“CuriousMarc” 2-3-2 R2-D2 System Overview

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Foreword

The R2-D2 robot seen in the Star Wars movies has three legs. The legs are in supposedly articulated: the center leg is retractable in the body, while the two outer legs have the ability to pivot around their shoulder articulation.

Thus the robot can be seen in two configurations. In “2-leg” mode, he is standing straight up on its two outer legs with the center leg retracted in the body. In “3-leg” rolling configuration, the center leg is extended and the two back legs are tilted backwards (see Figure 1). In the amateur robot building community, the “2-3-2 capability” refers to the ability of the robot to transition from the 2 legs posture to the 3 legs configuration and back.

The original robots seen in the Star War series actually lacked this capability. In the earlier three Star Wars movies (Episodes IV to VI), where R2-D2 is always an actual robot (in the later movies, he is either an actual robot or a computer graphic generated one), different robots are used for each configuration. The “2-leg” robot is usually not moving, and has space inside for a dwarf actor (Kenny Baker[1]) to sit in and bring him to life by moving the dome and shaking it. You can actually spot two small leg tubes under the body where the dwarf actor can slip his feet.

The 3-legged robots, of which many versions were used, were remote controlled units with fixed legs configuration, the center leg being in fixed extended position and the outer one always leaning back at a fixed 36° angle.

Only one version of the robot, the “pneumatic R2”, had the ability to switch from 2 legs to 3 legs, but not the reverse. This was accomplished by powerful pneumatic actuators. This transition is first seen in a short scene[2] of the movie “A New Hope” (Episode IV).

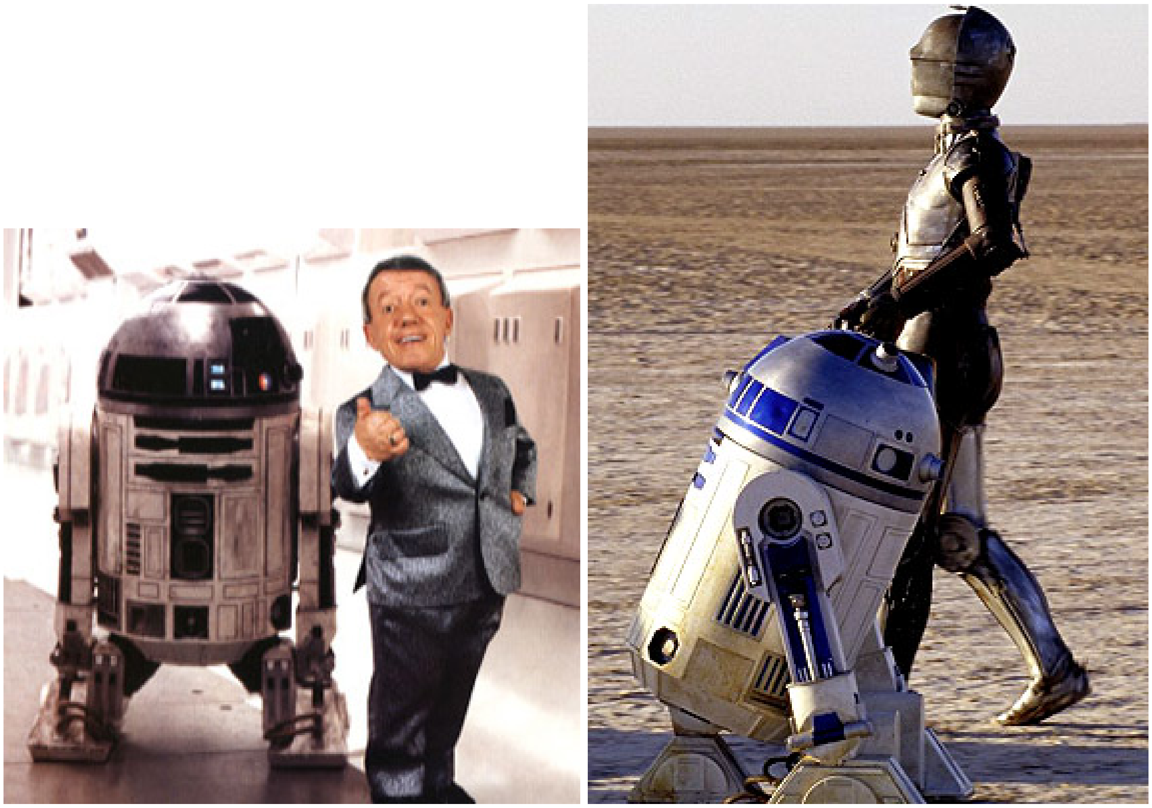

Figure 1: Left: Kenny Baker and his R2-D2 in 2-leg configuration. Note the tube extensions connecting the underside of the body to the foot shells for the actor's feet. Right: R2-D2 rolling around in his familiar 3-leg configuration.

Therefore, building an actual 2-3-2 enabled R2-D2 replica goes beyond what the actual movie robots could do, and is generally known as a challenging task for the amateur builder. The difficulties arise not from one particular constraint, but rather from the combination of several of them:

- the limited space available inside the robot, particularly when taking into account the space needed for batteries to operate the robot for long sessions.
- the relatively swift motion necessary to imitate the lifelike 2-3 transition seen in the movie
- the large static and even larger impact forces that the legs and mechanism have to survive once rolling
- synchronizing the movement of the center and outer legs while keeping the robot in balance during the 2-3 and 3-2 transition.
- limited amateur budgets.

Despite these hurdles, several builders have succeeded in building 2-3-2 enabled robots [3,4,5,6,7,8,9,10,11]. A good discussion of the different approaches used can be found on our builder's community web forum at astromech.net[12].

This document was put together at the request of one of us (Blake Mann), encouraging all 2-3-2 builders to document their designs to help guiding other builders. It summarizes my own approach to the problem, which owes much to the other builders referenced above. The step by step building progress of my 2-3-2 droid, along with many videos and pictures, is also chronicled on my builder's log on astromech.net[13], where I post under my forum moniker "CuriousMarc".

Shoulder Actuation Mechanism

Figure 2 is a diagram of R2 in 2-leg and 3-leg position. When not standing upright, the angle between the center leg and the outer legs is 36°, which is the amount the shoulder flange on which the outer leg is attached should be rotated by the mechanism.

