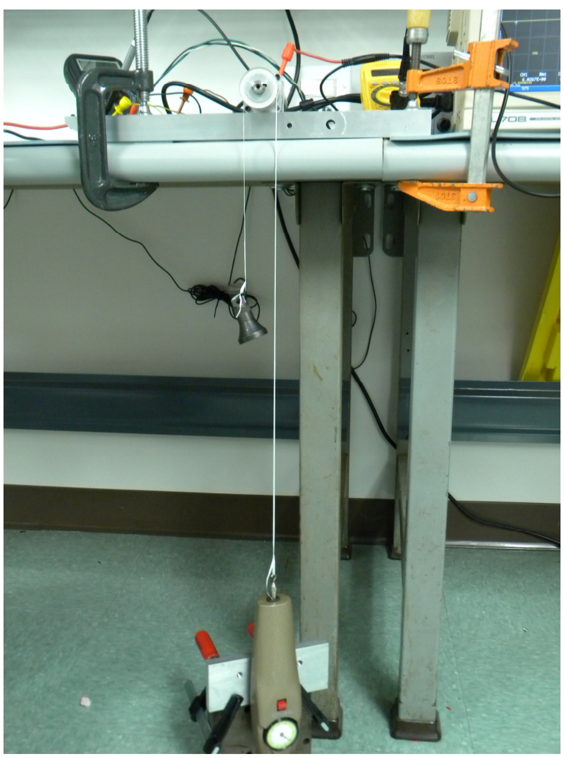
Issue: Talon SRX (with Ver 3.3 firmware) does not limit current in motor windings correctly.

Concern: The lack of proper current limiting is a potential safety concern for teams. The same issue that affects current limiting also affects the motor current returned by the Talon in response to a getOutputCurrent() function call. While not necessarily impacting safety, this may be confusing to teams trying to regulate motor torque based on measured current.

Background: The problem with the Talon current limit became apparent when we were trying to use a CCL-9015 motor (Andy Mark am-0912) motor for our 2018 intake mechanism. We wanted to limit the current so that if/when the intake wheels stalled, the motor current would remain within a safe limit in order to avoid overheating the motors. We observed the actual motor current exceeding 15 amps despite setting the current limit to 3 amps in our software. After confirming that our software settings were correct, we instrumented a motor for external current measurement and observed that the Talon was not reporting motor current accurately. In fact, the reported motor current differed from actual motor current by more than a factor of 5 in our test case.

Experimental Setup: We setup an experiment to carefully measure the current drawn from the battery as well as the current in the motor windings. We were particularly interested in the current when the motor is stalled as this is the condition when motor current can be significantly larger than when the motor is spinning.



We mounted our motor with a BaneBots 4:1 single stage gearbox to a bracket and extended the output shaft of the gearbox over the edge of our bench. We mounted a 44 tooth, 3 mm pitch timing belt pulley to the gearbox output shaft to act as a capstan hub. We wrapped a few turns of dental floss (remarkably strong and supple "cord") around the hub then connected one end of the floss to a mechanical force gauge (Chatillon DPP-10) and on the other end we attached a 120 gram weight in order to tension the floss. We selected the direction of wrap so that with positive current in the windings, the force gauge would be placed in tension. With the power to the motor off, we zeroed the force gauge.

Figure 1 Motor with 4:1 gearbox connected to force gauge.

In order the establish a baseline condition for the motor, we did an initial test with a DC power supply with adjustable voltage and current limits (HP 6267B). We installed a precision .020 current shunt (Empro HA-5-100) with 4-wire Kelvin connections in series with the positive lead of the motor. The lab supply was configured to limit the motor current to 6 amps. The voltage was adjusted until the current limit became active.

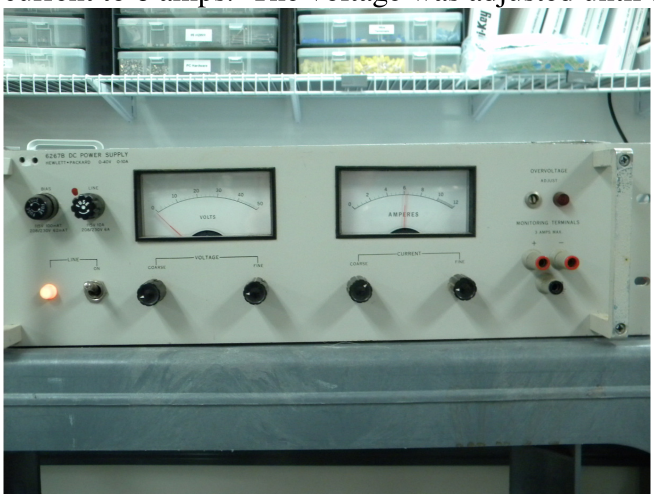


Figure 2 DC power source.

