's hard.

There are some general strategies designers have come up with that help while we play within the rules that physics gives us. Like any rules, there are times for them to be broken but you should be conscious of the rule so you can break it with success. Every design is a compromise.

10.1 Load paths

When we consider structures and systems that we build, we need to think about the forces that go through them, not only at the point of application, but how they propogate through.

Theorem 6 *Loads can only be transferred, not evaporated.*

Proof: Consider the links in a chain. When you pull on a chain, the load isn't seen only by the first link. The load is transferred from your hand into the first, then into the second, the third, so on and so forth until eventually it is resolved into the ground, and transferred back to you via your feet. At no point does the load disappear. When you have a force in your system, all the parts in the loop must be built in order to handle the force.

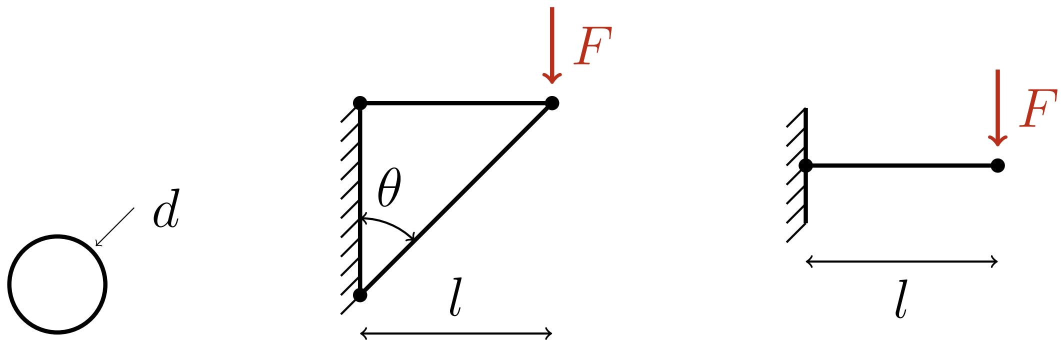
It also follows that because of this, direct load paths tend to be the best course of action. If you're worried about links in a chain failing, remove links and make the chain shorter. Don't use a baseball bat to pull sideways on the chain- pull the chain directly. The straighter and more direct your path, the stronger and stiffer the link will be.

Note I say stiffer. There can be times where you want non-stiffness, like in a suspension! Look at any suspension system and you'll see specifically designed points where the load is very indirect and winding. Springs are a fantastic example of this.

10.2 Axial Versus Bending

Theorem 7 *Axial is stronger and stiffer than bending.*

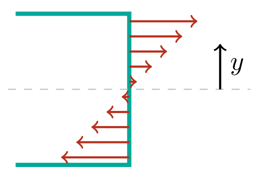
You've probably heard that triangles are a very strong shape. This is essentially a rudimentary understanding of this principle that axial is stronger than bending. If you're designing structures with long, slender tubes, a good rule of thumb is to make sure that structure is *triangulated*. I'll demonstrate this with two structures with load F acting down on them. Both are constructed from round bar as shown.



(a) Round tube (b) Trussed structure (c) Cantilevered structure

Figure 10.1: Trussed versus cantilevered structures.

The stress that the cantilevered beam sees varies along the cross-section as shown below.



$$\sigma = \frac{My}{I} = \frac{M}{S} \tag{10.1}$$

Figure 10.2: Stress (red arrows) in a cantilevered beam (teal).

The stress is the highest at the outer portions of the tube, and can be found by the bending moment M induced on the tube, the radius of the tube y and second moment of area I (not to be confused with moment of inertia), or the section modulus S. You can conduct your own research into these if you want, but an important takeaway from this is that increasing the diameter of the tube will have a huge impact on I, so we'd ideally want a very large I.

For our example of a round bar,

$$I = \frac{\pi}{64} d^4 \tag{10.2}$$

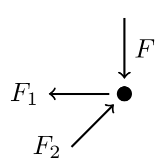
$$S = \frac{\pi}{32} d^3 \tag{10.3}$$

and in our cantilevered structure, the bending moment at the base is simply $M = F\,l$. This means that we can find the maximum stress as:

$$\sigma_{cantilever} = \frac{Fl}{\frac{\pi}{32} d^3} \tag{10.4}$$

Which isn't very meaningful until we compare that to the trussed structure.

