

hardware and software emergency stops are disengaged. The cRIO software waits one second after removal of a stop condition before sending non-zero commands to actuators.

During the Summer 2010, a wireless emergency stop system will be added to allow un-manned operation.

**Manual Driver Control** Simply disconnecting electrical power from the actuators would not be enough to prevent an accident if the safety officer driver were unable to then manually take control of the vehicle. All actuation components have been designed to ensure the driver can manually operate the vehicle while the actuation system is unpowered. This enables the vehicle to be manually driven between autonomous missions, and allows the driver to retake control in an emergency.

The linear actuators that control the accelerator and brake pedals of the vehicle are electromagnetically clutched. When power is removed from their clutch line, they slide freely with minimal resistance. In testing, the Gator's factory installed brake pedal return spring is enough to return the brake pedal back to its neutral position when the clutch is disengaged. The factory installed accelerator pedal return spring was not strong enough on its own, so an additional, stronger return spring was added in parallel to the existing system.

The power steering conversion installed on the Gator has been intentionally designed to avoid using a large gearbox. Instead, we have installed a large, easily-backdriven motor to control the steering column during autonomous operation. When this motor is disconnected from power via the emergency relay, the driver can manually operate the steering wheel without an unusual amount of resistance.

Ensuring that all actuation systems are operable after removing power allows the safety officer driver to take control of the vehicle should a dangerous situation arise.

## 6 Mechanical Systems

The mechanical modification of the vehicle has focused on drive-by-wire actuation, electronics and sensor mounting, and operator interface construction.

The three actuation systems necessary for drive-by-wire operation are the brake pedal, the accelerator pedal, and the steering. Both brake pedal and accelerator pedal actuation are accomplished using linear actuators from PQ Controls. Steering actuation is accomplished using a heavily modified after-market power steering conversion kit available for the Gator XUV.

Sensors, computational power, and power supplies are mounted in various locations throughout the vehicle. The primary electronics box is mounted on two vibration isolating rails in the bed of the vehicle and contains the computers, the CompactRIO, the power supplies, and most of the power distribution elements on the vehicle. The vehicle also includes a roof-mounted optics-quality pegboard for sensor mounting—current roof-mounted sensors include a SICK scanning LIDAR and a NAVCOM GPS antenna with provisions for other sensors. Additionally, a forward-facing stereo-vision camera is mounted inside the cab.

Inside the cab, a daylight-visible monitor and keyboard/mouse tray provide an operator interface for the software programmer. In case of emergency, a dashboard-embedded E-stop

button allows the safety officer, seated in the driver's seat, to reclaim manual control of the vehicle.

The individual mechanical subsystems are outlined in more detail below.

### 6.1 PQ Controls Linear Actuators

Both the accelerator and the brake actuation systems utilize Model 751 linear actuators available from PQ Controls (Figure 9).



**Fig. 9.** PQ Controls Model 751 linear actuator

These actuators have a 3 inch throw and supply up to 90 pounds of force. The accelerator pedal requires approximately 20 pounds of force and 1.5 inches of throw, while the brake pedal requires approximately 45 pounds of force and 0.5 inches of throw. This allows for comfortable margins of safety for both force and distance. The actuators run on 12VDC and draw 3.8 Amps of current at stall.

Control is accomplished through a 1-4V command line where voltage maps linearly to position. Note that the end position and linear scaling factor are based on the voltage at the time of power-up, so for simplicity's sake, the actuators should always be powered on at 1V in the fully relaxed position.

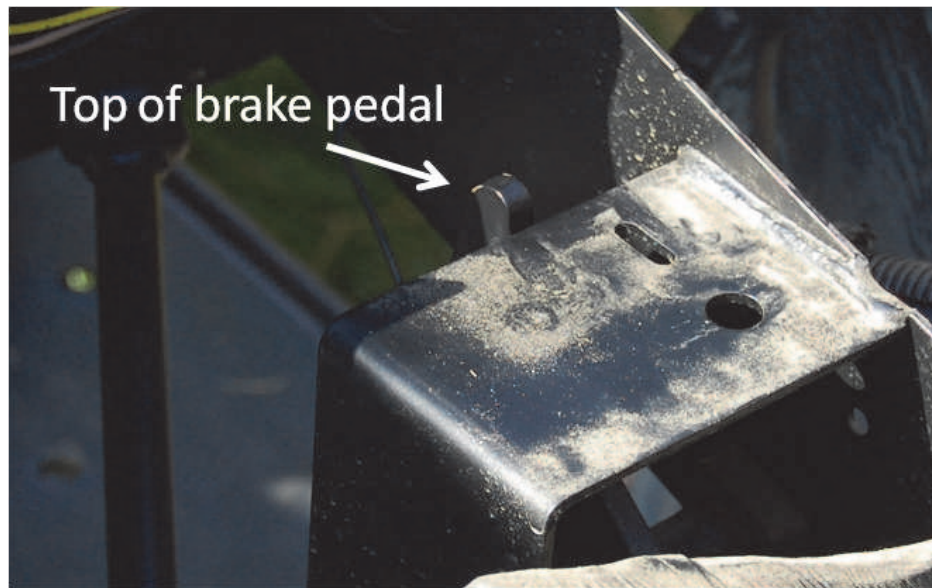
A separate 12V clutch line provides the capability for emergency override—when power is cut to the clutch, the actuator arm can slide relatively freely, requiring only 8 pounds of force to move. This is well under the force provided by pedal return springs and the force which a human operator can easily apply. For simplicity, the linear actuators' clutch and power line have been tied together, so cutting power to the clutch also removes power from the actuator as a whole.

The actuators are environmentally sealed and resistant to humidity, water, dirt, dust, and mud.

### 6.2 Brake Actuation System

The brake pedal actuation system consists of a PQ Controls linear actuator mounted to the vehicle frame and coupled to the brake pedal. The existing brake pedal mounting bracket—

which is located above and behind the top of the brake pedal—provides a convenient attachment point for a linear actuator mount. This bracket is shown in Figure 10.