We connected a digital volt meter (DVM; B&K 391) across the current shunt. We also connected a differential oscilloscope probe across the current shunt. The oscilloscope (Yokogawa DL708) has the capability to apply a linear scale to the voltage measurement, so we adjusted the 'scope settings to scale the voltage measured across the current shunt by 1/.020 or 50. The scaled readings corresponded to amperes of motor current (ie: "1" on the 'scope equates to 1 amp of motor current or an actual voltage across the shunt of 20 mV).

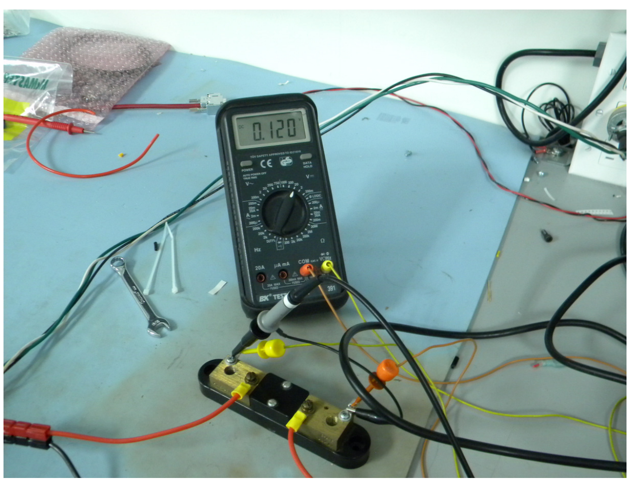


Figure 3 Current shunt with Kelvin connections and DVM to monitor voltage across the current shunt.

We also measured the temperature of the motor case, since we were ultimately interested in limiting motor current in order to limit temperature rise in the motor. We used a surface probe with a digital thermometer (Traceable Products 4000CC). The ambient temperature during the tests remained constant at 21.4° C during the tests.

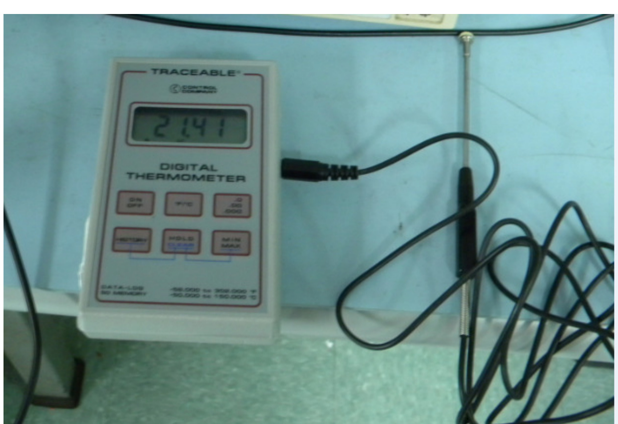


Figure 4 Digital thermometer with surface temperature probe.

There was no appreciable air flow over the setup. We noted that under stall conditions the small fan that cools the brushes of the motor was inoperative during all these tests (a worst case condition for the motor, but also representative of the stall condition we were interested in).

We used a second DVM to measure the voltage across the motor terminals. With the DC source connected and limited to 6 amps, we observed ~1.1 volts across the motor terminals. The indicated power dissipated in the motor was ~6.6 Watts.

We left the DC source connected to the motor for 15 minutes then measured the motor case temperature close to the brushes (appeared to be the hottest area of the motor). We measured a case temperature of 40.3° C.

With a DC source driving the motor, the current measured with the oscilloscope confirmed the measurement across the shunt resistor reported by the DVM.