For the trussed structure, we will assume that all the joints are pinned, so the members of it act as links. This isn't a particularly realistic assumption, but it is in some ways a conservative one. We can then analyze the node where the force F is applied.



$$\sum F_x = 0 \quad \rightarrow \quad F_2 cos(\theta) - F = 0 \tag{10.5}$$

$$\sum F_y = 0 \quad \rightarrow \quad F_1 - F_2 sin(\theta) = 0 \tag{10.6}$$

Figure 10.3: Free-body diagram for node of force application.

We can then solve for the forces in the links:

$$F_1 = Ftan(\theta) \tag{10.7}$$
$$F_2 = F\frac{1}{cos(\theta)} \tag{10.8}$$

For simple links like these, the stress is simply the force in the link, divided by the cross-sectional area.

$$\sigma_{truss,1} = \frac{F}{\frac{\pi}{4}d^2}\ tan(\theta) = \frac{F}{\frac{\pi}{4}d^2}\frac{sin(\theta)}{cos(\theta)} \tag{10.9}$$
$$\sigma_{truss,2} = \frac{F}{\frac{\pi}{4}d^2}\frac{1}{cos(\theta)} \tag{10.10}$$

This isn't immediately comparable to the cantilever, as it doesn't have l in its expression, and the cantilever example doesn't have θ. But we can consider the example of:

F	d	θ	l
100 lbf	0.5 in	30 degrees	10 in

$$\sigma_{truss,1} = \frac{100\text{ lbf}}{\frac{\pi}{4}(0.5\text{ in})^2}tan(30\text{ degrees}) \qquad = 295\ psi \tag{10.11}$$
$$\sigma_{truss,2} = \frac{100\text{ lbf}}{\frac{\pi}{4}(0.5\text{ in})^2}\frac{1}{cos(30\text{ degrees})} \qquad = 588\ psi \tag{10.12}$$
$$\sigma_{cantilever} = \frac{100\text{ lbf }10\text{in}}{\frac{\pi}{32}(0.5\text{ in})^3} \qquad = 81500\ psi \tag{10.13}$$

Those values are so extremely disparate! OK, we're using really thin rods though. If we used that additional weight we save by not having the truss support to beef up the cantilever rod though, we'd get better though, right? After all, that d term is cubed in the cantilever equation!

$$\sigma_{cantilever} = \frac{100\text{ lbf }10\text{ in}}{\frac{\pi}{32}(1.0\text{ in})^3} \qquad = 10185\ psi \tag{10.14}$$

Sure, doubling the cantilever rod's diameter gets us an 8-fold decrease in stress, but we're still off by orders of magnitude from the axial case.

Indeed, designing good load paths trumps adding material every time.

10.3 Big Sections

Theorem 8 *Wide but thin is stronger and stiffer.*

Recalling the equation for bending stress,

$$\sigma = \frac{My}{I} = \frac{M}{S}$$

and looking at a number of shapes and their equation for I,

we notice that the second moment of area I (not to be confused with the moment of inertia) grows roughly with the cube of the tube diameter. If we think about this and the geometry, that would mean that in a

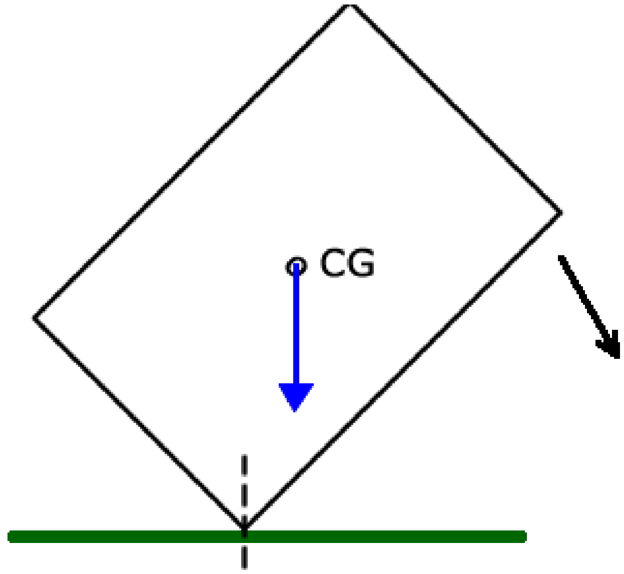


Figure 10.4: Center of gravity of an object that is tipping.

piece of tubing with the same cross-sectional area, we could get a greater I by maximizing the diameter and minimizing the wall thickness. There is a problem with taking this to an extreme (consider the humble aluminum beverage can), but in general, the effect of increasing the diameter of a section dwarfs the effect of increasing the thickness by the same relative amount.