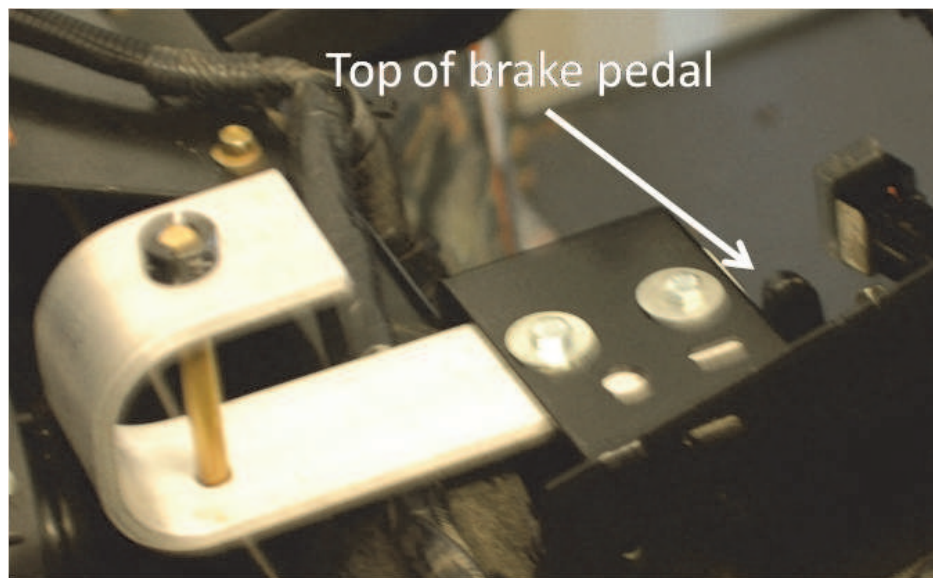
**Fig. 10.** The brake pedal mounting bracket.

Although this bracket provides a convenient mounting point that keeps the actuator away from the operator's feet and legs, space limitations under the Gator's hood prevent the linear actuator from being mounted in the typical fashion—that is with its mounting axis parallel to that of the axis of rotation of the brake pedal. Instead, the actuator must be turned on its side and mounted on a perpendicular axis in order to fit within the available space profile.

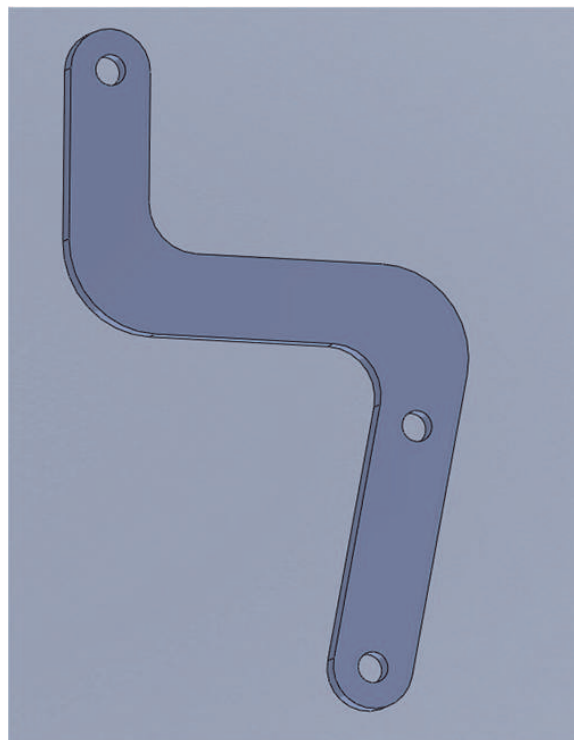
The actuator mounting bracket consists of a bent bar of 0.25" 6061 aluminum bar stock that holds a steel pin on which the actuator is mounted. Shaft collars prevent the pin from sliding free. In the future, the aluminum mounting bracket could be replaced with one made of black anodize steel, although this is not necessary for normal operation of the vehicle. The actuator mounting bracket bolts to the Gator brake pedal mounting bracket via two post-machined holes. Figure 11 shows the assembly before the linear actuator is added.

To allow the linear actuator to actuate the brake pedal, a brake pedal extender arm (shown in Figure 12) is manufactured from 0.25" aluminum plate and bolted onto the brake pedal. It is recommended that the brake pedal be removed from the vehicle prior to drilling the brake pedal extender arm mounting holes in order to ensure accurate hole placement and alignment.

Because the actuator is mounted on an axis which is not parallel to the axis of rotation of the brake pedal, an additional parallel axis of rotation must be introduced in the coupling linkage. This is accomplished through the use of a double clevis link—a device consisting of two parallel, pivoting pins held at a constant distance from one another. These linkages are



**Fig. 11.** The actuator mounting bracket mounted to the vehicle frame.



**Fig. 12.** The brake pedal extender arm.

available off-the-shelf from numerous hardware suppliers—the one currently used in the Gator is pictured in Figure 13. A 5/16th inch clevis link was use because it was the smallest readily available.



**Fig. 13.** The 5/16th inch double clevis link used in the current design.

The linear actuator rod is coupled with the double clevis link using a 5/16th inch ball-joint rod end. The other pin of the clevis runs through a bronze bushing which is press-fit into the exposed end of the brake pedal extender arm. The assembled linkage is shown in Figure 14.

A completed CAD model of the actuation system is shown in Figure 15. The CAD model is useful for understanding how the linkage converts the linear motion of the actuator to rotary motion of the brake pedal. The assembly is shown at both extremes of its actuation range—note how the double clevis linkage allows power to be transmitted without the actuator binding.

The brake pedal actuation system is fully functional and has not yet experienced a mechanical failure of any kind during testing. The completed system is shown in Figure 16.