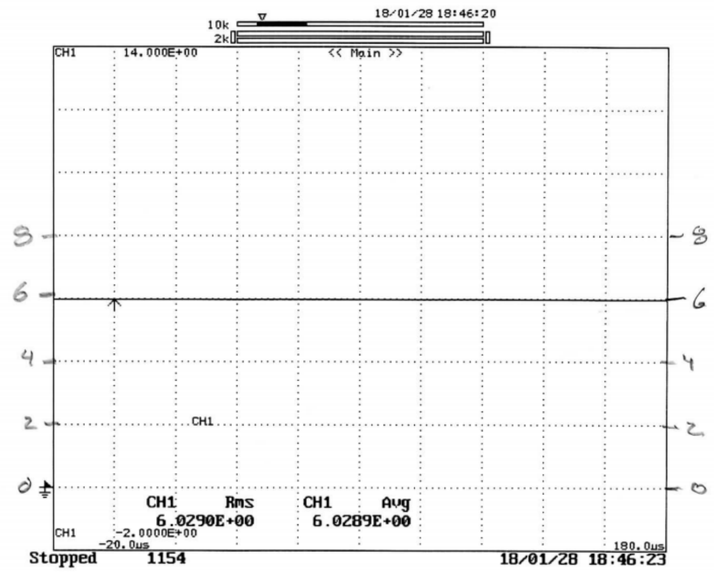


Figure 5 Motor current with DC source: 6.03 Amps.

The force gauge indicated a tension in the floss of ~1 lb (~4.45 N). However, the friction in the gearbox made the force measurement less certain. Turning the power source on and off indicated a clear increase/decrease of tension in the floss.

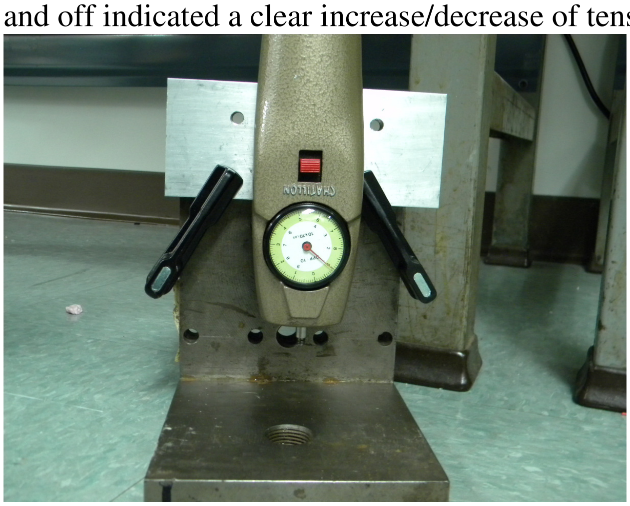


Figure 6 Force gauge indicating 1 lb tension with DC source.

With a motor torque constant of ~.0068 N-M/A we would expect a motor torque of .0408 N-M with 6 Amps current in the windings or a torque of .16 N-M at the gearbox output shaft. With a timing belt pulley radius of .049 M, the expected tension in the floss would be 3.3 N. The indicated tension of ~4.45 N is within the expected ballpark given the significant amount of friction in the gearbox and the cogging torque of the motor brushes.

We removed the DC power source and connected the motor to a Talon SRX (Ver 3.3 firmware) that was powered from a Power Distribution Panel and controlled with a roboRIO using the CAN interface. A trivial Java program was created to configure the Talon for percentOutput (open loop voltage based on PWM duty cycle) and continuous current limit of 3 amps. The current shunt was placed in series with the M+ output of the Talon. We adjusted the percent command until we observed nearly the same actual current in the motor windings as indicated by the current shunt.

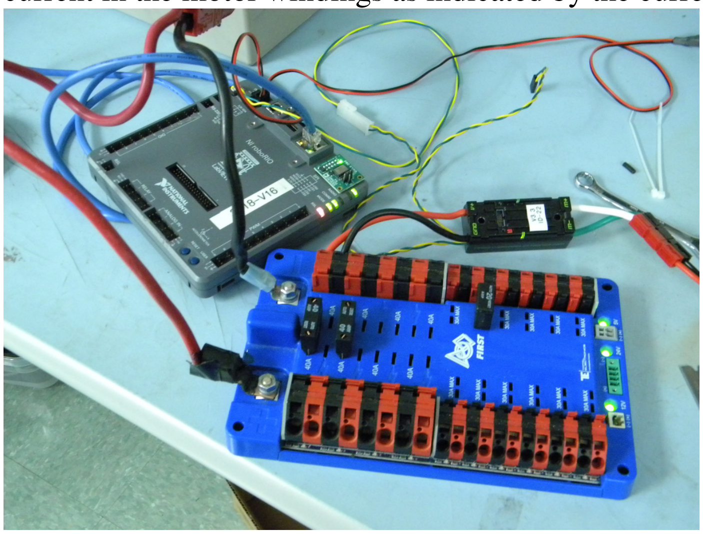


Figure 7 roboRIO and power control panel used to power Talon SRX.