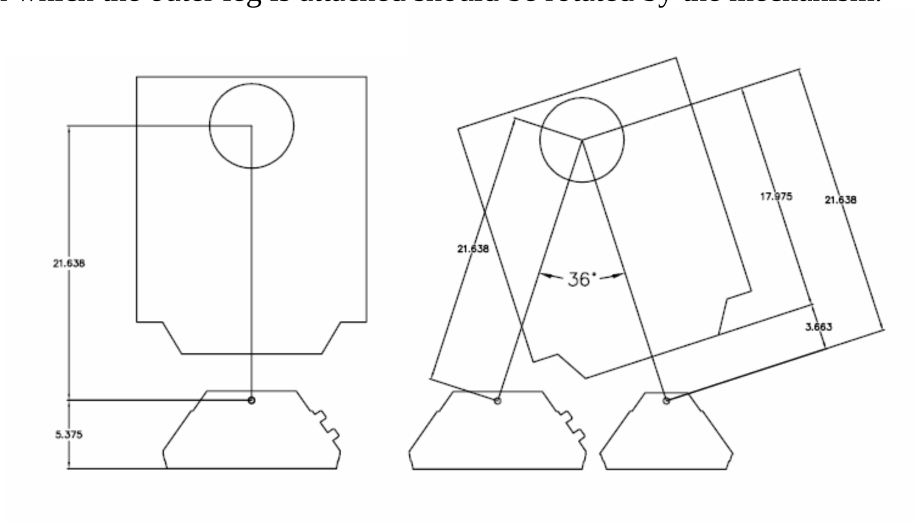

Figure 2: R2-D2 in 2-legs and 3-legs posture

My shoulder actuation mechanism is shown in Figure 3. It uses a linear actuator instead of the more commonly used, but bulky and fragile, satellite motor arrangement (the "satellite motors" owe their name to their original function, which was to rotate satellite TV dishes).

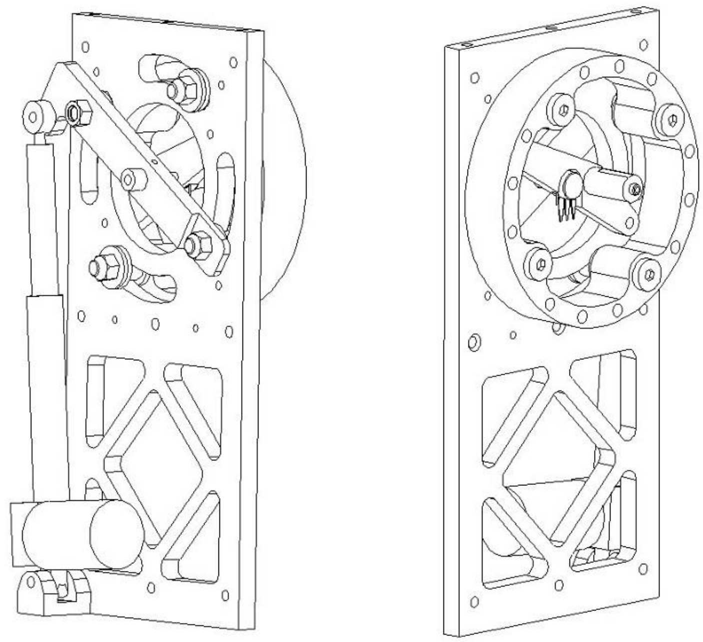

Figure 3: Views of CuriousMarc's R2-D2 shoulder actuation mechanism

My R2 is based on the COM-8 frame, made by James Van Reenen (see Figure 4). My COM-8 Frame model is a modified version of the JAG 5 frame originally developed by Jerry Greene. The COM-8 plans are not publicly available, but the dimensions follow the Jerry Greene plans very closely, which are available on his web site [14]. I adapted my mechanism to fit the existing frame with little or no modifications. Indeed, one need to drill only two ¼" holes in the COM-8 shoulder plate to accommodate my shoulder mechanism.

Figure 4: COM-8 Frame before adding the 2-3-2 mechanism.

The COM-8 shoulder mounting plate is shown in Figure 5. Like the one on the JAG-5 frame, it incorporates 4 curved races that allow for the shoulder flange to rotate through the necessary range. The frame also comes with bronze bushings that slide into the curved openings, so a fair amount of 2-3-2 readiness is already built into the frame.

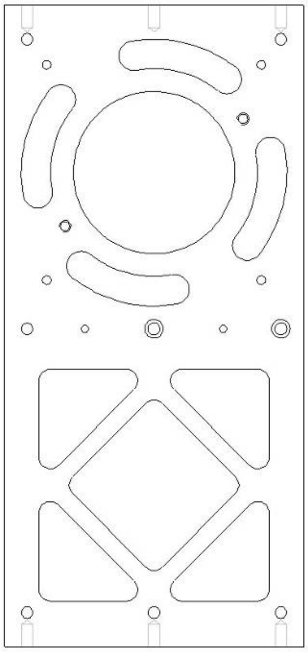

Figure 5: Shoulder mounting plate that comes with the COM-8 frame, showing the 4 curved 48°openings.

The actual races allow for 48° of movement, 38° in the backward direction (2° more than needed for 3-leg position) and an extra 10° forward, so R2 can actually look down when standing in 2-leg position. My mechanism supports the full range of motion, both backward and forward.

The first task was to size the actuator. Initial calculations showed that two 100 lbs actuator with a 3” stroke would easily cope with a 150 lbs robot, 48° rotation, and a 1 to 2s rotation time using a relatively short lever arm compatible with the available physical space around the shoulder. I chose a 100 lbs semi-custom unit from Motion System[15], model 85615 [16] (see Figure 6). This unit has several advantages. It is very compact and fits behind the shoulder plate, is available in 12V drive, has very fast movement (available either 1”/s or 2”/s, I used the slower 1”/s model). Most importantly, it has a re-circulating ball screw which allows it to free-wheel at both travel ends, eliminating the risk of mechanical damage.

There are a boat load of options that need to be specified when ordering the actuators, and the final part numbers are 85615-LH-15-3-SBC-0.250-DC1-RE-CT and 85615-RH-15-3-SBC-0.250-DC1-RE-CT. They also became more prosaically known as the “85615 R2-D2” RH and LH actuators (units are not symmetric, you need a right handed and left handed one), I suspect you can re-order them using that simplified code.

The actuator connects at the bottom with a small anchor that I machined, and at the top to a J-bar, as shown on Figure 7. The J-bar connects to the original COM-8 shoulder screws, with the simple addition of slippery Rulon and Nylon thrust washers sandwiched between the bar and the shoulder plate. The J-bar dimensions are given in Figure 8, and are intended to give full 48° range of motion with a 3.0” stroke from the actuator.

Figure 6: Linear Ball Drive Actuator model 85615 from Motion System Corp.

Figure 7: Actuator installed in the frame, connected to an anchor at the bottom and to a J-bar at the top.