### 6.3 Diesel actuation system

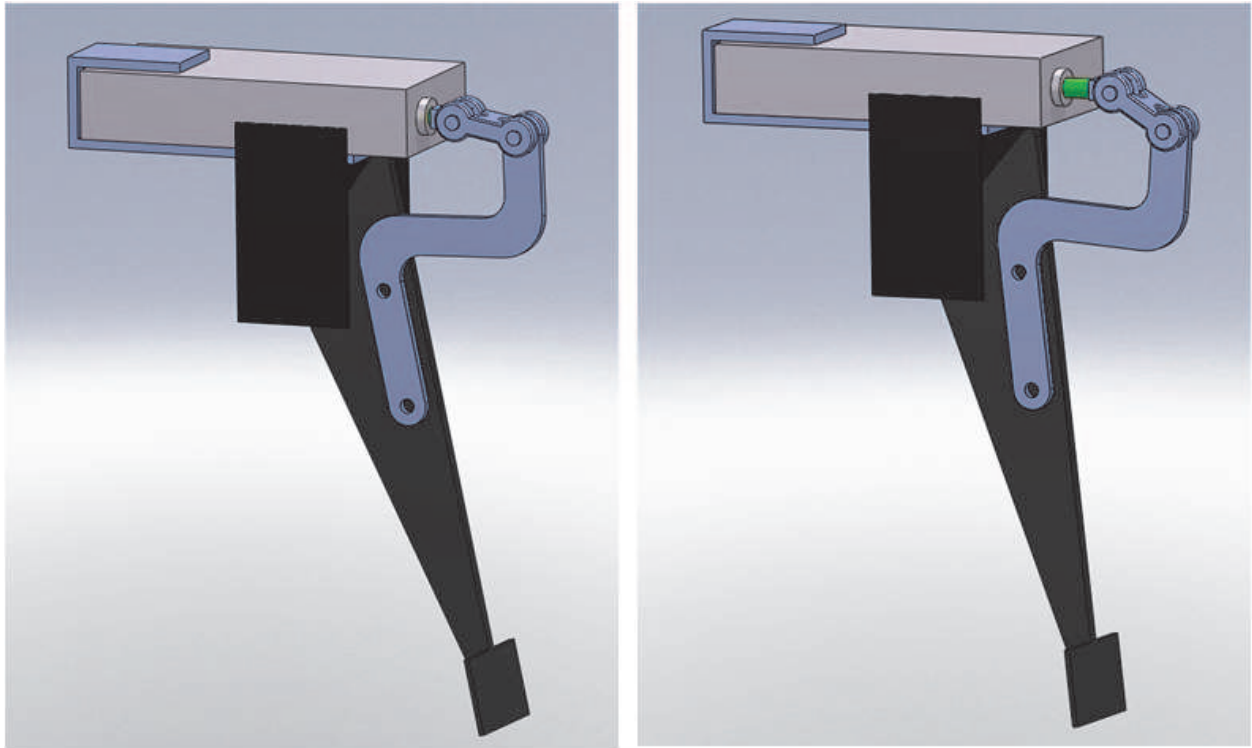
Our diesel actuation system is based on the same PQ Controls linear actuator as the brake actuation system. It takes advantage of the portion of the diesel pedal arm that connects to the return spring (see Figure 17). It consists of a mounting plate, a U-bracket which holds a pivot joint to mount the actuator, the actuator itself, and an arm which connects to the return spring section of the pedal arm. The return spring itself is not removed, but is simply slid to one side so both systems can mount to this section of the pedal arm.

**Actuator Mounting** The mounting plate for the actuator takes advantage of the center column of the vehicle being pre-drilled for a cup holder. The cup holder is held to the center column with four expanding panel clips and can be removed easily by pulling out the four retaining pins for the clips. This exposes the center column, which is made out of 0.125" steel, and four 0.28" holes drilled to mount the cup holder. An adapter plate to connect the U-bracket was machined out of 1/4" aluminum using the abrasive water jet cutter. Mounting this plate was a challenge, since the center column is welded shut from the bottom, and the