The same is also true of shafts in torsion / carrying torque.

Additionally, notice how multiple moments of inertia are listed for some shapes. Consider a piece of rectangular box tube. It can be bent in two orientations. One has a much larger effective diameter, so is the stronger and stiffer direction. Consider the orientation you lay tube when making structures.

10.4 Minimize, Centralize, and Lower Mass

Theorem 9 *The most sstable and agile vehicle is a small point mass on the floor.*

Minimizing the center of gravity of mobile platforms is almost always an extremely important design consideration, as it is what determines the fundamental tipping characteristics of the platform. For a non-accelerating and free-standing object, if the center of gravity passes outside of the support base of the object, it will begin to fall. For accelerating objectss, a higher center of gravity will tend to make the object tilt against the direction of acceleration, increasing the likelihood of tipping.

Minimizing overall mass is often a desirable goal, as decreased mass will make the same amount of force result in quicker acceleration, or require less force for the same acceleration. This will either reduce the time spent doing something, or the energy required to do it.

Centralizing mass can also be desirable, although the effect is often less pronounced. An object with spread-out mass is much harder to accelerate rotationally versus one with concentrated mass (even of the same mass), again, meaning higher centralization will facilitate lower energy consumption or decreased time-to-target.

10.5 Spread the Base

Theorem 10 *The wider the base, the more stable.*

Similar to how increasing the diameter of a section increases strength, so does increasing the diameter of bolt patterns, sprockets, gears, and just about anything that transfers load.

Increasing the diameter has another benefit beyond strength, and that is backlash.

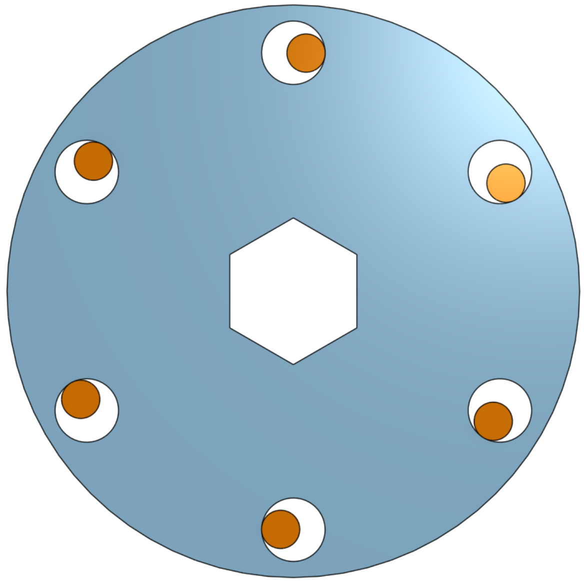


Figure 10.5: Loose-fitting pins (orange) in a hub (blue).

Consider the pins in a hub illustrated above. While a bit exaggerated, clearance between components is necessary to ease assembly, and to deal with manufacturing tolerances. These clearances and tolerances are generally fixed with respect to the diameter of the bolt circle, however. We could minimize the angular slop in this assembly by increasing the diameter.

An interesting conclusion of theorems 6 and 10 is that using a linear actuator of some sort on a pivoting mechanism can be more precise and strong than one driven by a rotary actuator at its pivot point.

10.6 Abbe Error

Abbe error, or *sine error* refers to the error that can come about when parts are not aligned angularly as they were expected to be.

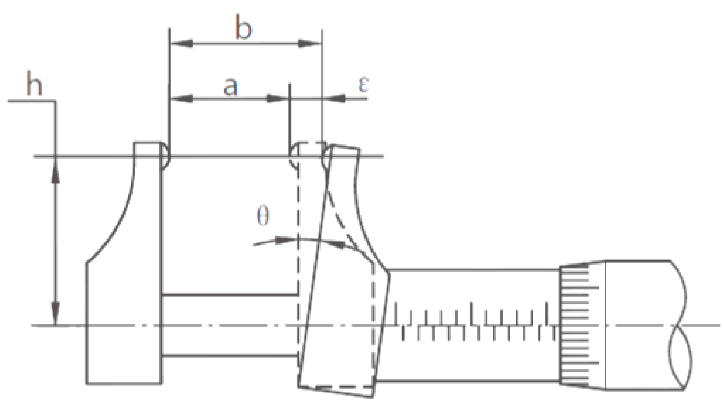


Figure 10.6: Abbe error on a micrometer.

