Designing A Mini Sumo Robot
Using a Tamiya Gearbox
BCIT TTED 5060

1.0 Introduction

This is an update and addition to “The Tethered Mini-Sumo Robot: A Teacher’s Guide”. That document lays out a timeline for implementing the various components of this project with a junior technology class, and has an example marking template along with some suggested class activities. This is intended to incorporate additional technical detail as well as address some of the recent advances in designing and programming an autonomous mini sumo robot with senior students. While this document follows a “step by step” process, it offers many options and alternatives with the intention that the final implementation of the project is best left to the professional judgement of the teacher.

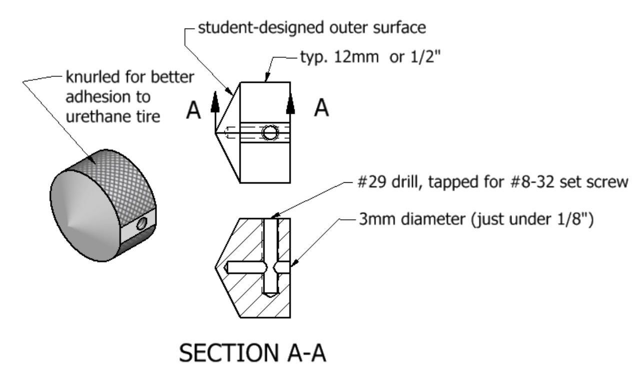
1.1 Before You Begin

If you are going to allow students to design their own mini-sumo robots, an activity which I highly encourage, they are going to need to know the basics of orthographic drawing. Being able to create and comprehend a 3-view drawing will help the students place their components correctly in to their design. If the students have had no formal exposure to orthographic drawing, consider taking ten to twelve hours of class time to teach them how you want it done. Another option would be to consider using Google Sketchup, or a commercial CAD product such as Autodesk Inventor. At least one of the Tamiya gearboxes is available for download for use in Google Sketchup. I have found that in addition to being a very cost-effective way to start the year with students, teaching/reviewing orthographic technique has resulted in a much higher standard of design and reduced student frustration with this project.

2.0 Start With the Wheel and Tire

The first question to ask is “how are you going to make your wheel?” The reason this is the first question to ask is because your method for making your wheels will determine a number of important factors such as the diameters of wheel that you have available to you and the coefficient of friction of your tire. You need to know this information so you can make an intelligent choice for your gearbox ratio. Here are two ways to make wheels, and two ways to cast tires. There are, undoubtedly, many other options that will work, but these methods are a tried and true starting point.

Fig 1. A Typical Aluminum Mini-Sumo Wheel



2.1 Aluminum Wheels

If you have access to enough machine lathes to keep your students occupied (I was able to do this with the two lathes in my shop, and some careful organization of “lathe time” for each student) and a supply of 1” diameter aluminum or steel rod, then you can turn metal wheels on the lathe, as shown in Figure 1. The students will enjoy doing their own “creative” design for the outer surface of the wheel. I recommend the aluminum wheels, as aluminum machines up easier for a student who is probably doing their first lathe project, and is much easier to drill and tap for mounting a set screw, however steel wheels offer the benefit of “weight where you want it”. When drilling the axle hole, you can get away with using a 1/8” bit, but a 3mm one works perfectly with the 3mm hex axle shaft. The students should drill their axle hole as deep as they can without going through the outer surface. Once the student has turned two (roughly) identical wheels, I have them file a small flat and centre punch for the set screw hole. Placing the set screw about 1/3 of the way out from the inner surface of the wheel works best as it reduces the play, or wobble, in the mounted wheel. I have the students drill the tap hole about ¾ of the way through the wheel, so that we can cut thread all the way to the intersection with the axle shaft without having to use a bottoming tap. When I first had students tap the hole for the set screw we had many, many broken taps. It turned out that the students didn’t realize that the tap would STOP when it hit the bottom of the hole! By discussing how a tap works, and demanding that students turn the tap with “just two fingers” (technically one finger and their thumb) rather than their whole hand, and emphasizing that breaking the tap in the hole would ruin their wheel, I was able to get the tap breakage rate down to a reasonable level.

