Joining Elements

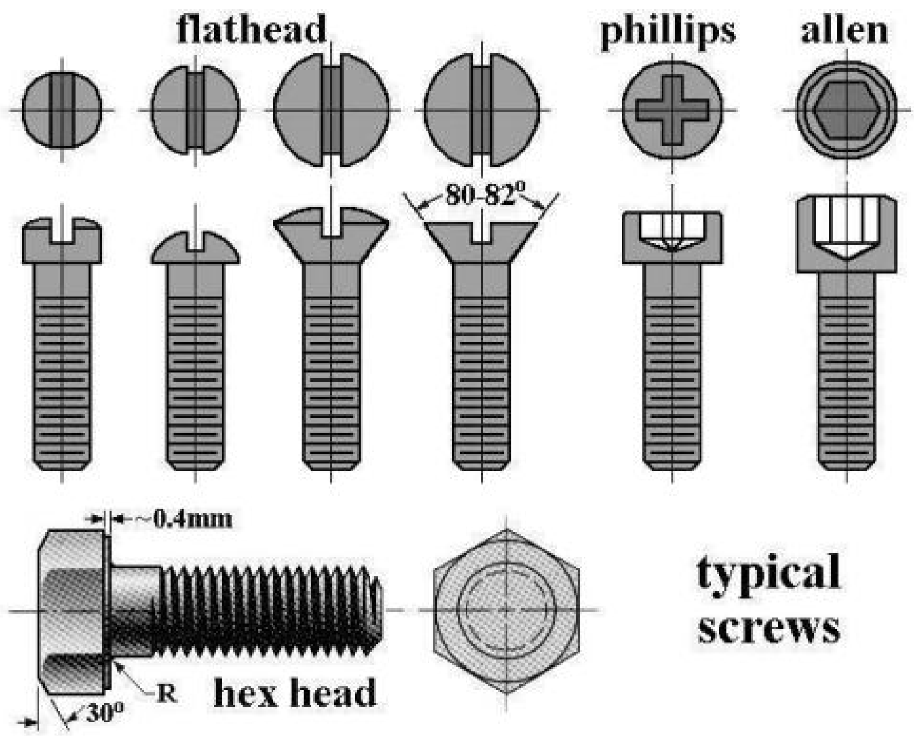
Joining elements are used to keep the robot parts held together in a rigid and strong bond. The main types are described below.

Screws

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

The main types of screws are presented to the right.

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



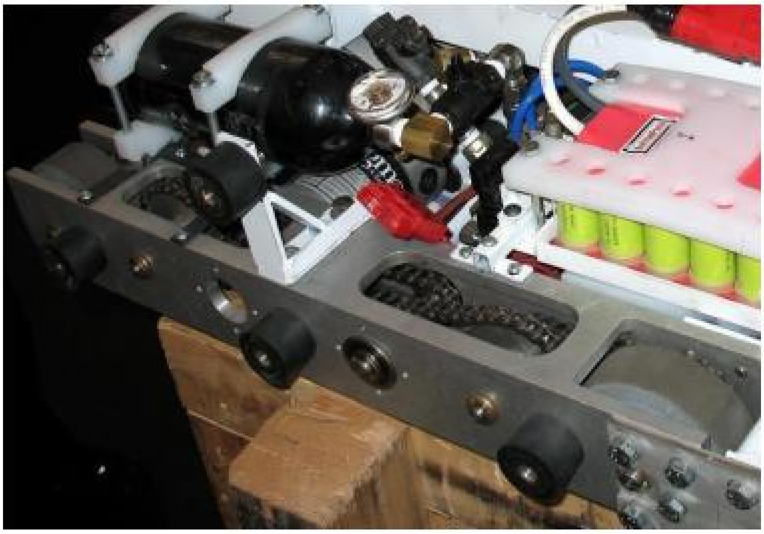
Hex head – easily tightened with open-ended wrenches. Always use the 8.8 or 10.9 class types (made out of hardened steel), they have twice the strength of regular (mild steel) screws. Except for the few extra cents they'll cost, high class screws mean a free gain in strength, since their weight is the same as low class ones. Stainless steel screws have higher strength than mild steel ones, but much lower than hardened steel screws, so they should not be used in structural parts (besides, they are much more expensive).

Allen – the highest strength screws, use the 12.9 or 10.9 class types (made out of hardened alloy steel), they have 3 times the strength of regular screws. Despite their higher impact toughness, don't use stainless steel screws: their low yield strength will let them easily bend during combat, making it difficult to disassemble the robot. Stainless steel Allen bolt heads are also easier to strip than hardened steel ones. The figure shows, from left to right, the button, standard and flat head (flush head) types. The flat head types are good for thick plates used in the robot's exterior, because they are embedded flush to the plate surface, with less chance of being knocked off by spinners. Avoid using flathead screws to fasten thin sheets, in this case the button head ones should be used, they also work well against spinners. Flat head screws require that the plates are countersunk, which reduces joint strength. To avoid this, do not countersink too deep to create a knife-edge condition in the countersunk member. A knife-edge creates a significant stress riser, as well as it allows the fastener to tilt and rise up on the countersunk surface. As a general rule, at least 0.5mm (0.02in) of the plate thickness should not be countersunk, as pictured to the left.

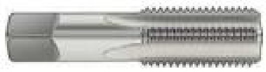
Self-drilling – these screws don't require tapped holes since they cut their own thread as they're fastened, being very practical. They're good for wood and sheet metal, but they're a bad option to fasten thicker sheets and plates in the robot structure: they're made out of low strength steel, and they're easily knocked off due to the lack of nuts or properly threaded holes.