The error is equal to:

$$error = h\ sin(\theta) \approx h\ \theta \text{ (for small } \theta) \tag{10.15}$$

Expressed verbally this means that

Theorem 11 *Angularity adds up, proportional to the distance.*

If precision matters, minimize the angular error of your mechanism, or minimize the lever arm associated with the angular error.

For example, if a turret is shooting a target from 30 feet away, and its rotational accuracy is 1 degree, this results in a potential error of 6 inches!

10.7 Tolerance Stacking

Consider stacking multiple blocks that are all 10 ± 1 mm thick to achieve a height of 100 mm. We would need 10 blocks, and so the error would compound among each block, up to ± 10 mm! Clearly, one singular component would be better, even if it had a lower tolerance of even ± 5 mm.

Considering also that more components means more cost, and more potential weak links,

Theorem 12 *Minimize the number of components.*

This also means that you should measure outputs as closely as possible. E.g. if you have the option to place an encoder on a motor or on the output shaft of its gearbox, the gearbox is usually preferable. While this may decrease the resolution of the encoder, the reduced backlash will result in a higher accuracy.

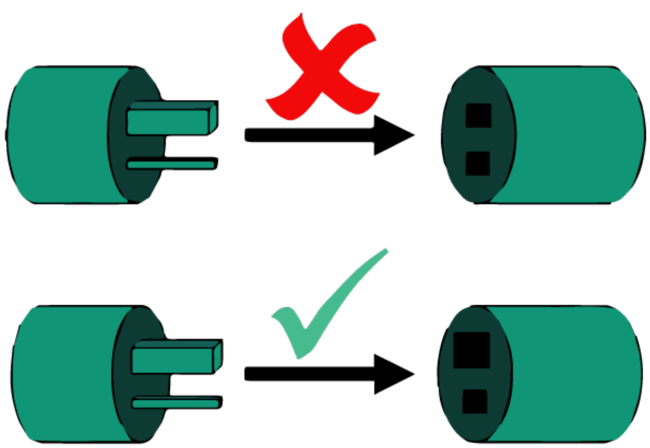
10.8 Loosening

Positive retention is ensuring that vibrations and loads will not effect the positioning of components. This means avoiding slots for adjustment (that do not have additional locking schemes like cams), and bolts that must be "just properly tightened" in order to work properly.

We discussed a number of mechanisms for keeping bolts from loosening under vibration in section 3.4.2. Most of these solutions don't cost much to implement. There's generally no reason not to do them. And so,

Theorem 13 *Positive retention is awesome, let's do more of that.*

10.9 Poka-Yoke



Poka-yoke is Japanese for "idiot-proofing". It refers to designing processes that cannot be messed up, or at least not without warning. Think of plugs that cannot be installed backwards, or a shaft that has a special keying on it to ensure proper clocking. Even the brightest of us can be idiots in the moment, so in short,

Theorem 14 *If someone can screw it up, don't let them.*

Commonizing the types and sizes of fasteners is also useful for field service and production-line efficiency. Reducing the number of part and tool sizes which a technician must carry can greatly improve productivity, as does reducing the number of different parts which must be purchased, stocked, and inventoried. This is why oftentimes on mass-produced products some fasteners seem grossly oversized- if you look closely, you may see other nearby fasteners which use the same size head, or even the exact same bolt. Even in competitive environments, the technician effort saved by using a larger but common bolt size can make the difference between making the next match and not- making up for the weight increase in spades.

10.10 Design for Manufacture, Assembly, Service, and Tuning

Theorem 15 *Don't make techs hate you.*

The parts for your machine need to be built. After they're built, they need to be assembled together. After assembly, they will be serviced at some point. One of your objectives as an engineer is to not make the people involved with this process frustrated. If you can add a little bit of material, or avoid making a strange hole, for the sake of your machinist, do it. The many things you can do to make manufacture easy depend on the processes being used.

Designing for assembly and service is a little more straightforward. There are a few general principles:

- Provide clearance for tools (wrenches, sockets, and rivet guns) both in the axial and radial directions.

- Commonize the tools needed to put a system together. If you need to use both 1/4" and #10 screws, use button head 1/4" and socket head #10, so that the same allen wrench can be used. Better yet, just use all 1/4" or #10.