The Talon did not limit the current to the programmed value of 3 amps. Rather, it was the commanded voltage divided by the series resistance of the current shunt (.020 Ω) plus motor winding (0.19 Ω) that limited motor current.

The Talon was less stable than the DC power source (understandable given the intended application and cost difference between a laboratory power source and the low cost motor controller). The motor current indicated by the DVM (measuring across the shunt) varied between .090 and .13 volts (indicating between 4.5 and 6.5 amps). Moving the motor armature slightly would affect the current reading due to changes in brush resistance - since the Talon was commanding voltage and the current depended on the DC resistance.

The oscilloscope was configured with 2 channels reading across the current shunt. Channel 1 was configured to apply a 400 Hz low pass filter to the shunt voltage (scaled by 1/.020, to indicate in amps). Channel 3 (also scaled by 50) was configured with 500 kHz bandwidth in order to reveal the variation in motor current within a PWM cycle.

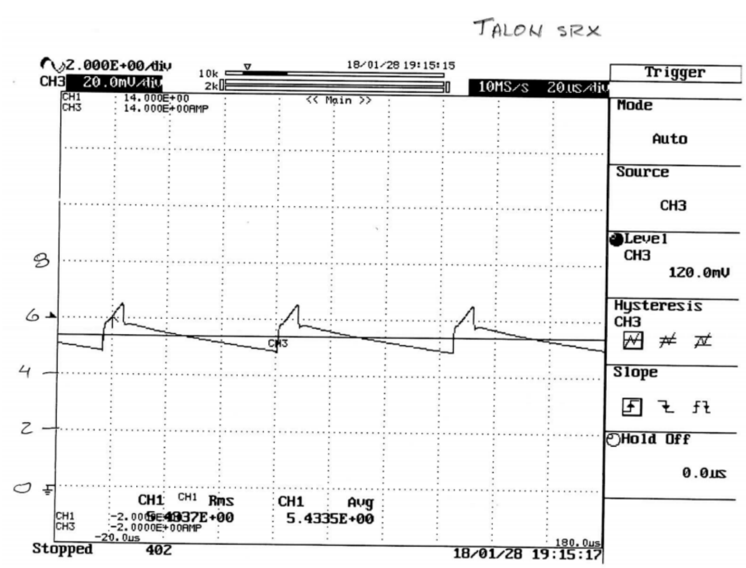


Figure 8 Motor current when powered by Talon SRX.

The flat line is the average motor current (5.43 Amps at the moment the trace was captured). The trace from channel 3 clearly shows the increase in current during the ON portion of the PWM cycle and the decrease during the OFF portion of the 64.1 µSec cycle. The mechanical time constant of the setup is significantly lower than the 400 Hz low pass filter used on channel 1. Therefore, the torque delivered at the output of the gearbox shaft is essentially constant.

The indicated tension was similar to what was observed when driven by the DC source.

Figure 9 Tension when powered by Talon SRX at ~6 Amps.

The 4th channel of the 'scope was connected differentially across the motor terminals to observe the actual motor voltage.

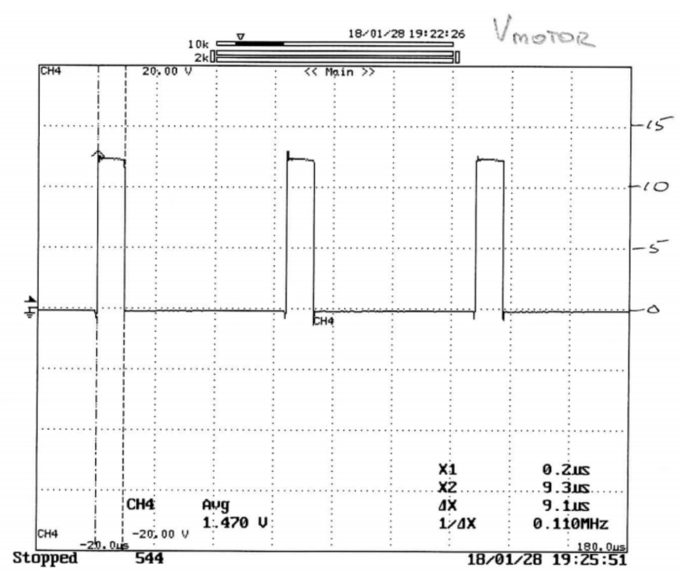


Figure 10 Motor voltage at motor terminals.