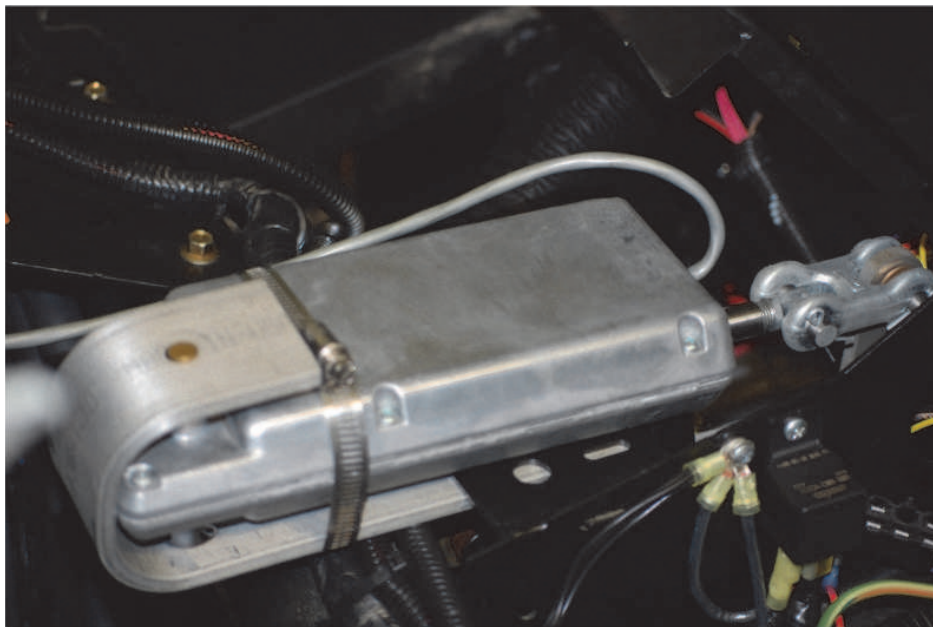


**Fig. 14.** The assembled brake pedal actuation linkage (top view).

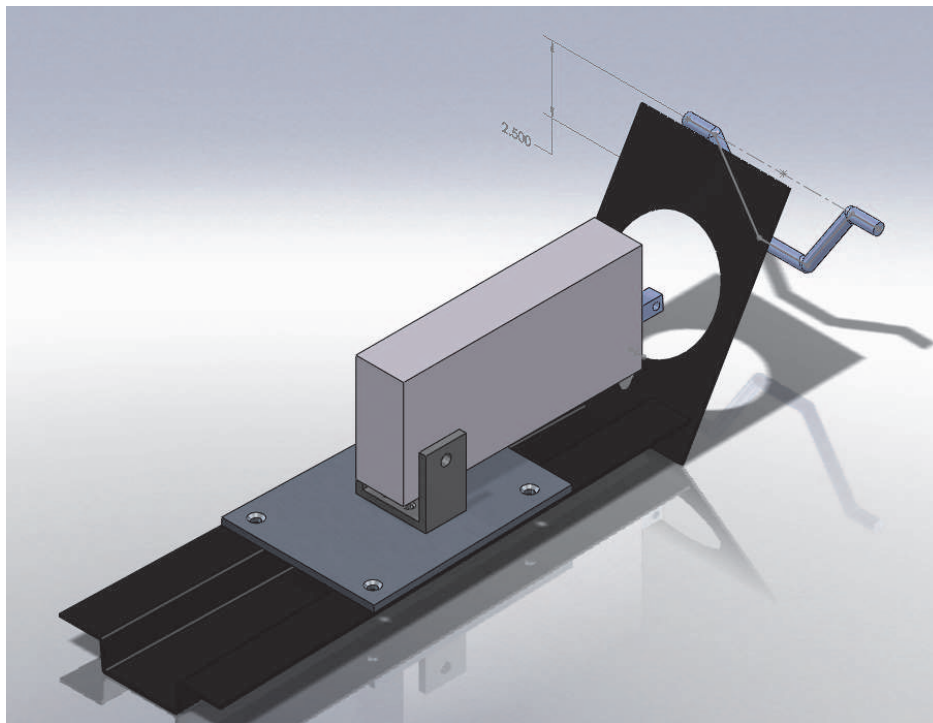




**Fig. 15.** The brake pedal actuation system, shown with the pedal at rest (left) and depressed (right).



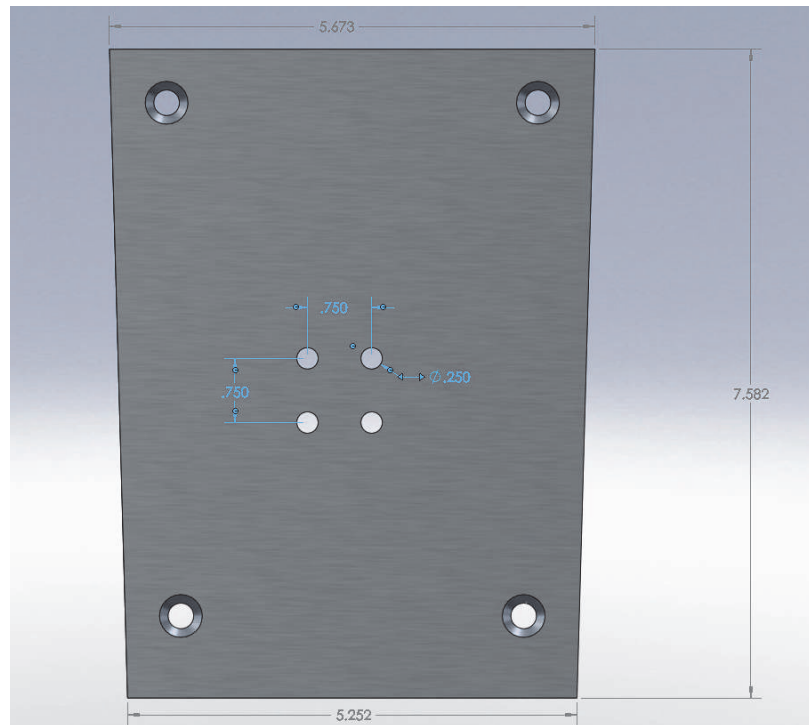
**Fig. 16.** The brake pedal actuation system fully installed on the Gator.



**Fig. 17.** A CAD rendering of the entire Diesel actuation system. The full pedal arm is not shown, but would extend from the left side of the center column of the vehicle.



power transfer shaft for the front differential is directly below two of the cupholder mounting holes. To minimize vehicle modifications, four open-end knurled rivet nuts were inserted into the four cup holder mounting holes, which must be expanded to a size of 0.4" to fit. These nuts are secured with a rivet gun, and 1/4-20 cap head screws are used to secure the mounting plate.



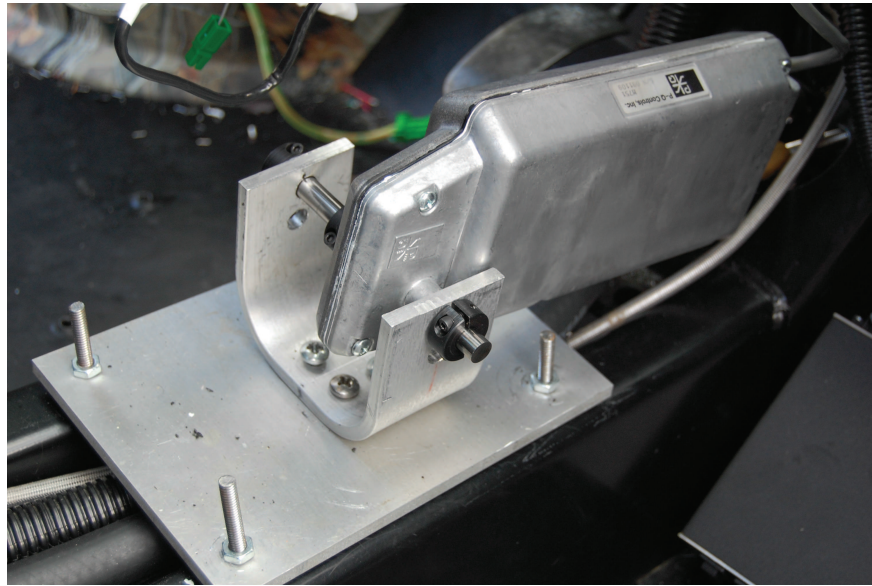
**Fig. 18.** A cross section of the adapter plate for the actuator mount.

