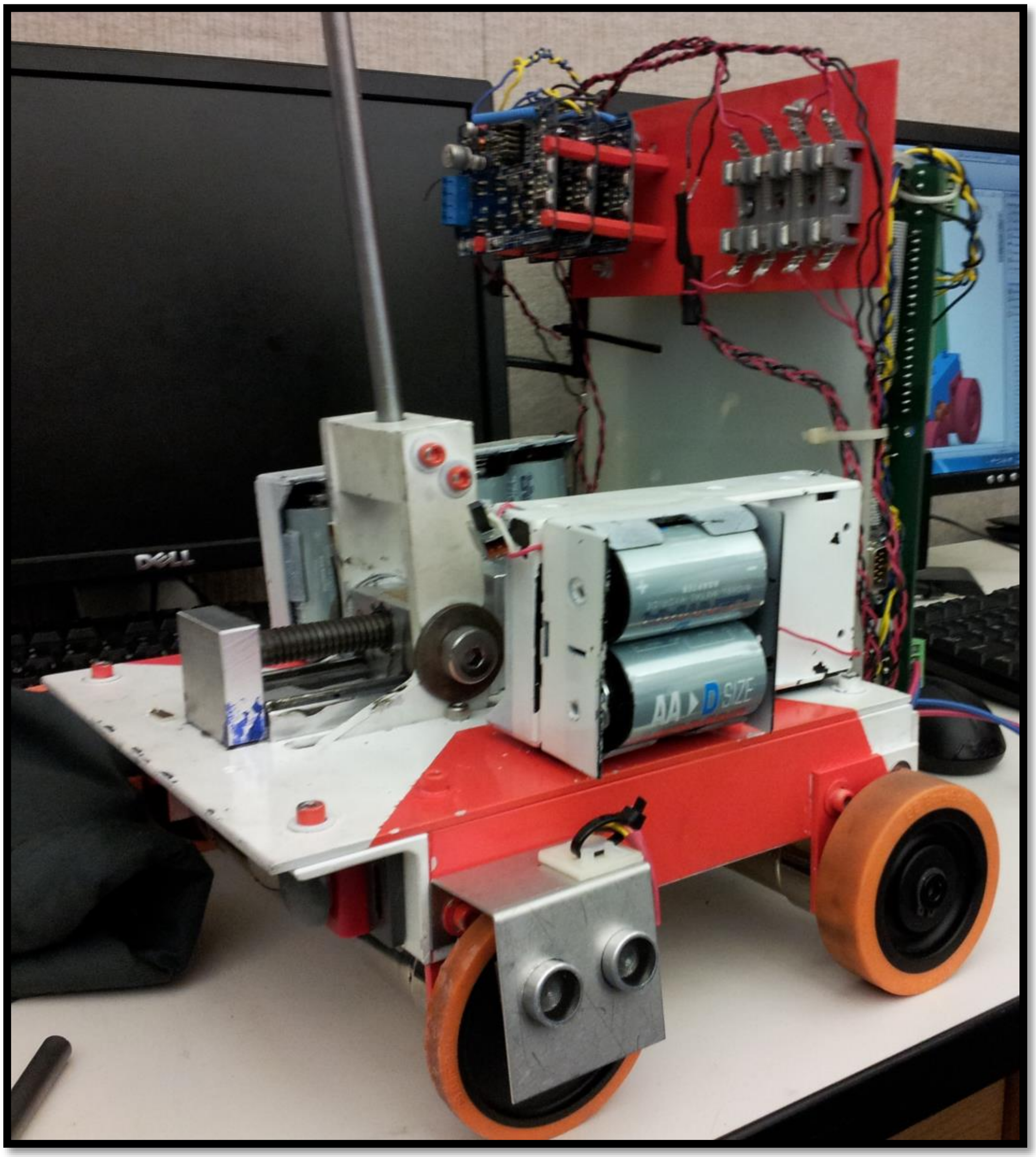
# Motor Sizing Calculations Report
# *Panthra* Bulk Material Transporter