2.2 Dowel Wheels

If you don’t have access to a lathe, or need a quicker method of whipping up wheels, consider using hardwood dowel. A ½” long piece of 1” diameter dowel with a 3mm (or slightly undersized 7/64”) axle hole can be epoxied on to the end of the axle shaft. If you want a larger diameter wheel you can either use a larger dowel, or cut out pieces of ½” thick plywood or MDF using a hole saw. Just remember that you have to pull the centering drill bit out of the arbor as it is usually well over 3mm in diameter, and you’ll have a hard time mounting your axle on a ¼” hole!

Figure 2: Silicone Tire Mold used at BCIT

2.3 Urethane Tires

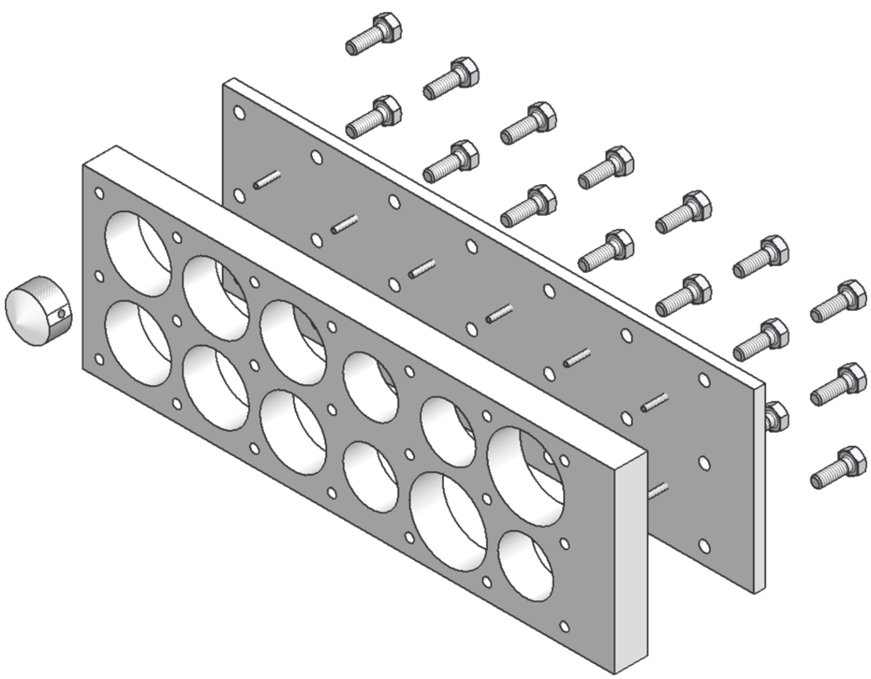
We have tried several different methods of creating tires, from using O-rings to using commercially purchased radio control car and Lego tires, but have had the most success casting our own tires out of urethane rubber. We use “Por-a-Mold 2020 by Synair 1:1 Polyurethane Molding Rubber”, which is commonly used in mold-making. Por-a-Mold is commonly available in British Columbia from Industrial Plastics and Paints as well as Coast Fibertek. Por-A-Mold comes as a two-part resin (see Figure 2) and, like Epoxy, will begin to set when part A is mixed with part B. The urethane resin is sensitive to moisture, so it is important that the containers be sealed tightly when not in use. Although the two, one litre containers shown are fairly expensive ($50 or $60 for the pair, last time I purchased any) they will last you for several years of mini-sumo wheel production if you keep them sealed and stored in a cool, dry environment. It is also important to measure carefully when mixing Part A and Part B to ensure you have a 1:1 ratio. “Eyeballing” it is insufficient, and will produce sticky, messy wheels that don’t set up properly. I have used syringes, while BCIT’s master tire caster, Eugene Duruisseau, uses small measuring cups. You’ll have about five minutes of working time with the resin, once mixed, and should allow several hours for it to set.

Fig 3: A Close-Up of the BCIT Wheels

At BCIT Eugene has created a silicone mold for casting individual tires. This is an efficient method as it allows you to cast many tires well in advance of the project, and students can just stretch them over their wheels. To create the mold Eugene turned several aluminum tires in a range of sizes to suit different mini-sumo wheels, and then cast a soft, silicone mold around the aluminum tires. Now he simply pours the mixed urethane in to the silicone mold, waits for them to set, and pops them out, ready to be used later. He has also successfully experimented with adding various colours (powdered coloured chalk) and even sparkles to the tires. Figure 3 shows close-ups of an original aluminum wheel, the silicone mold, and the high-level of detail reproduced in the urethane tires.