The four holes in the middle of the panel are threaded for 1/4"x20 bolts. These allow for the U-bracket to be attached to the mounting plate. This bracket is cut out of a 1/4" sheet of aluminum using the abrasive water jet cutter, with 4 .255" holes for the 1/4-20 bolts which attach it to the mounting plate, and two .380" holes which will be 3.15" above the mounting plate when the bracket is bent.

A 0.375" hardened steel drill blank is fitted through the U-bracket and the mounting hole in the actuator. The drill blank is restrained using two shaft collars, and the actuator is kept from moving side-to-side (and potentially side-loading) using one additional shaft collar.

**Actuating the Pedal Arm** To connect to the pedal arm, the actuator uses a 3/8"x16 threaded rod, which connects to a locked-down split hanger collar (McMaster part #3023T23), held in place by a locknut. The collar uses a delrin bushing to reduce friction on the pedal arm, and to account for any misalignment between the hanger and moving shaft. Since the

PQ Actuators are built with a 7/16"x20 threaded actuator arm, a threading adapter was machined out of a section of brass rod.



**Fig. 19.** A view of the entire accelerator actuator system.

**Performance** Because the return force of the unpowered linear actuator is greater than that of the unmodified diesel pedal return spring, an additional, stronger spring has been added in series, which means the force to fully depress the pedal is 19 now pounds, with an action arm of 6" and a throw of 6", depending on the position of the speed regulator bolt. The return spring mount is only 2.5" long, so the force required to depress the pedal by pushing on the return spring mount is approximately 45.6 pounds. Since our actuator can produce up to 90 pounds of force at a throw of 4", this performance requirement is well within its operating range.

#### 6.4 Steering Actuation

The steering actuation uses a pre-existing power steering assist kit that is modified to meet project requirements. This steering plan is similar to a system prototyped on the summer 2009 research vehicle, the Yamaha Rhino, and is designed by the same manufacturer. The kit required two main modifications: the addition of a more robust controllable motor and the creation of some sort of feedback method from the device. The stock motor from the power steering kit does not provide feedback and lacks sufficient power to control the vehicle in worst case conditions. Both of these issues are addressed by installing a larger motor with a built-in encoder. This solution requires several additional changes to the pre-existing kit:

its position in the gator, the motor attachment to the rest of the power steering unit, and the motor interface with the power steering unit to deliver power.

The motor has to deliver 150 in-lbs at the steering wheel (twice that for a sizable safety margin). The motor is limited also to 5A at 12V to remain compliant with the cRIO 9505 motor controller. The 150 in-lbs requirement was determined through experimental measurement, by turning the steering wheel from left lock to right lock and back while resting on the grass at a standstill. The motor chosen to meet these specifications is provided by Potomac Electric, and has a 4" diameter and a length of 8" with a 5/8" diameter shaft.

In order to rotate the power steering kit into a more favorable position, an adapter plate was designed to fit between the power steering assembly and the brace that attaches it to the chassis. Keeping the motor in the original orientation would have required major modifications to the chassis and dashboard in order to fit the motor.

Inclusion of the larger motor required development of a method for attaching it to the rest of the unit. The original motor attached to the power steering housing through an aluminum heat shrunk collar with through holes for two bolts. The diameter of the new motor made a direct analog unfeasible, requiring design a larger collar which offset the motor enough to allow use of the two existing bolt holes from the previous motor mount. Figure 20 shows this adapter.

The original motor delivered power to the steering kit through a non standard spider coupling, requiring design of a corresponding piece that fits on the new motor. The motor shaft is attached to the new spider coupling with a keyless bushing (Figure 21 shows the new coupling).

When power is cut to the motor the operator has full control of the vehicle and is able to back-drive the motor.

In addition to the various adaptor pieces the motor is secured by a harness on the back of the motor. The harness is shown in Figure 22 and consists of a 4" rubber-coated u-bolt, two machined plates, a threaded rod, and a split clamp hangar which attaches to pole running through the dashboard.

## 6.5 Wheel Encoder Mount System

To provide velocity feedback for vehicle control, the Gator utilizes an optical wheel encoder. The wheel encoder mounting consists of an ANSI 35 sprocket and chain system pictured in Figure 23.

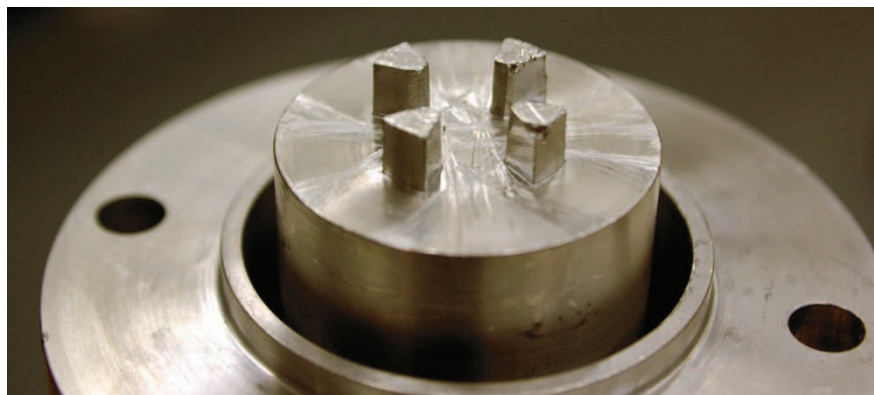
One sprocket is attached to the optical encoder shaft, and the other is driven by the driveshaft located under the utility bed on the right side of the Gator. The driveshaft sprocket was manually split and fitted with socket head cap-screws in order to mount it around the shaft without requiring major disassembly of the Gator platform.