- Maximize the number of ways the assembly can be put together. At least do this at the higher levels. You shouldn't need to remove 30 pounds of machine to tighten a screw. Another way to think about this is "design for random assembly order".

- Prioritize the common service routines. If a certain bolt is going to be loosened/removed a lot, make sure it's easy to get to.

Designing for tuning can save you hours of valuable test time. If you foresee that a mechanism will need to be adjusted, try to ensure that adjustments are simple to make, and that the adjustment can be measured and recorded in a lab manual for reference.

- Quick pins are the ultimate in quick adjustment. The new position is immediately evident, adjustment doesn't require a tool, and there is no concern of loosening.

- Slotted shims, depending on how they are placed, can be a good option for adjustment. They allow the tuner to write down at a glance what the current position and newly adjusted position are for testing. However, a set of shims is required to make adjustments- meaning that the machine is not self-contained and requires a special toolkit. They also cannot be used to adjust under preload (i.e. adjusting suspension on a car while it is on the ground).

- Tie rods are a simple option for adjustment in many cases. Unlike shims or pins, though, they do not provide any inherent feedback about where they have been adjusted to. The eye-to-eye length could be measured and recorded, but this requires additional tools and may be prone to error.

- Slotted holes (by themselves) are poor methods of adjustment (See: "Loosening"). They can be improved by using a set screw to push against the part in the slot and provide positive positioning. Like tie rods, they do not provide any inherent information about where they have been adjusted to.

- Set screws to clamp on rods are awful methods of adjustment. They are extremely prone to loosening... but can be useful for prototypes. They come with (or can be made to have) different tips that are more suited to frequent or infrequent adjustment.

Chapter 11

Choosing Motors and Gear Ratios

"Power is worthless, if improperly wielded."

These last chapters will walk through some analysis required to actually design systems.

For any system powered by motors we may have a number of concerns.

a) How fast we can get from one point to another: *cycle* or *sprint* time.

b) How much electrical energy or current is consumed during the maneuver.

c) Maximizing how much force can be pushed in a worst-case scenario.

d) Achieving a target velocity in a given time.

e) Achieving all of these goals, for various different targets (e.g. different cycle distances).

This chapter covers how we can use some calculations to design a system with the right amount of motors and an appropriate gear ratio to achieve your targets.

11.1 What Do Gears Really Do?

If we have a motor with a pinion of N_m teeth, mating with a driven gear of N_d teeth, we would achieve a gear ratio of

$$G = \frac{N_d}{N_m} = \frac{\omega_m}{\omega_d} = \frac{T_d}{T_m} \tag{11.1}$$

This also works with belts or sprockets and chain (though you may need to keep an eye on the direction of rotation, as gears can reverse the direction of rotation).

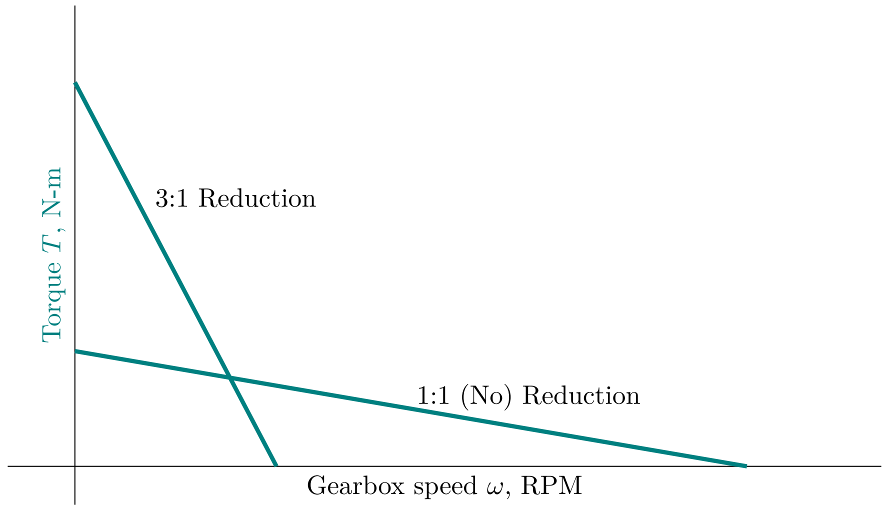


Figure 11.1: A 3:1 gear reduction shifts the effective motor curve of a gearbox.