At David Thompson, however, I wanted the students to be involved in the casting process, and happened to have some UHMW Polyethylene left over from an earlier project which I used to construct a mold as shown in Figure 4. I laid out a grid for ¼” bolts to attach a sheet of ¼” to a sheet of ¾” thick UHMW, then drilled and tapped the holes so that the two sheets could be securely fastened together. Then I took the sheets apart and used a Forstner bit to drill out tire diameters of various sizes: 1¼”, 1½” and 1¾” in the thicker sheet. I reattached the two sheets and used the centre point of the forstner bit as a transfer punch to mark the exact location of the centre of the large hole on the thin sheet. I drilled and tapped this hole to take a #4-40 x 5/8” machine screw, which would serve as a centering pin for the mini-sumo wheel.

Figure 4: UHMW Mold for Casting Tires



Before casting their tire to their wheel, the students must insert their #8-32 set screw so that it sits flush with the surface of the wheel. They fill the socket head of the set screw with Vaseline or other grease so that the urethane does not fill up the head, thus making it impossible to drive the set screw. If you have purchased mold release, now would be a good time to spray the inside of the mold with a light coat. It isn't usually a big deal if you don't, the urethane doesn't stick to the polyethylene very well at all.

With the ¼" bolts holding the two sheets together, the student places their mini-sumo wheel on the #4-40 centering pin of the hole corresponding to their desired wheel diameter. They mix the correct amount of polyurethane and pour it in to the mold so that it just covers the knurled part of the wheel. Normally, for efficiency, several students do their tires at the same time.

When the tires have set, the ¼" bolts are removed and the wheels and tires are popped out of the mold as a single unit. The student presses an Allen Key through the tire material to access their set screw and screws the wheel on to their axle. In the event that the tire should separate from the wheel, a bit of Cyanoacrylate adhesive (crazy glue) can reattach them fairly permanently.

Congratulations... you should now know what diameter wheels you will have available to build your robots!

3.0 Torque, Traction and Gear Ratios

Now that you know what diameter wheels will be available to your students, you can do some physics calculations to predict the robot's pushing power and speed. I'm going to confine my calculations to the Tamiya 70168 four speed "Double Gearbox" and the two speed Tamiya 70097 "Twin Gearbox". (Note: The 70168 is also available in clear plastic as the 89918, and the 70097 is available in clear as the 89915. Detailed specs are available at www.pololu.com and the gearboxes are available in bulk in Canada from www.borgfeldt.ca. Bulk orders may require several weeks for shipping, depending on your source.)

Both gearboxes come with the Mabuchi FA-130-18100 motor. There are several motors available with the same physical dimensions as the FA-130 that have higher power outputs. You may choose to allow students to use alternative motors in their gearboxes, or you may choose to restrict them to the FA-130 from the kit. With my high school students I tend to restrict them to the kit motors. With my BCIT students, I encourage them to "hot rod" all they want. One possible upgrade motor is the Mabuchi FC-130-SA-2270. It has a maximum power output a little over twice that of the stock motor. Note, however, that the high current draws from more powerful motors will result in a reduced battery life and may require an upgrade from the L293D motor controller chip. See the section on electronics for more details. Note also that the stock motors, properly geared and matched to the correct diameter wheels provide an excellent combination of pushing force and speed, and that the pinion gear on the motor is a simple press-fit plastic part that has been known to slip. There may be little advantage to be had in upgrading to a more powerful motor.