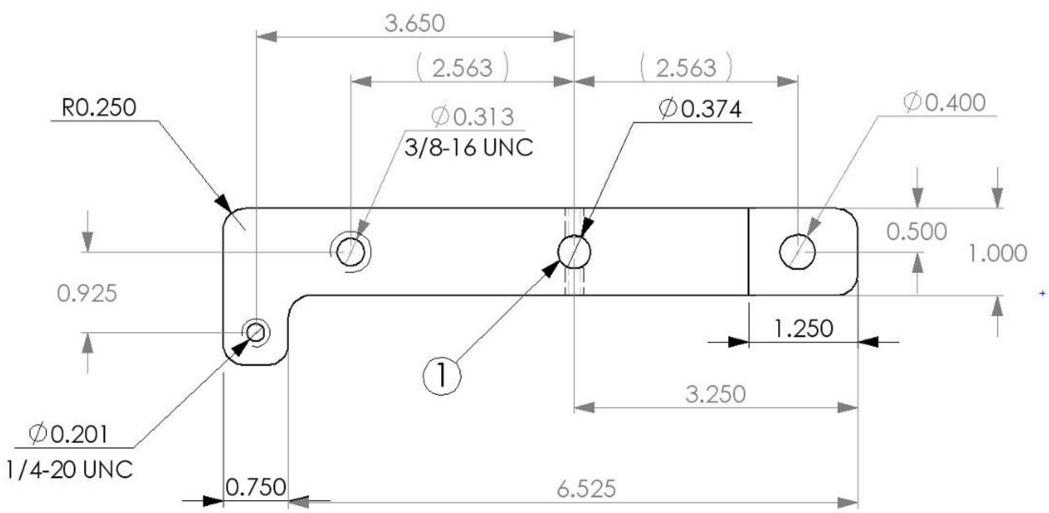

Figure 8: J-bar dimensions. This J-bar is intended for a 3” stroke actuator. The bar is 0.375” thick.

I also modified the attachment method of the leg to the shoulder flange to enable quick disconnecting of the outer JAG legs without having to dismount the entire mechanism, as shown in Figure 9.

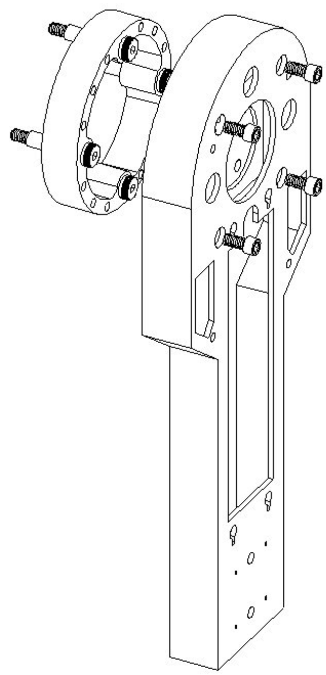

Figure 9: Modified leg to flange assembly.

Outer Leg servo control

I control the outer leg position in a continuous and analog fashion like a regular servo. I used a linear 10kΩ potentiometer as a position sensor. When connected to a motor controller having feedback capability, this effectively transforms the leg actuator into a giant servo. This way, no limit switches are necessary, and the 2-leg, 3-leg and look-down positions can be adjusted using the RC transmitter programming, or software in the 2-3-2 motion controller as I describe later on. Also, all intermediate positions of the leg can be accessed.

A spanner was designed to fit inside the shoulder flange opening and hold the position sensing potentiometer, as well as a mounting pin for the ankle angle control bar to be discussed below. The spanner mounts on the outside of the shoulder plate using the two aforementioned ¼” holes drilled in the plate. Drilling these holes is the only modification necessary to the COM-8 hardware. The spanner is shown in Figure 10.

For the servo motor control, I used a RoboteQ AX500 dual 2x15A controller[17]. To be fair, this is a bit of an overkill, as the motors do not consume more that 2A and I do not use any of the advanced features. Simpler units from Polulu (use units with position feedback) might be a more economical fit[18].

 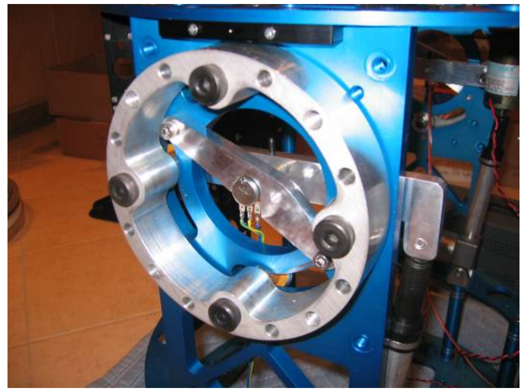

Figure 10: Spanner with the potentiometer and anchor pin attached (left), spanner mounted on the outside of the shoulder plate (right).

Outer Ankle Locking

One of the trickiest aspect of the 2-3-2 mechanism is the locking of the ankle pivots. The foot shell normally connect to the leg ankle at a pivot point, and is left free to rotate around that articulation. However, the outer ankle-to-foot pivots need to be rigidly locked in 2-leg position so the droid doesn't fall over. But, in 3-leg mode, the foot shell needs to be at 18° from the horizontal, bisecting the 36° angle of the leg to the body (see Figure 2). Strictly speaking, the outer ankles do not need to be locked at a specific angle in 3-leg position and could be left free. However, builders prefer the added stability and traction provided by locked ankles when driving. Also, reverting from free ankles to locked ankles during the 3-2 transition is a tricky balancing and timing business.

I therefore opted for a simple passive ankle control mechanism, which I believe was first documented in the Carr-Hunger droid. In this implementation, the angle between foot and ankle is maintained at exactly half of the angle of the body to leg at all times via a steel rod, mechanically tying the leg-to-shoulder angle to the foot-to-leg angle.

A few pictures should clarify how this works. A narrow steel bar extends through the whole length of the leg as seen in Figure 11. It goes through a small opening at the bottom of the ankle and is tied to an anchor screw in the foot shell near the pivot point, as shown in Figure 12. The top of the tie rod is attached to a pin near the shoulder pivot point (Figure 13). I have used both stock steel pins (the one in Figure 10) and machined brass pins (see close up in Figure 14) with equally good results. The steel pin is easy to procure, but needs to be force fitted into the spanner, while the machined pin is simply screwed in, but you need to machine it. Choose your own evil…

The trick to maintaining the correct half-angle relationship is to locate the tie point in the foot twice as far from the pivot point as the tie point at the shoulder. In my case, the shoulder pin is ¾" from the center of rotation of the shoulder, while the foot shell tying screw is 1½" from the ankle pivot point, satisfying the needed geometric relationship.

Figure 11: Outer leg. Note the narrow steel bar running from the foot to the shoulder opening and used for foot angle locking.

Figure 12: Lower portion of the outer leg. The ankle tie rod goes through a small opening at the bottom of the ankle and is attached to an anchor screw on the foot shell.

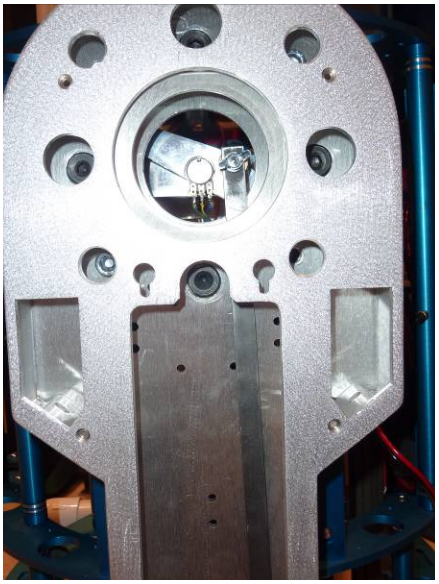

Figure 13: The top of the ankle tie rod is attached to a pin near the shoulder center of rotation.