The 3:1 ratio reduces maximum speed, but increases the maximum torque. It also changes the RPM at which maximum power and efficiency occur. A gearbox that has too much gear-down:

- Quickly gets up to its maximum speed and remains there throughout the majority of its action.
- Operates beyond the speed necessary for peak efficiency of the motor.
- Operates for too long, wasting electrical power.

Whereas a gearbox that is not geared down enough:

- Operates below the speed necessary for peak power or efficiency of the motor.
- Pulls excessive current, wasting electrical power.
- May not even move at all in the first place, lacking the strength to overcome load placed on it.

But how do we know that we've geared appropriately? We could definitely test all the different ratios, gather all the operating data, and then draw a conclusion... or we could do some preemptive math. Don't worry- you don't even need to get your hands too dirty. All of the rough stuff has been done already- you just need to know how to use the design applications to get the answer you want.

But knowing roughly what's going on is important. There's an old joke in engineering,

"All data is wrong. But this data, having gone through an incredibly sophisticated computer, is somehow ennobled and none dare question it."

Which roughly translates to: "You can't just mash buttons and trust the results".

11.2 Developing a Generalized Mechanism Model

11.2.1 The Simple Flywheel Case

Let's examine a simple case of a motor accelerating a flywheel. This is also (essentially) the same as any system with no friction or gravity-fighting (like an ideal drivetrain).

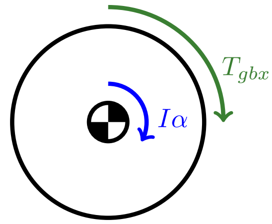


Figure 11.2: Free-body diagram of the flywheel

We can apply conservation of angular momentum to the flywheel.

$$T_{gbx} = I\ \alpha_{wheel} \tag{11.2}$$

This tells us about the rate of acceleration α, but what about the velocity ω?

$$\alpha_{wheel} = \frac{d\omega_{wheel}}{dt} \tag{11.3}$$

$$\omega_{motor} = G\omega_{wheel} \tag{11.4}$$

$$GT_{stall}\frac{\omega_{free} - \omega}{\omega_{free}} = \frac{I}{G}\frac{d\omega}{dt} \tag{11.5}$$

This is a "differential equation" ($\frac{d\omega}{dt}$ and ω appear in the same equation). These are tricky to solve. *There be dragons ahead. If you don't care to know all the intricate mathy details, skim ahead. I don't blame you.*

11.2.2 The Full-Blown Calculus Approach

We can solve differential equations with calculus!

let $$B = \frac{G^2 T_{stall}}{I} \tag{11.6}$$

Substitute: $$B\ \frac{\omega_{free} - \omega}{\omega_{free}} = \frac{d\omega}{dt} \tag{11.7}$$

Separate and integrate: $$\int B\ dt = \int \frac{\omega_{free}}{\omega_{free} - \omega} d\omega \tag{11.8}$$

Compute integral (introduces C): $$Bt + C = -\omega_{free}\ ln[\omega_{free} - \omega] \tag{11.9}$$

Solve for ω: $$\omega = \omega_{free} - C\ e^{-\frac{Bt}{\omega max}} \tag{11.10}$$

Solve for C with initial condition $$\omega(0) = 0 \rightarrow C = \omega_{free} \tag{11.11}$$

$$\omega = \omega_{free}\ [1 - e^{-\frac{G^2\ T_{stall}\ t}{I\ \omega max}}] \tag{11.12}$$

$$\omega_{gbx} = \frac{\omega_{free}}{G}\ [1 - e^{-\frac{G^2\ T_{stall}\ t}{I\ \omega max}}] \tag{11.13}$$

If we plot this algebraic solution with some generalized values, we can start to investigate what it really means.

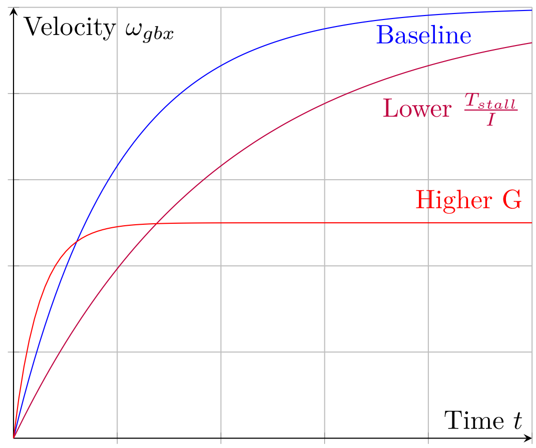


Figure 11.3: Flywheel example solution, with different representative parameters

This assumes that there is no constant load, or friction. This behavior is generally true, but not exactly true.