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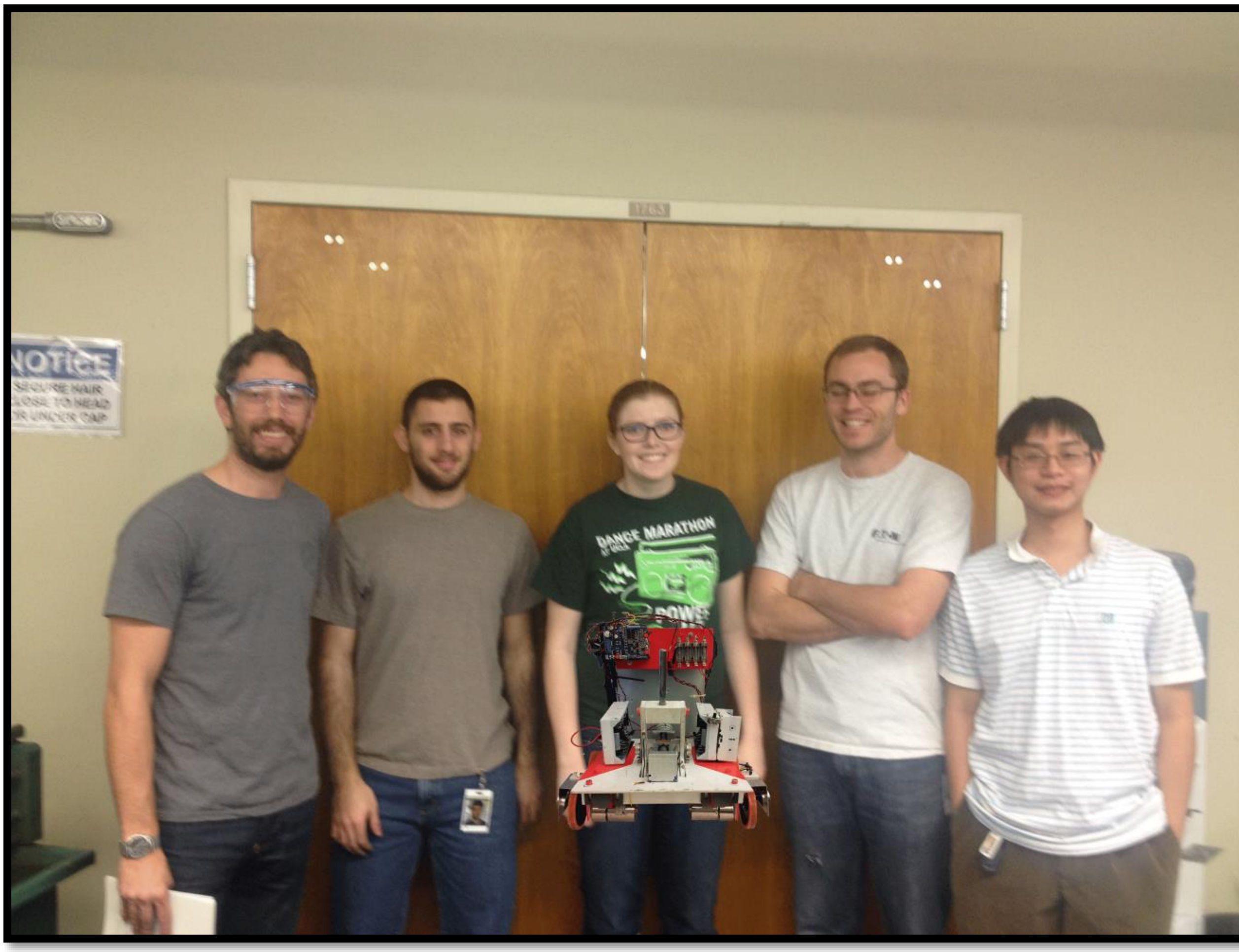


**Figure 1: Team 3 (from left to right: David Walter, Asher Katz, Alex Noe, Chris Underhill, and Wilson Lam)**

# Abstract

The following final report outlines the design of our transporter *Panthra*. We start by outlining the design requirements for our transporter. Then we move on to our first three original designs and analyze the strengths and weaknesses of each, showing why we selected our *Panthra* design. We then go into a more detailed design description about the five subsystems of our transporter: the vehicle delivery system, the payload delivery system, the vehicle support structure, the electronics and control system, and the vehicle sensor array. Next we analyze power requirements for our transporter and the motor sizing requirements. These are calculations that we performed in our first three reports but with the most up to date numbers. We then go into the fabrication and testing of our transporter. . Lastly, we compare our design requirements with our design analysis to conclude that our design is satisfactory.