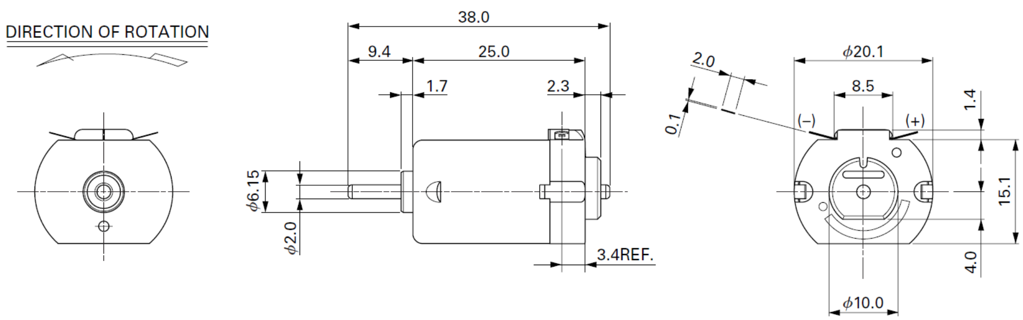
For those seeking more power and more control, check the internet... there are many excellent servo motors that can be adapted to continuous rotation for use in mini-sumo robots, as well as other motor/gearbox combinations.

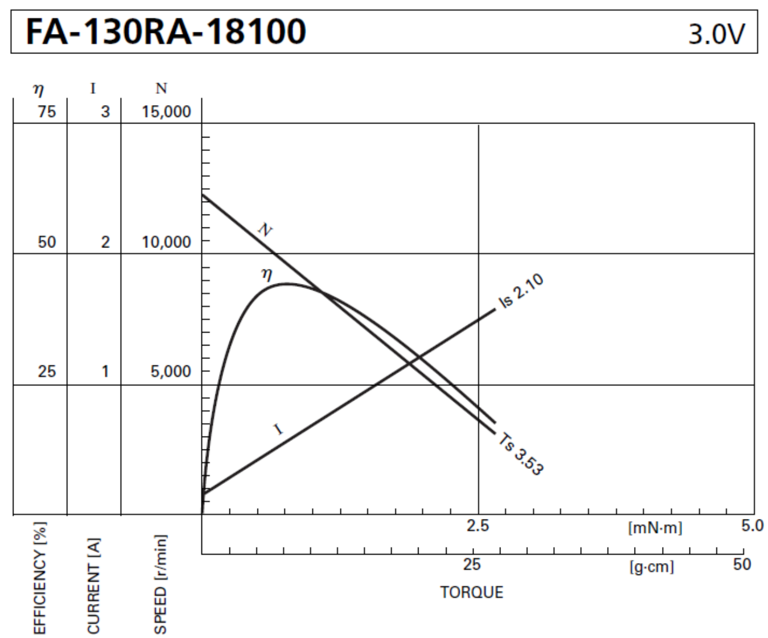
The stock motors were designed to work at three volts. We will be running them at closer to five volts by the time battery internal resistance is accounted for. See Table 1 for motor performance specs for the FA-130 and FC-130 at three volts, and an estimate of their performance at 5 V.

Table 1: Mabuchi Motor Power Curves and Power Specifications

		No Load		Maximum Efficiency					Maximum Power					Stall	
Motor Mabuchi Part#	Test Voltage	Speed RPM	Current A	Speed RPM	Current A	Torque mN m	Power W	Eff. %	Speed RPM	Current A	Torque mN m	Power W	Eff. %	Torque mN m	Current A
FA-130-RA-18100	3	12300	0.15	9710	0.56	0.74	0.76	45	6113	1.13	1.77	1.13	33	3.53	2.1
	5	20500	0.25	16183	0.93	1.23	2.11		10188	1.88	2.95	3.14		5.88	3.50
FC-130-SA-2270	3	1350	0.27	10740	1.05	1.37	1.54	49	6800	2.17	3.33	2.37	36	6.71	4.1
	5	2250	0.45	17900	1.75	2.28	4.28		11333	3.62	5.55	6.58		11.18	6.83

Note: 5 volt figures are estimates based on expected power supply from mini-sumo battery pack
Motor specifications and data sheets are available on-line from http://www.mabuchi-motor.co.jp/en_US/product/p_0304.html





3.1 Peak Velocity and Pushing Force Calculations

The performance data in table one can be used to derive performance data for the gearbox as a unit. Let's begin by calculating the peak pushing force that the robot can generate. The peak pushing force of a brushed, permanent magnet, DC electric motor occurs at zero RPM... the stall point for the motor. Look to the right of table one and you will see the values for stall. Let's use the value of 5.88 mNm, which represents the torque at the shaft of the stock motor, powered by five volts, when the motor is stalled.