11.2.3 A Brute-Force Approach

We don't need to solve that differential equation using calculus. Or math. We can use basic arithmetic and computers to simulate it! We can do this with a 'numeric differential equation solver', like Euler's Method:

$$\frac{d}{dt}f(t) \approx \frac{\Delta f(t)}{\Delta t} \tag{11.14}$$

$$f(t_{i+1}) = f(t_i) + \frac{d}{dt}[f(t_i)]\ \Delta t \tag{11.15}$$

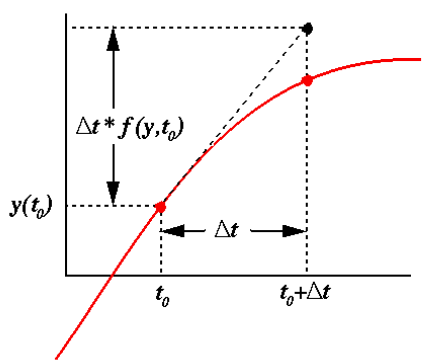


Figure 11.4: Graphical representation of Euler's method.

Another way of putting it... "the next value is the current value, plus the rate of change times the timestep of the simulation". We just need to get an expression for the $\frac{d}{dt}f(t)$ we are interested in, and write some code that will repeat this process with a small enough Δt. This process is sometimes called 'discretization' since we are taking a continuous field of time t and separating it into little Δt chunks.

Let's go back to our flywheel example, and add resistance M_{resist} to it. This M_{resist} can be anything- it can represent friction, air resistance, a spring, you name it! The numeric simulation approach makes this trivial.

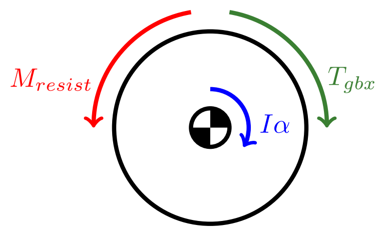


Figure 11.5: Free-body diagram for the flywheel, with additional resistance M_{resist}.

We can go through and repeat the same analysis as before.

$$T_{gbx} - M_{resist} = I\alpha_{wheel} \tag{11.16}$$
$$\alpha_{wheel} = \frac{d}{dt}\omega_{wheel} \tag{11.17}$$
$$\tag{11.18}$$

We can solve to yield the equations we need to perform Euler's method:

$$\frac{d}{dt}\omega_{wheel} = \frac{T_{gbx} - M_{resist}}{I} \tag{11.19}$$
$$\frac{d}{dt}\theta_{wheel} = \omega_{wheel} \tag{11.20}$$

My EveryCalc tool contains a Simple Mechanism Calculator you can use to leverage these physics.

11.3 Using the Simulations: Analysis/Optimization Examples

Let's consider an example drivetrain, with 4 NEOs, 8" diameter wheels, weighing about 143 pounds, meeting 30 N of resistive force. We want to go 10 meters. We have two gear ratio options to consider: a 10:1 gearbox, and a 7:1 gearbox. Which should we pick?

Before you look at the plots, go to the simulator and plug in those values, see if you can come up with an answer of which gets to the destination faster.