The encoder itself is bolted to a length of steel L-channel, which is in turn bolted to the frame of the gator using a pair of tap rivets. Using a sprocket chain allows the system to accommodate the slight yet inevitable misalignment that results from this assembly.

Because of the tendency of sprocket chain to stretch over time, all sprocket chain systems require some way to dynamically tension the chain. In this system, tensioning is accomplished



**Fig. 20.** Power steering motor mount.

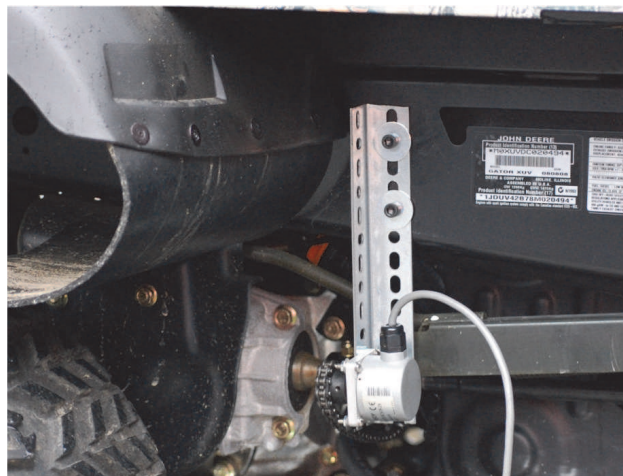


**Fig. 21.** Our manufactured spider coupling adapter mounted on the motor.





**Fig. 22.** Rear of the steering motor with additional support shown

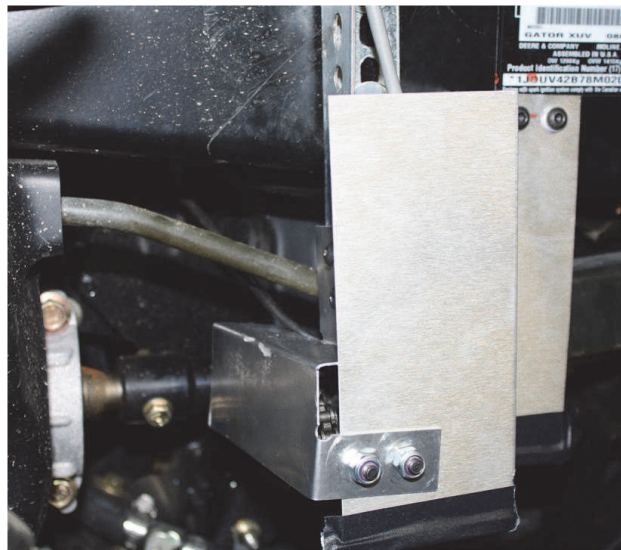


**Fig. 23.** Wheel encoder sprockets and mounts.

through the use of a flexible polymer sprocket ring designed to provide tension to roller chain systems without extra mounting hardware. Because of its natural elasticity, the polymer sprocket ring exerts a radial force on the sprocket chain loop, keeping the chain in tension as it spins.

Since velocity feedback will be derived from the rotary motion of the encoder, it is important to understand the ratio between encoder ticks and vehicle speed. Since the chosen encoder has 500 ticks per revolution and the sprocket system results in 16:9 gear ratio between the vehicle drive shaft and the encoder shaft, the encoder will register approximately 890 ticks per revolution of the drive shaft. There is a one-to-one correspondence between rotations of this shaft and rotations of the tires, which are approximately 23 inches in diameter. Using this as a baseline and calibrating further using fields testing, it was possible to establish a ratio of 3000 encoder ticks per foot of forward vehicle movement.

Since the encoder sprocket chain system is mounted low and on the exterior of the vehicle, it requires additional protection towards the ultimate goal of off-road missions. For this reason, a sheet-metal bash guard was designed and fabricated. The bash guard bolts to both the encoder mount L-channel and the vehicle chassis itself. The fully assembled system is shown in Figure 24



**Fig. 24.** Wheel encoder bash guard fully installed.

## 6.6 Generator Mount

The system's gasoline generator is mounted to the rear of the Gator's utility bed by two standard ratcheting tie-down straps. The straps attach to four 800-pound working load tie-down rings which have been installed in the base of the utility bed. The assembled mounting system is shown in Figure 25.





**Fig. 25.** The generator in its mount.

In preliminary tests on rugged terrain at high speeds, the mount has proven to provide sufficient stability. This mounting system was chosen for its simplicity as well as the ease of install and uninstall should the generator ever need to be replaced or removed for offboard testing. As an added benefit, this mounting scheme allows the preexisting rubber feet on the generator to provide shock absorption and vibration isolation.