Figure 14: Detail of the top attachment pin for the tie rod.

Center Leg Lift Mechanism

The center leg lift mechanism was a real head scratcher. One of the best fully documented mechanism I had seen was Mike Lambert's foot lift, whose plans are available on the Yahoo R2-builders group file section [19]. However I did not like the space it consumed at the top of the droid, nor the speed at which it operated. I wanted my foot to drop in a second or two to be more lifelike.

Problem is, when the foot is retracted in the droid body, there is very little space left for a mechanism except towards the top of the body. The mechanism needs a relatively long stroke of 10". And it has to be extra strong because the center leg has to survive shock impacts many times the weight of the droid from a sudden impact on the front wheels while driving and, unlike the outer legs, these strong forces are right in line with the movement one wants to achieve. Which means such mechanisms are usually large and slow.

After trying many zany configurations that either didn't provide the speed, the necessary travel length, the strength or the space savings, I finally arrived at a workable solution shown in Figure 15. This self-contained mechanism is also designed to fit into the COM-8 frame with very little modifications, needing just 3 pairs of extra holes on the bottom ring to attach the support brackets.

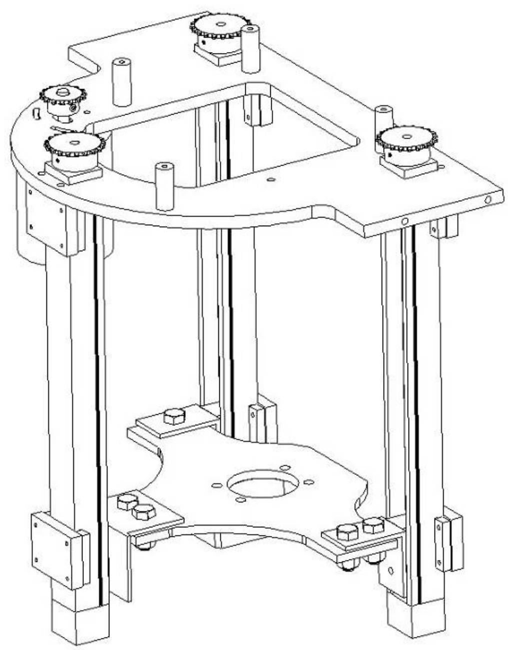

Figure 15: Center leg lift mechanism

Three screw-actuated linear slides assemblies are the key of the design. The ones I use are manufactured by PBC Linear[20]. These extruded aluminum units are relatively low cost actuators (that is, relative to most professional linear motion equipment!), very compact, yet have enough structural strength for our application. They can be ordered semi-custom in any length, with several choices of screw pitch. A shown in Figure 16, they are relatively simple units. A slider moves along in an extruded aluminum shell when turning the lead screw. The exact part number for the PBC slide is MLD028D-0AJ201-0338-000 (28x338 mm actuator, 10 mm lead screw).

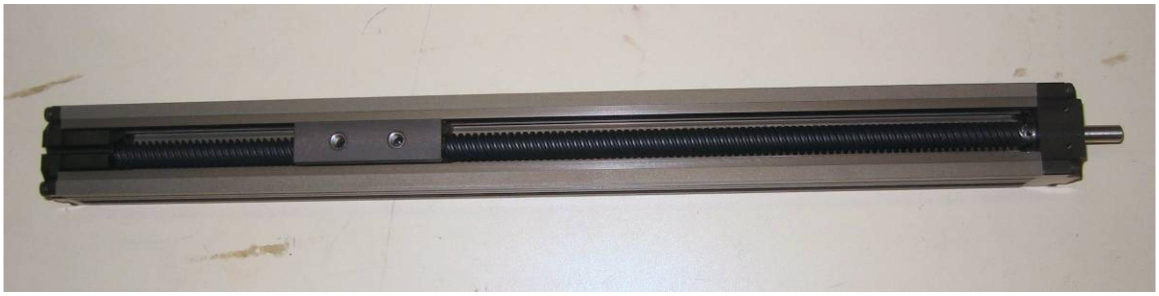

Figure 16: PCB Linear MLD actuator, part number MLD028D-0AJ201-0338-000. It has a 338mm main body length and a 10 mm lead screw.

One would be tempted to use only one of these slides. However, although they are acceptable (while not spectacular) in axial load performance, they are pretty poor in moment load. They would fail if a large force would tend to twist and rotate the slider. Unfortunately there would be plenty of that if only one of the units was attached to a side of the platform holding the leg. To go around that problem, I use three slides attached around the moving platform. They are all driven in unison by a chain and sprocket system, so that the platform always stays flat and no large moment force can ever develop. A quick calculation showed that the load of a 150 lbs robot including impact load was acceptable, albeit without much margin. Drive carefully as they say.

Next was the issue of travel. A full 10” of travel is needed to barely fit the leg inside the body. Add 0.30” of margin for over-travel at either end, the slider length and the length of the end cap of the units, and quite miraculously the unit barely fits inside the body without going above shoulder level. Beware that the slides protrude all the way down into the skirt, so resin skirts with thick solid sides are out.

Finally, there was the issue of torque and speed. Given the maximum 3,000 rpm critical speed of the screw, there are several combinations of lead screw pitch and drive speed that can achieve the desired 10”/s speed. I chose a 10mm lead screw, which yields a 1500 rpm actuation for the 10”/s speed goal. This would allow up to 2:1 gear reduction to increase torque from typical brushed electrical motors that run in the 2000-3000 rpm regime. Assuming this reduction and a 15 lbs leg weight, calculations showed that a motor with at least 50 oz/in torque and 40W would be needed. A cheap surplus 100W, 12V, 2500 rpm (no load) scooter motor fits the bill with good margin and is small enough to fit underneath the mechanism. The final gear ratio I used was 15 teeth on the motor and 20 teeth on the actuators. I used a #25 chain. The scooter motor has no trouble at all with my heavy center foot and achieved the calculated speed. My only complaint is that it is a bit noisy.

Figure 17 shows the parts needed to assemble the leg lift. They are the top platform and the sliding plate, and a bunch of mounting brackets. They would probably be difficult to replicate without having some machining tools, but could easily be made in a machine shop run. Figure 18 and Figure 19 show the completed assembly in the droid frame.

Pictures do not do much justice to the "life" a quick leg drop brings to the transition, however you can get a better idea from a YouTube video I posted at http://www.youtube.com/watch?v=v9vhstzh6Ok , which is also available along with a few more in my build log.

Figure 17: Aluminum pieces needed for the leg lift.