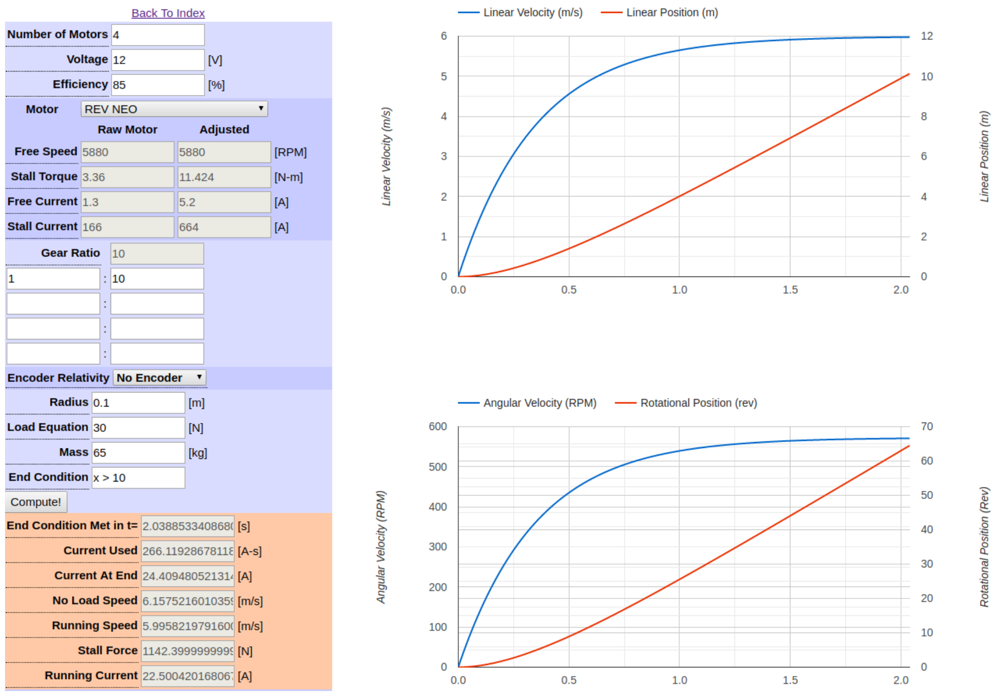


Figure 11.6: Baseline simulation, G = 10, t = 2.03 s

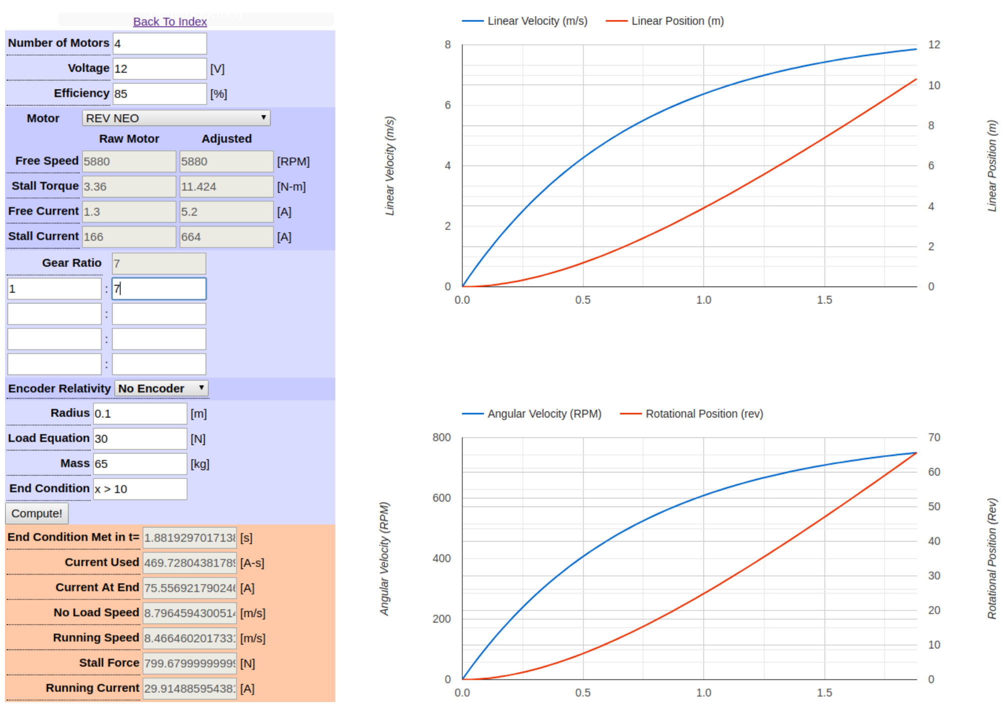


Figure 11.7: Alternative simulation, G = 7, t = 1.88 s

It looks like the ratio of 7 will get to our destination faster!

However, maybe this isn't our only concern. Drivetrains are complex mechanisms with many objectives (as we'll discuss later). This simulator uses a similar approach as discussed above to compute energy consumption, and it turns out that the G = 10 case has lower current consumption (almost half!) in this maneuver. It has more initial pushing power. It also gets to positions less than 3 meters away faster. There are a lot of trade-offs!

The calculator won't give you the right answer right off the bat, but it does free you from thinking about the numbers and math too much so you can focus on making system-level decisions, which is something that a computer can't quite so easily do.

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