The units, mNm, are milli-Newton metres. This is a measurement of torque, like the foot pound. The Newton is a metric unit of force equivalent to the weight of a roughly 100g mass on the surface of the earth, so one Newton metre is the torque you would get if you hung a 100g weight on the end of a 1m long stick, perpendicular to the ground. A milli-newton metre is one one-thousandth of that torque! (Not a whole lot.)

So this little motor has a maximum shaft torque of 5.88 mNm. Take this number and multiply it by the gear ratio that you have selected for your gearbox... let's say you choose the 114.7:1 option. This means that for each time the gearbox output shaft completes one revolution, the motor will have completed 114.7 revolutions... so the motor will turn faster than the output shaft, but the output shaft will have 114.7 times as much torque!

5.88mNm * 114.7 = 674 mNm   of torque on the gearbox's output shaft.

Now consider that this torque is being put to the ground by a wheel. Let's say you have chosen a 1.5" (38mm) diameter wheel & tire combination. The radius of your 38mm diameter wheel is 19mm, and the torque has to act over that distance, so divide by 0.019m.   (19mm = 0.019m)

674 mNm / 0.019 = 35,474 mN of pushing force.

To get Newtons of pushing force, divide mN by 1000.

35,474 mN / 1000 = 35 Newtons of pushing force. That means your robot can push with a force roughly equal to the weight of a 3.5 kg mass.

Now consider peak speed. The motor has an estimated "no load" speed of 20,500 RPM at 5 volts, but the drag of the gearbox means that we'll never actually run the motor at "no load". Until the robot is built we won't know exactly how much drag will be acting on the motor, so for now we're only able to estimate the peak speed. Let's use the peak efficiency reading for the motor as a starting point. For this motor that speed is 16,183 rpm. Divide that by our gearbox ratio, 114.7, to get the speed of the output shaft.

16,183 rpm / 114.7 = 141 rpm at the output shaft. Now convert that into revolutions per second by dividing by 60 seconds.

141 rpm / 60 = 2.35 r/s or revolutions per second. Now we need to multiply the rotational speed of the axle by the circumference of the wheel. We're using a 38mm diameter wheel on this robot, and circumference is pi*diameter, so:

2.35 r/s * 3.14 * 38mm = 280 mm per second, or about 28 cm per second. (That's one foot per second for you imperial folks!) That is a pretty good speed for the robot, and... as you'll see... the robot should have plenty of torque to spare at this gear ratio.

Table 2 provides a summary of all the possible gearing combinations for the Double and Twin gearboxes using 1¼", 1½", and 1¾" wheels.

Table 2: Gearbox Performance at 5V Using Stock Motor (assuming 90% gearbox efficiency)

		Peak Efficiency		Peak Power		Stall	Speed at Peak Efficiency (m/s)			Maximum Pushing Force (N)		
Gearbox	Ratio	mN m	RPM	mN m	RPM	mN m	1.25" (32mm)	1.5" (38mm)	1.75" (44mm)	1.25" (32mm)	1.5" (38mm)	1.75" (44mm)
70168	12.7:1	14	1274	34	802	75	2.13	2.53	2.93	5	4	3
70168	38.2:1	42	424	101	267	225	0.71	0.84	0.98	14	12	10
70168	114.7:1	127	141	305	89	674	0.24	0.28	0.32	42	35	31
70168	344.2:1	382	47	914	30	2024	0.08	0.09	0.11	126	107	92
70097	58:1	64	279	154	176	341	0.47	0.55	0.64	21	18	16
70097	203:1	225	80	539	50	1194	0.13	0.16	0.18	75	63	54