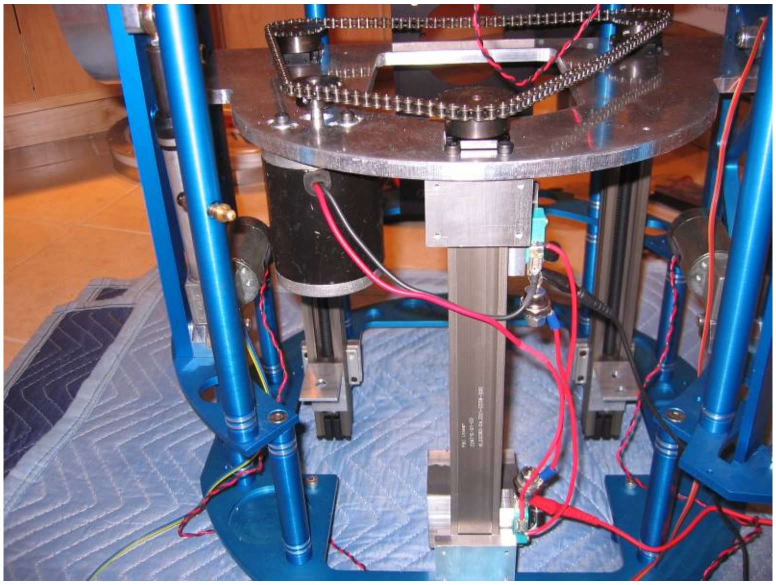

Figure 18: View of the leg lift mechanism during assembly.

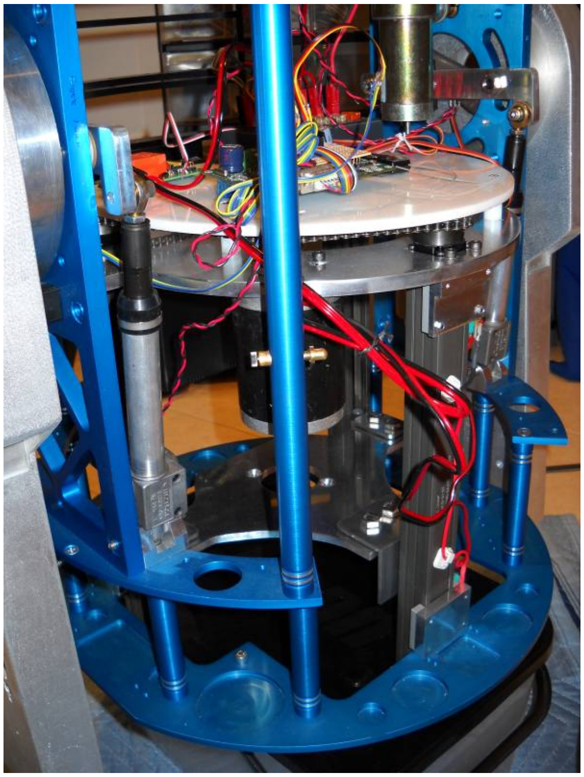

Figure 19: Completed Leg Lift mechanism.

Center Foot servo control

I used a simple RC dual relay board to actuate the center foot up or down from and RC signal. I bought mine from robotmarketplace.com[21] (Figure 20). The end travel is controlled by simple micro-switches in either direction, shunted by power diodes to allow reverse movement once the end travel is reached. One could also use a RC brush motor controller and gain some speed control, and maybe I'll upgrade to that when I get the time. Just be sure to size your relays or speed controller appropriately, the motor can draw up to 10A at full tilt.

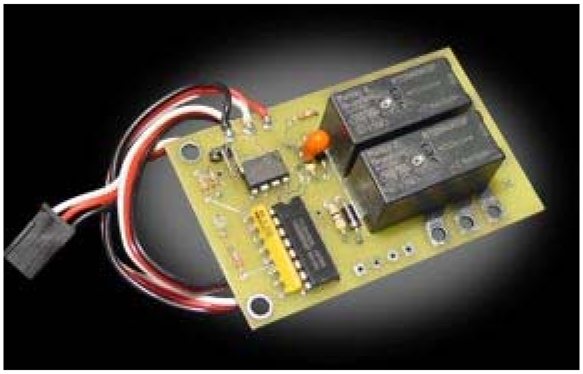

Figure 20: RCE220 RC Small Dual Relay Switch from robotmarketplace.com

One issue I had with the simple limit switch setup is that since the leg moves very fast and is heavy, cutting the motor supply was not enough to stop the movement. The assembly would travel past the limit switches and bump into the mechanical stops at both ends. In order to decelerate the foot more efficiently at the end of travel, I also use the motor as an electric brake by shunting it. I was able to accomplish this automatically by adding two more (powerful!) shunting diodes to the system as shown schematically in Figure 21.

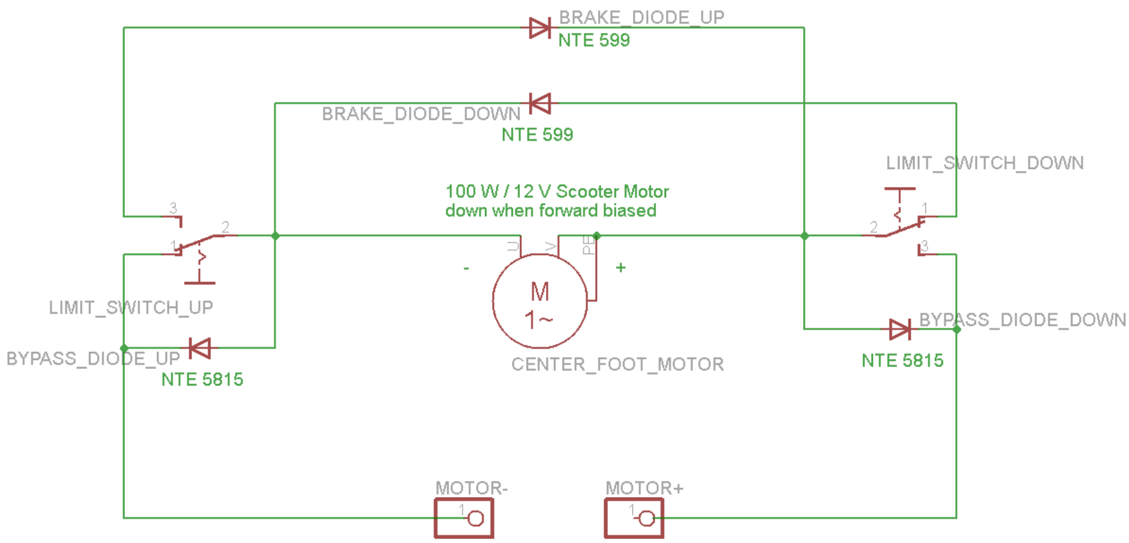

Figure 21: Limit switches and diodes for the end travel control. The two large NTE599 15A cont / 250A max diodes are for braking at travel end.

The diodes have to be of the larger kind, I use NTE5815 (Io 6A, Imax 400A) over the end switches and two NTE955 (Io 15A, Imax 250A) on a heatsink as the breaking diodes.