The duty cycle was 9.1/64.1 or 14% which matched the commanded "percentOutput". The average motor voltage was 1.47 volts for an indicated power delivered of 1.47 * 6 = 8.8 Watts.

After leaving the Talon driving the stalled motor for 15 minutes, the motor temperature was measured to be 40.6° C, nearly identical to the 40.3° C observed when a similar level of power was provided by the DC source.

A DC clamp-on ammeter (Craftsman 82369) was used to measured the current in the V+ lead of the Talon. The Talon was drawing an average of 1.1 Amps from a battery that was reported by the roboRIO to be 11.9 volts. The indicated power draw was therefore 13.1 Watts.

The roboRIO was programmed to read 3 values from the Talon and display them on the SmartDashboard: OutputCurrent, BusVoltage and MotorOutputVoltage.

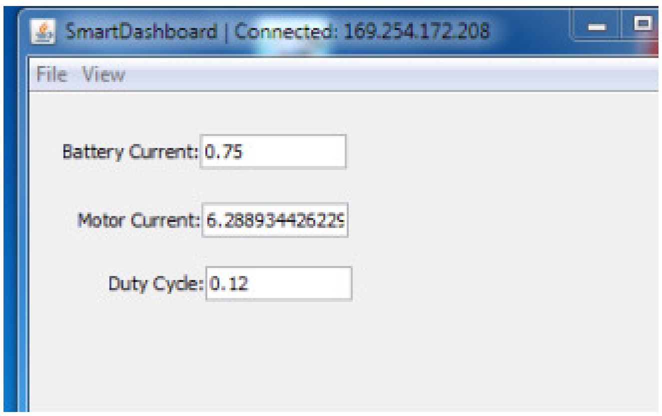


Figure 11 SmartDashboard readings from Talon SRX.

The value returned by the Talon is listed as "Battery Current". The ratio of motor voltage to bus voltage is displayed as "Duty Cycle". The value shown as "Motor Current" is the current reported by the Talon divided by the duty cycle. Note that the values reported by the Talon fluctuate and also have modest resolution (0.125 Amps for current) so they will not agree with the values reported by the external instruments at all times.

Note that the reading returned by the Talon as "OutputCurrent" differs from the actual motor current by a factor of 8.4 (~1/.12) and the actual motor current is twice the value programmed as the limit on continuous current.

Clearly, there is a problem with the current measurement of the Talon and that measurement renders the current limit ineffective.

Root Cause: Improper scaling of low-side current sense.
The Talon (apparently) measures current with a sense resistor on the low-side of the H-bridge. This is a well know means of measuring current in an H-bridge, though it does present some challenges. The current in the sense resistor is identical to the current in the motor windings only during the ON portion of the PWM cycle (see Figure 12).

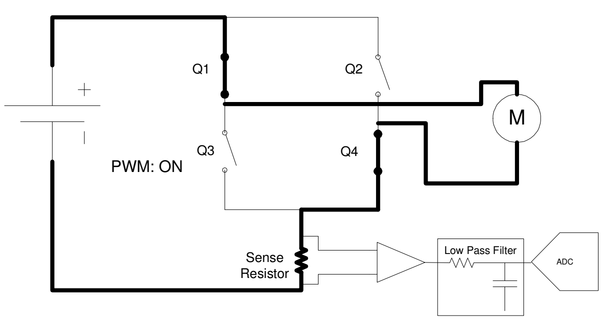


Figure 12 Motor current passes through low side sense resistor during ON portion of PWM cycle.

During the OFF portion of the cycle, the motor current circulates through the FET switches without passing across the sense resistor.