## 6.7 Steering Limit Switches

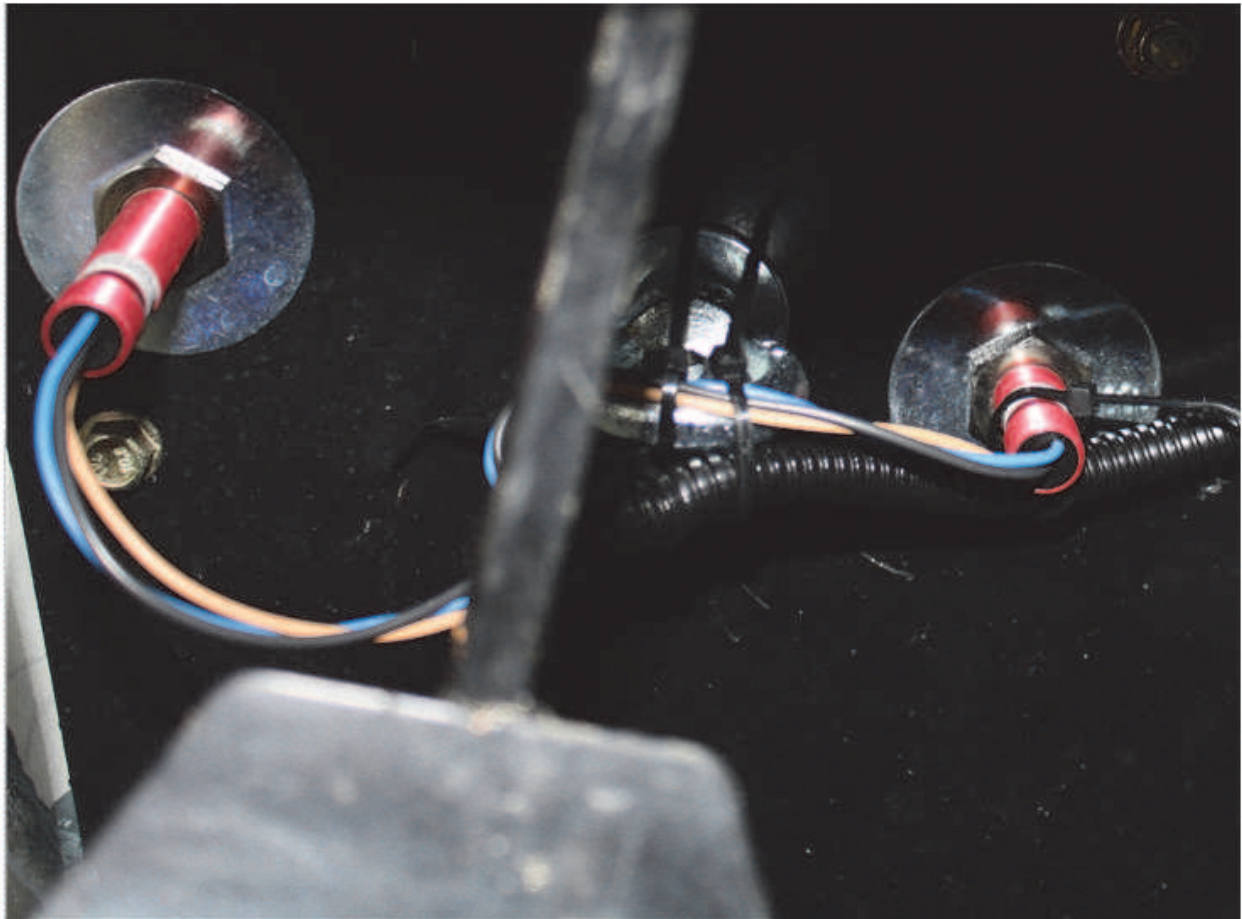
Since the steering motor encoder provides only relative position feedback, it is important to have an absolute measurement of steering position so that the vehicle can automatically calibrate regardless of the positions of the steering at startup. In the Gator AGV, this is accomplished through the use of a pair of magnetoresistive proximity sensors mounted such that the steering rack-and-pinion will trigger one at each mechanical steering endpoint.

The sensors used are Cherry MP100502 Hall Effect sensors, which output 5 volts normally and drop to 0 volts in the presence of a magnetic field of sufficient strength aligned with the sensor. One such sensor is pictured in Figure 26.



**Fig. 26.** A Cherry sensor.

The sensors are mounted through two pass holes drilled through the cab behind the pedals in such a way that the sensing ends are aligned with the steering rack shaft. A cab view of the back ends of the two mounted sensors is shown in Figure 27. The mechanical design of these sensors allows their effective length to be easily adjusted using the built-in clamp nuts, which is important since the effective range of the sensors is quite short and therefore precise axial positioning is required.



**Fig. 27.** Cab view of the back ends of the installed limit sensors.

To provide magnetic pickup points along the steering rack, two 3/8th inch ring clamps are attached to the rack itself, and a small circular magnet is affixed to the end of each clamp. This allows the magnetic pickup points to be easily adjusted, which in turn sets the effective position of each limit sensor as well as the steering range that they encompass. Also note that the Hall Effect sensors are only sensitive to one magnetic pole, so proper orientation of the magnets is important.

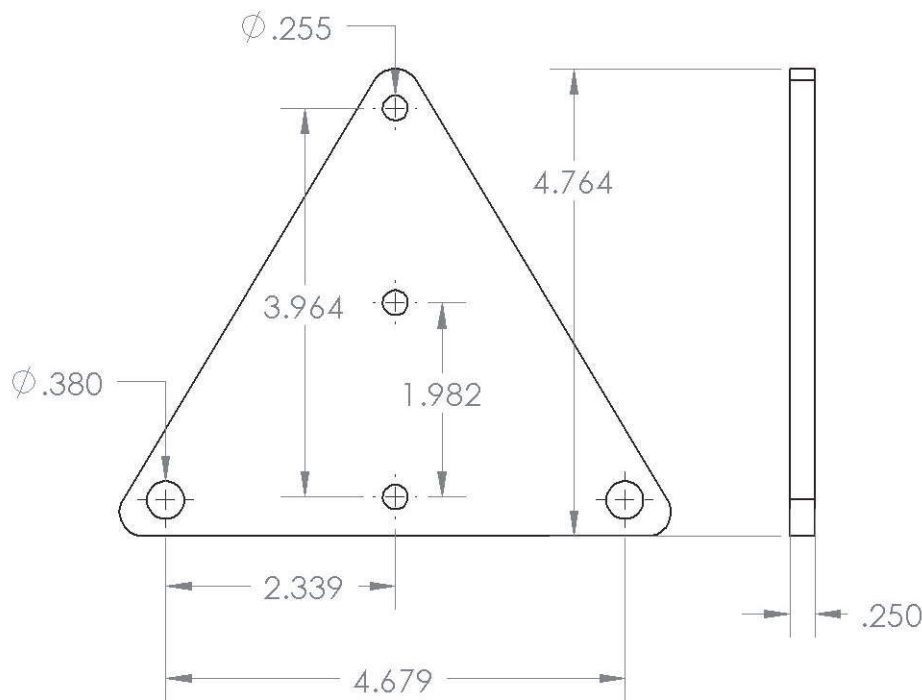
Ideally, the magnetic pickup points are adjusted so that they will trigger the limit sensors precisely inside the mechanical limit of the steering. This allows the automatic steering

calibration routine to run regardless of the initial position of the steering column, as a turn in a certain direction will always hit the same sensor. Additionally, this allows the limit sensors to double as a shutoff triggers if a problem develops with the steering control software during a run, while at the same time preserving the maximum useable range of steering.