Center Foot considerations

I used a two caster setup for my center foot. By using two casters, the center ankle articulation is left unlocked, and the foot naturally adjust to the required angle, which continually varies during the 2-3-2 transitions. The largest caster I could fit is a 3” caster from Mitsumi[22]. Another builder (TinyP[23]) discovered them, they are the only ones whose swivel radius is small enough for two casters to fit in the foot shell without interfering with each other or with the shell skirt when turning around.

One must be careful to introduce some kind of shock absorption device between the actuation mechanism and the center foot wheels, or all shocks would be transmitted directly to the screw actuators. The heavy Mitsumi steel casters are designed for very heavy loads (which is probably why the swivel radius was kept so small), and therefore come with very hard wheels. To provide some shock absorption, I replaced the wheels with soft neoprene wheel from another 3” caster (Figure 22). To provide further shock absorption, I added rubber absorbers (vibration mounts) between the caster plate and the foot shell (Figure 23).

Figure 22: Misumi casters, with the original hard wheel at right, and grafted with a soft neoprene wheel at left

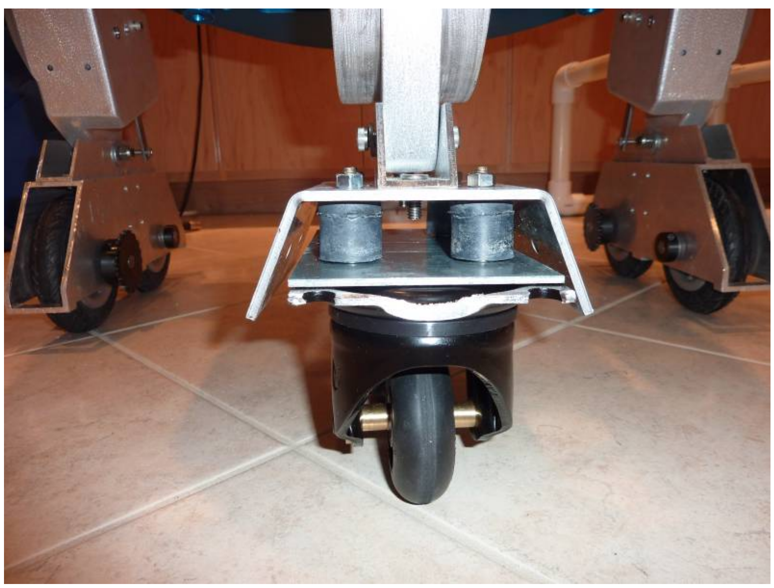

Figure 23: Rubber mounts are inserted between the caster place and the foot shell for shock absorption.

2-3-2 Motion Controller

With the simple system described above, I was able to do manual 2-3-2 transitions right from my RC controller without further ado. I controlled the outer leg servo with my flap lever, and the center leg via a 3 position switch. However, one has to be careful to first lower the center leg, then move the legs – and the reverse for the 3-2 transition. Do that in the wrong order and the droid will do the dreaded "face plant".

Most 2-3-2 builders add some form of a controller to synchronize the outer leg and center foot movements for the transitions. I chose to implement this function via a microcontroller, which I can program to output the correct servo signals to feed my three leg servo controllers (two outer legs proportional servo control, and the center leg up/off/down control). It's a significant programming investment to implement it, but once it's done it becomes extremely flexible, since all optimizations can be done via software.

The basic system architecture is shown in Figure 24. The microcontroller reads 3 channels from the RC receiver (outer leg channel, center leg channel, and failsafe channel) and 1 analog channel (position sensor of the left outer leg). It outputs 3 servo channels, one for each outer leg and one for the center leg.

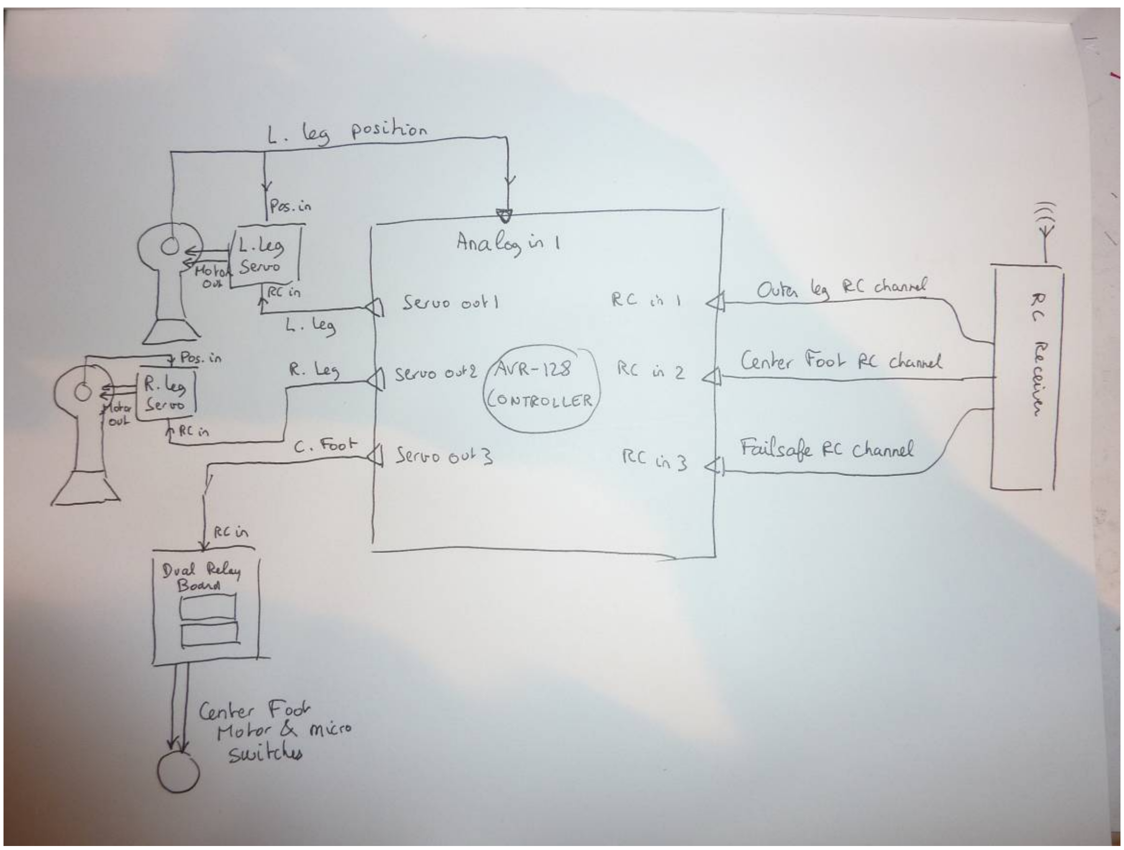

Figure 24: 2-3-2 control architecture

I used a small and inexpensive Olimex development board powered by an 8-bit Atmel AVR ATmega128 microcontroller[24] depicted in Figure 25. In essence it's very much like an Arduino with a small keypad and LCD screen and a more powerful processor. The amount of microcontroller hardware you get nowadays for about $50 is just downright mind-boggling. This little controller has a 16 MIPS RISC processor, EEPROM, RAM, Flash Memory, 4 independent timers, a real time clock, two independent serial interfaces with support for RS232 and I2C, a whole bunch of PWM generators, 53 pins programmable for input or output, 8 ADC inputs, 8 external interrupts, brownout protection, 6 sleep modes, a bootloader section, in-situ programming, JTAG debug… The list just goes on and on, and so does the 386 pages long manual! And, let's not forget, unlike PC processors, power consumption is just about negligible. It's a robot maker paradise or hell, depending on your love of hard core C programming.