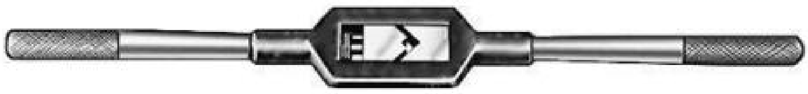
Sandwich mounts – they are basically 2 screws held together by a piece of rubber or neoprene. Besides the male-male version from the figure, there are also threaded ones such as the female-female and male-female. They are excellent dampers to mount the electronics into the robot, leaving it mechanically and electrically isolated from the structure. Note that velcro is also a good choice for light parts, such as the receiver.

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



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

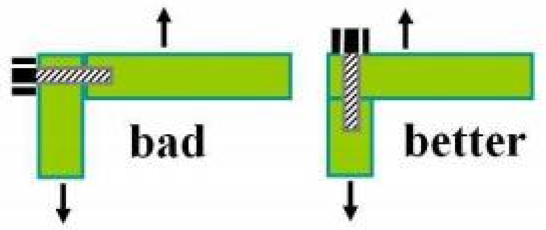




The thickness to be tapped in the piece should be at least equal to the thickness of the nut that would be used with the screw, to avoid stripped threads. In addition, avoid tapping low strength aluminum (such as 6063-T5) and Lexan, their threads will have relatively low resistance. Also, avoid tapping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

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

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

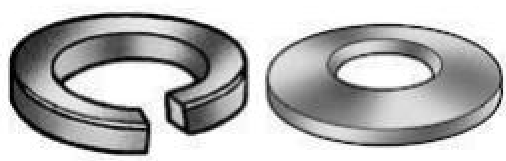


Screws shear much more easily than they break due to traction forces. Therefore, pay attention to the forces that would most likely act on each part of your robot. For instance, in the figure to the right, two parts are joined using a screw to transmit a vertical force. The configuration with the horizontally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

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

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

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



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

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

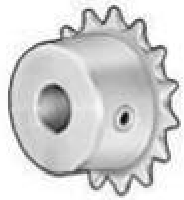
- counter nuts: if in the middle of a frantic pitstop you don't find any spring lock washers or locknuts, simply add a second nut to the screw (the counter nut), and tighten it well on top of the other one. The pressure between the 2 nuts will help preventing the screw from becoming unfastened.

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

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

Shaft Mounting

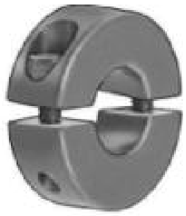
To attach pulleys, gears, sprockets and wheels to the robot shafts, keys and keyways are the best option. Keys are usually square steel bars that are inserted between the shaft and another component inside channels called keyways. They are an efficient way to deliver high torques. They also work as a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



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

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

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



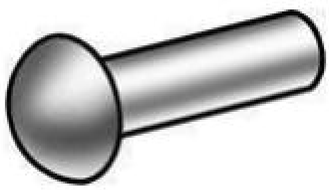
As discussed before, threaded shaft collars are also a great option. The threads guarantee that the collar won't move axially even during huge impacts. This is important to maintain, for instance, a constant pressure against other components without letting them get loose. The spinner Hazard uses threaded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

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

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

Rivets

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



Spinners love riveted robots. Rivets are only applicable to join metal sheets, in special aluminum ones, not plates. They're a bad choice even for steel sheets, which would be better off if they were welded together.

Remember that the small flange that holds the rivets is made out of a material that you were able to deform by hand, using a manual tool, as pointed out in Grant Imahara's book [10]. Besides, to disassemble the robot, you would need to drill the rivet to remove it, which consumes as much or more time than unfastening a screw.

Hinges

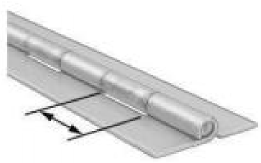
Hinges are an excellent solution to attach wedges. Articulated wedges have the advantage of always being in contact with the arena floor, with zero clearance. This avoids other wedges from getting underneath them. They're also a great solution to make an invertible wedge: if the robot is flipped over,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

Two important types are the hinges with lay flat leaves and the ones with tight-clearance leaves.

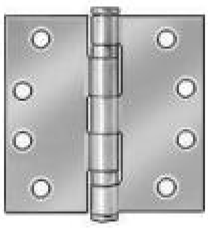
The tight-clearance type can be seen in the figure to the right, in its open and closed configurations. Their disadvantage is that the hinged part cannot be laid flat on a surface, which might be a problem to mount them to the robot's walls.

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

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



Another option is the use of door hinges (pictured to the right). In this case, it is a good idea to use only two of them for each wedge. Any misalignment when using 3 or more of those hinges might make the wedge articulation become stuck in certain positions.



In this case, the wedge's own weight won't be enough to guarantee that it will touch the floor. The highest strength door hinges found in the market are made out of stainless steel (SS) type 304, which still has low S_y. Make sure that the pins are also made out of SS, not brass. Use oversized door hinges, remembering that the loads will be taken by only two of them.

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

Welds

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

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

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

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

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

Finally, it is important to clean the parts before welding, and to chamfer thicker plates to guarantee a through-the-thickness weld, increasing strength. The choice of filler material is also important. As mentioned before, grade 2 (commercially pure) titanium makes a great filler for grade 5 titanium (Ti6Al-4V) – although grade 2 has lower strength, its higher ductility prevents cracking from the thermal effects during the welding process, resulting in better impact toughness during battle.