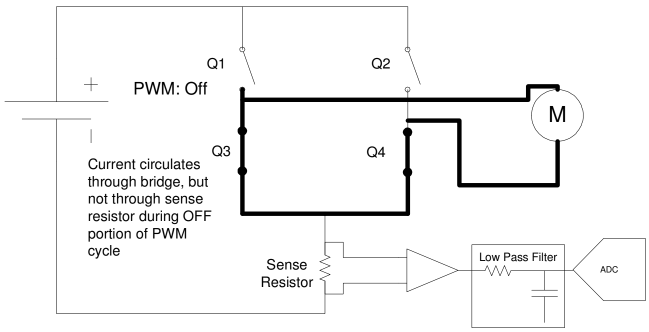


Figure 13 Motor current circulates within H-bridge during OFF portion of cycle, bypassing sense resistor.

The average voltage sensed across the sense resistor during the ON portion of the cycle is equal to the average current in the motor. However, when the duty cycle is low, the ON period can be very short and requires a high speed ADC synchronized to the PWM cycle to capture the data. Furthermore, the actual voltage measured across the sense resistor is typically small (to minimize losses) and always situated nearby to FETs with very large dV/dT transients. The result is often some feedthru to the current sense voltage that corrupts the waveform making accurate measurement of current, particularly at low current levels, difficult. An alternative approach is to average the sense resistor voltage over the PWM cycle with a low pass filter set substantially lower than the PWM frequency.

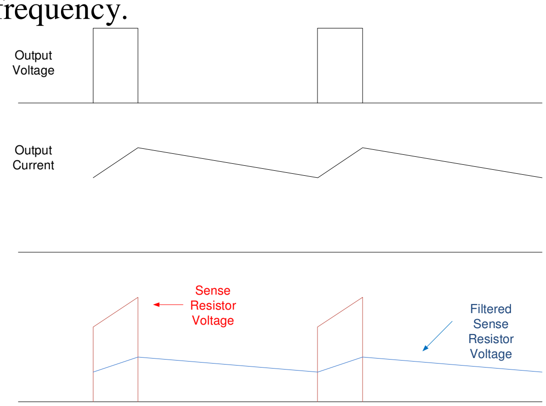


Figure 14 Output voltage, motor current and sense resistor voltage during PWM cycle.

The ADC requirements are much relaxed and the short duration voltage transients have much less impact on the average voltage measurement. However, the resulting voltage is therefore indicative of the current drawn from the battery, not the current in the motor windings. The winding current can be estimated however, by realizing that the motor current must be related to the battery current by the ratio of battery voltage to motor voltage (subject to minor losses in the Talon) due to conservation of energy. Also, the voltage ratio is simply the inverse of the PWM duty cycle.

The **Talon is reporting actual battery current rather than motor current due to the lack of correcting the current sense voltage by the PWM duty cycle**. Fortunately, it should be a simple matter for CTRE to correct this error with a software revision.

Meanwhile, until CTRE corrects the problem, Teams should be aware that the Talon SRX does NOT limit motor current (unless duty cycle = 100%, at which point motor voltage equals battery voltage and hence battery current = motor current). We found experimentally that, for our operating condition with a 30% voltage command, when the motor is stalled, a current limit setting of 1 resulted in ~10 Amps in our intake motors. This results in ~20 Watts dissipation in the motor which is tolerable over a 2.5 minute competition. Unfortunately, the software interface to the Talon limits the current limit settings to integers so one is limited in the resolution that can be achieved.

Note that with integer setting of (battery) current limits, the power delivered to the motor can be limited in multiples of 12 Watts (assuming nominal 12 volt battery). While the average power dissipation may be tolerable for short duration operations, the actual motor current can be very large. Consider the CCL-0915 motor with ~0.2Ω resistance. If you mistakenly assumed that setting the current limit in the Talon to 5 amps would limit the current in the motor to 5 amps and therefore the power dissipated at stall to ~5 Watts (5^2*0.2 = 5), you would be surprised to find that the actual current in the motor at stall would be ~17.3 Amps (sqrt((5*12)/0.2)). The motor heating at the expected level of 5 Watts would be minimal even if the motor were stalled for the duration of a competition. The heating at 60 Watts would be **12 times greater** than expected and possibly a significant concern if the motor were allowed to remain stalled for any significant time.

Teams are also cautioned that, with the absence of current limits on motor current, and the resulting very large currents in the cabling between the Talon output and motor terminals, it is imperative that the connections and wire size selected for the intervening connections be selected properly and crimped or soldered carefully. With inexperienced hands stripping wires and making crimp connections, the potential exists to have poor connections that can be potential hot spots if the motor is stalled and currents are allowed be significantly larger than expected.