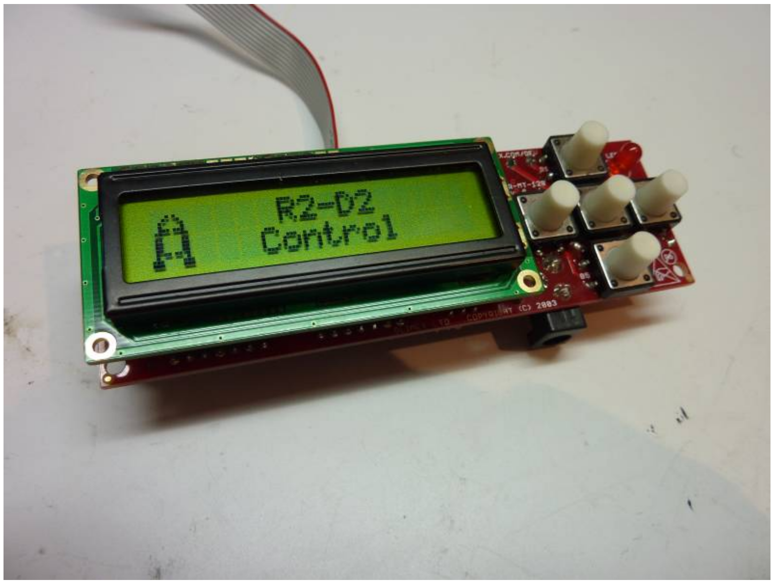

Figure 25: Olimex AVR-MT-128 microcontoller board

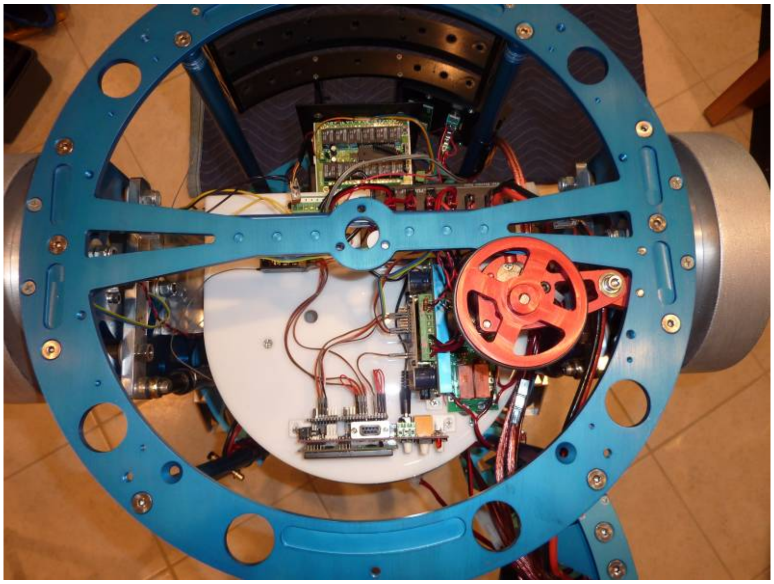
Figure 26: View of the installed electronics. Controller is at the bottom, to the right is the outer leg servo controller. The relay board for the center foot is partially visible under the dome wheel.

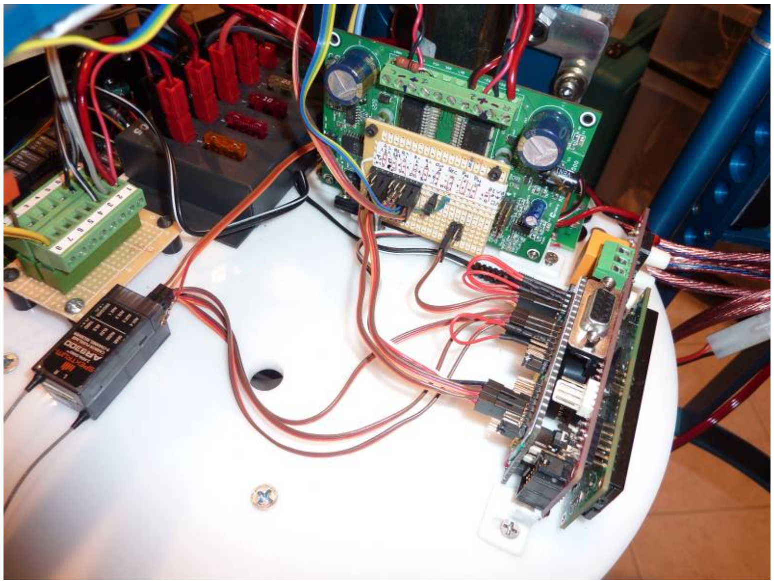

Figure 27: Close-up view of the electronics. RC receiver to the left, outer leg servo controller to the top, microcontroller to the right.

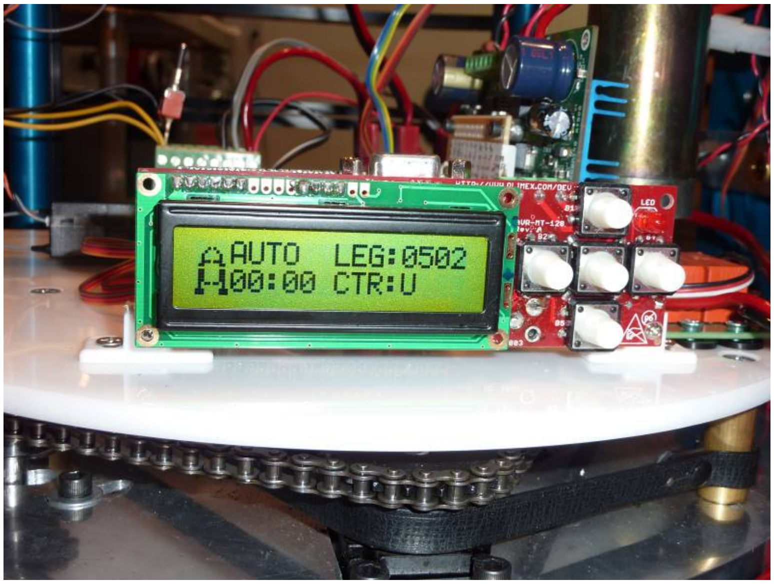

Figure 28: Controller display in auto mode. The outer legs have been commanded in 2-leg position, as indicated by the close to 500 µs leg channel value read from the RC transmitter. Accordingly, the center leg has been brought to up (U) position. A cumulative run-time counter is at the lower left – R2 has been up for less than a minute and still shows 00:00.