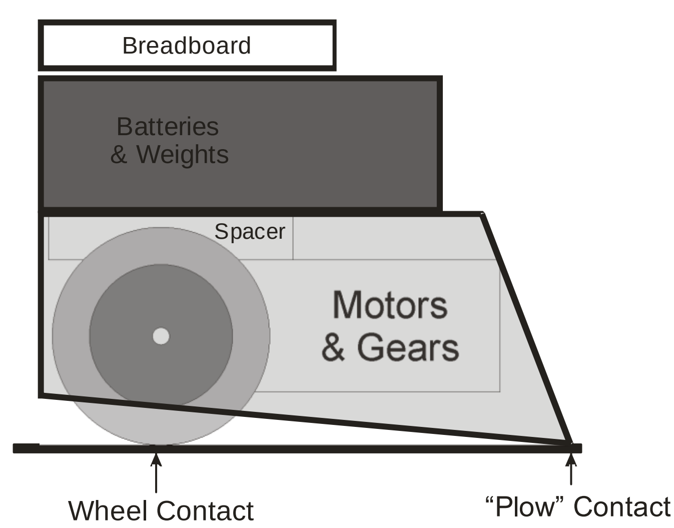
3.2 *Useful* Speeds and Pushing Forces

You will note that some speeds are "blacked out" on this chart. I highly recommend against using these high speeds as they will make the robot very difficult to control and offer very little in the way of pushing force. At the opposite end of the scale, the 344:1 and 203:1 gear ratios can result in a very slow robot. Students wishing to choose these gear ratios may consider finding a way to construct a larger diameter wheel/tire combination.

Just as a very fast top speed is less than useful for the robots, it is also possible to have excess torque, as there are two factors that determine the maximum pushing force of the robot. The first, the motor/gearbox/wheel combination, you have just calculated. The second is the amount of traction that the robot can achieve while in contact with the playing surface. To calculate this you need to know two things... the "coefficient of friction" of the urethane wheels on the playing surface, and the amount of mass supported by the robot's wheels. We shall consider that, first.

If you sketch a 2-D side view of a typical mini-sumo robot (see Figure Five) it should contact the ground in two points... where the wheels meet the ground and where the "plow" or business end of the robot meets the ground.

Figure 5: A "Balanced" Mini-Sumo



The weight of the robot will be balanced between the “plow” and the “wheel” contact points. The more weight that is placed near the “back” of the robot, the greater the fraction of the robot’s weight that will be supported by the wheels. The more weight supported by the wheels, the greater the traction that you will be able to generate using the wheels. Note, however, that you do not want 100% of your weight over the wheels, or it will be very easy for your opponents to get underneath your “plow” and flip you in the air.

Let’s assume that you have built your robot to the maximum allowable mass of 500g, and have arranged your components so that 80% of the robot’s mass is situated over the drive wheels. This means that 400g of mass is supported by the drive wheels, and 100g by the “plow”.

Using a conversion factor of 1kg of mass equals 10 Newtons of force (it is actually 9.8 Newtons for each kilogram, but 10 is a much nicer number to work with!), we have 400g, or 0.4kg of mass over the rear wheels.

0.4kg * 10N/kg = 4 N of force acting through the rear wheels.

To determine the maximum traction of the robot we can multiply this “normal” force (normal being the mathematical term for “at a 90 degree angle”, in this case to the ground) by the coefficient of friction. I haven’t figured out the exact coefficient of friction for a clean urethane wheel, but I would guess it is close to 1.5.

4 N * 1.5 = 6 N of pushing force.

That means that this particular robot can push with a maximum force of 6 newtons. If we go back a step or two, however, you will recall that the motors and gears are capable of producing a pushing force of 35 Newtons. That means that our wheels will start to spin long before the motors ever reach their stall point. Still, it’s not too bad that a little 500g robot can push with a force equivalent to about 600 grams!

This is also a good sign as it means that even when the robot is engaged in a brutal pushing battle that the motors will not be operating near their stall currents. The high currents that these motors experience at stall have to potential to overheat the motor control chip, drain the batteries quickly, and burn out the motors rapidly.

When we design larger robots we try to balance off the maximum torque from the motors and gears so that it is about the same as the maximum traction that we can achieve from the robot’s wheels and tires, but in this case it simply shows why you don’t have to worry too much about a student showing up with an “extra powerful” motor instead of the stock motor. The limiting factor in pushing force is the mass of the robot (and the coefficient of friction of the tires) and the limiting factor in the speed of the robot is the operator’s ability to control it!

Note that these calculations match up very nicely with the math skills that junior students have, and also tie in nicely with parts of the Physics 11 (friction) and Physics 12 (torque) curriculum. This is a great opportunity to teach your students about gear ratios!