## 6.8 Monitor Mount

To mount the Nortec SUN-1710-P daylight-visible monitor in the cab, we replaced the original mounting support, a 1.315" steel bar, with an extended 19" section of steel pipe. This way, the monitor could be mounted using its original mounting hardware: two 1/4"-20 dome head bolts – one to hold the bracket for the monitor, and the second to adjust monitor angle. The mounting holes for these bolts were drilled 6" and 6.5" from the top of the pipe section, so that the monitor would clear the windshield, and to allow for the current mounting of the stereo camera. The latter hole was tapped.

To support the monitor and mounting bracket, a triangular section was waterjet cut from 1/4" aluminum. This plate connected to the steel pipe section via three 1/4"-20 screws, and to two vibration damping clamping hangers (McMaster-Carr part #2615T14) via two 3/8"-16 screws. These hangers clamp on to the exposed 7/8" pipe-section supporting the Gator dashboard.



**Fig. 28.** Monitor mount adapter plate spec. All dimensions are in inches.



Finally, to stabilize the monitor, a 3-11/32" strap hinge was used to connect the pipe to the dashboard. This hinge does not bear any downwards load, but rather stabilizes the monitor against sideways vibrations, and therefore the 1/4" self-tapping screws which connect the hinge to the dashboard are sufficient.

## 6.9 Cabin Wire Routing

There are four areas where cables are routed into the cabin of the Gator. The first two passthroughs are previously existing holes, located behind the driver-side seat and designed for 3/8" conduit. Conduits for communications with the cabin e-stop button and linear actuator are routed through these holes, and follow pre-existing conduits running along the left roll bar of the Curtis cab, with their last zip-tie fastening in the center of the hood, under the dashboard.

The power cables for actuators and steering motor are passed through another pre-existing hole, this one located behind the battery compartment, behind the driver's side seat and directly above the FWD crankshaft located on the passenger side of the vehicle.

The final pass-through is located between the two seats, a half inch above the seatbelt mounting brackets. It is not pre-existing, and is drilled to be 1.45" wide, to allow for a VGA cable for the monitor to be passed through. Conduits for monitor power and signal, as well as USB and IEEE 1394 connectivity and signal from the Cherry magnetic sensors (used as end-stops for steering and located in the driver side firewall) in the cabin are passed through this hole.

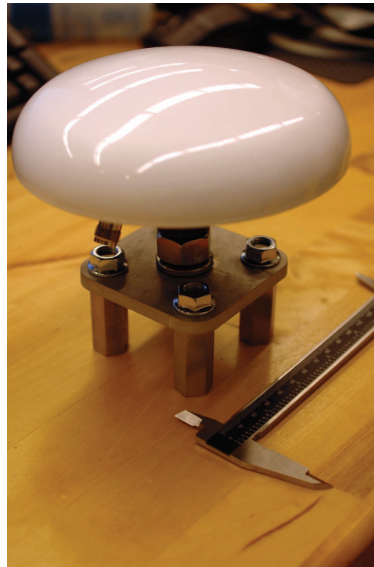
## 6.10 GPS mount

To fulfill our goal of GPS-guided navigation within a parking lot, we needed to mount a GPS antenna. The mount had to be less than 6" in height, as it would have to clear the top of the parking container with 10" of entryway clearance while mounted on top of a roof-mounted pegboard approximately 2" in height.

The GPS mount consists of a 2"W x 2"L x 1/4"T sheet of aluminum drilled to accommodate 4 3/8" holes spaced to correspond with 4 3/8" holes in the pegboard, and one 5/8" hole in the center. Four 3/8"x16 standoffs are used to elevate the plate, to accommodate for the head of a 5/8"x11 bolt which is attached threads-up to the plate using a nut with locking washer. The antenna is designed to screw onto the large bolt and is then held on using a locknut with built-in serrated washer. Altogether, the unit measures approximately 5.5" in height.

## 6.11 Electronics Enclosure Modifications

The electronics enclosure holds all of power and computational electronics, and required three modifications: cooling vents, power and signal wire ports, and a system for mounting the electronics inside the box.



**Fig. 29.** Our GPS Mount.

The cooling system uses two 120mm computer case fans and two weatherproof vent covers (such as those used for hot air exhaust in houses) mounted on two 5" vent holes. These exhaust vents will be weather-sealed during installation using outdoor caulk.

Signal wires are routed out of a third 5" weatherproofed vent on the bottom of the box, as are all power wires.

The electronics plate is designed to be mounted on a supporting frame using several bolts, to reduce plate flexure and potential damage from shocks from rough terrain. The supporting frame is fastened to the sides of the electronics box using screws that have been weatherproofed with silicone sealant.

### 6.12 Electronics enclosure mounting

The electronics enclosure is mounted to the vehicle using two pieces of square channel high tensile steel with corrosion resistant coating bolted to the bed of the vehicle. The box is then attached to the steel with four vibration-damping sandwich mounts allowing for a smooth ride. This simple system is robust and requires relatively little assembly.

## 7 Vehicle Software Architecture

The Gator's software is based on the Olin Intelligent Vehicles Lab's LabVIEW Robotics Operating System (LvROS) developed during the summer of 2009. The architecture is designed for use on a variety of mobile robotic platforms. Substantial resources have been committed to improve the logging/replay and embedded portions of the system. Here a brief overview of the system's goals and code architecture is given, followed by a more detailed examination of