In regular auto mode, the controller simply monitors the outer leg lever position from the RC transmitter. Starting from 2-position, the first little bit of lever position does nothing, then past a certain point the center leg deploys, and the outer leg follows the position of the lever. The outer legs can be moved all the way to full back 3-leg position, or can be brought to any intermediary position using the lever. If the controller senses that the outer legs are brought back all the way upright to 2-leg position, it automatically raises the center leg. While this happens, some basic info is available on the LCD screen for monitoring (Figure 28).

Note that for safety, the controller also monitors an extra “failsafe” channel. If this channel has no signal, goes into a predetermined failsafe state due to a loss of signal at the receiver, or is manually set by a switch on the RC transmitter, all 2-3-2 leg movement is disabled.

In addition to the auto mode, the controller also supports a direct RC mode, a manual mode, a calibration mode and a diagnostic mode. In RC mode, the controller simply passes the RC signals from the transmitter to the outer and center leg, in essence reverting back to my earlier manual control setup. In manual mode, legs can be activated locally at the robot using the controller keypad. The calibration mode is used to set the 2 leg and 3 leg position, even out the two outer legs via software in case there is a small angular difference between them, and set the points at which the 2-3 and 3-2 transitions occurs. Finally, in diagnostic mode, numerical values read for each RC channel (I can read up to 6 of them), each servo output value (also 6), and each analog input (4 of them) are displayed for diagnostic purposes.

Power system

Even with a relatively compact system, battery space is quite limited in a 2-3-2. To save space and weight, I have been using Lithium-Polymer batteries instead of the standard lead-acid ones. The Lithium-Polymer units have 5 times the energy density of lead-acid batteries. I used three 10Ah/14.8V packs[25] connected in parallel, for an equivalent capacity of 30 Ah. The batteries are small enough to fit in the back door (Figure 29).

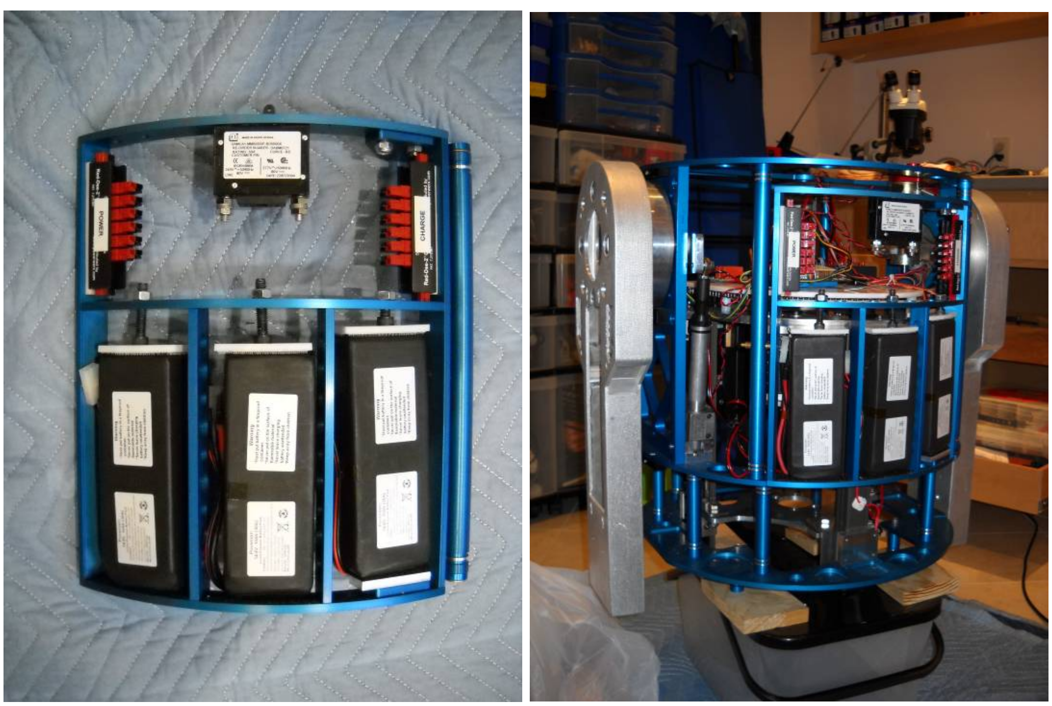

Figure 29: 3x 14.8V/10Ah Lithium Polymer batteries fit in the back door.

However in actual use I found that the droid was balanced too far to the back – which helps the 2-3 transition, but unfortunately makes driving on 2 legs a bit iffy. The droid would be susceptible to falling backwards when accelerating. I therefore later moved one of the batteries to the front for balance. Fortunately they are so small that you can fit them pretty much anywhere.

Closing Remarks

Figure 30 shows the finished installation. Completion of my 2-3-2 system is recent, so I do not have much extended data on actual use, but it has performed well right from the get go.

Figure 30: Finished 2-3-2 installation. Note the batteries in temporary position for balance trials. Eventually I settled on two batteries in the back door and one in the front.

There are a few things I'd change if I was going to make revision 2. The 10mm pitch screw for the center foot elevator is probably a bit too much. The center leg has a slight tendency to retract under the weight of the robot. I eliminated that by introducing a little bit of friction with a belt on the side of the motor shaft, but this is an afterthought kludge in an otherwise clean design. If I had to redo it, I would probably use a 5mm screw instead and compensate for speed with less of a gear reduction.

It is also conservatively designed and expensive. To cost reduce version 2, I would use only one shoulder actuator instead of two, and simply connect the two legs via the classic gas pipe. It would save one actuator and one motor controller cost. Also, now that the three screw system has been proven to work, I would not use pre-made slide assemblies whose precision widely exceeds what we actually need. Instead I would just use regular lead screws, nuts and a few ball bearings and build them into my own mechanism.

Another thing one could do is lighten the frame. Everything gets simpler and more reliable when weight is lower. Since all the weight of the center leg is now transmitted to the top plate of the center foot lift mechanism, the frame itself really does not have to support any weight. Also the horizontal plate greatly reinforces the frame, as do the three vertical slide units. I have effectively built a stronger inner frame inside the original frame. Consequently, the original frame, which is quite heavy, does not need to provide much structural strength anymore. It could be made much lighter without compromising the robot structural integrity.

We have reached the conclusion of this article, however we are at page 23 of what is after all just a quick overview. This should serve as a stern reminder of the significant complexity and challenges that a 2-3-2 system adds to a build. It can be done, and I hope this write-up encourages other builders to take the plunge, but it is definitely not for the faint of heart nor the faint of budget.

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