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| Symbols | Descriptions | Units |
|---|---|---|
| $F_m$ | Gravitational force on the machine | $lb_f$ |
| $M$ | Mass of the machine | $lb$ |
| $N_f$ | Normal force of both front wheels | $lb_f$ |
| $N_r$ | Normal force of both rear wheels | $lb_f$ |
| $L$ | Distance between front wheels and rear wheels | $in$ |
| $L_c$ | Distance between rear wheels and center of mass | $in$ |
| $h_c$ | Height of the center of mass | $In$ |
| $F_{Tf}$ | Tractional force of both front wheels | $lb_f$ |
| $F_{Tr}$ | Tractional force of both rear wheels | $lb_f$ |
| $F_T$ | Total tractional force of all wheels | $lb_f$ |
| $F_N$ | Normal force of payload | $lb_f$ |
| $\mu$ | Coefficient of friction | *unitless* |
| $\theta$ | Angle of incline plane | ° |
| $F_{prop}$ | Propulsion force | $lb_f$ |
| $F_{rol}$ | Rolling force | $lb_f$ |
| $F_{m,v}$ | Vertical weight component | $lb_f$ |
| $F_\mu$ | Friction force | $lb_f$ |
| $F_{inertia}$ | Inertia force | $lb_f$ |
| $\mu_{rol}$ | Coefficient of rolling friction (resistance) | *unitless* |
| $p$ | Drive screw pitch | *rev/in* |
| $e$ | Drive screw efficiency | *unitless* |
| $T$ | Torque | *lb-in* |
| $T_{prop}$ | Propulsion torque | *lb-in* |
| $F_g$ | Gravitational force | $lb_f$ |
| q | Load | $lb$ |
| L | Length | $in$ |
| r | Radius | $in$ |
| R | Resultant force | $lb_f$ |
| $I_x$ | Polar moment of inertia | $in^4$ |
| $\sigma_{yp}$ | Yield stress | *Ksi* |
| KE | Kinetic energy | $lb_f$-*in* |
| G | Modulus of rigidity | *Psi* |
| V | Volume | $m^3$ or $in^3$ |
| $J_L$ | Load inertia | *lb-in-*$s^2$ |
| $J_{ls}$ | Lead screw inertia | *lb-in-*$s^2$ |
| $J_m$ | Motor inertia | *lb-in-*$s^2$ |
| $J_t$ | Total inertia | *lb-in-*$s^2$ |
| $\alpha$ | Angular acceleration | $rad/s^2$ |
| $T_f$ | Friction Torque | *lb-in* |
| $T_{req}$ | Required Torque | *lb-in* |
| g | Gravity | $m/s^2$ |

# 1. Introduction

Our goal is to design, fabricate, test, and demonstrate an autonomous bulk material transporter. The transporter needs to follow a predetermined pathway and dump a payload into a collection bin. We need to come up with an effective, creative solution for this task. The transporter will be composed of two main systems: the drive system and the payload delivery system. The drive system needs to autonomously negotiate the cuverd 90° turns and up to 20° inclined ramps of the set path. Once the transporter reaches the end of the pathway, the payload delivery system must offload the lead disks into a container separated by 3" from the ramp structure. The drive system must then return the transporter to the start of the pathway.

Our budget for this project wass $350, which forced us to put a premium on material salvage and ingenuity. Exotic and specialized materials were off the table due to our budget constraints. We also put a premium on simplicity for our system. Dealing with the intricacies and problems of even a simple robot system proved challenging so we attempted to keep our ideas simple, using basic mechanics and gravity's help to achieve our goal.

We have designated our model *Panthra*. Our three original designs were given Thundercat names, from the 1980's children's TV show. Our final model was a combination of *Panthro* and *Tygra*, so we named it *Panthra* as a combination of the two.

A bulk material transporter of this nature is somewhat state of the art. In the application of transporting radioactive lead disks, previous methods have relied on human operators and individually sealing the contaminated disks in bulky packaging. The materials can then be handled and moved with the same methods of standard hazardous cargo. With an autonomous transporter, humans are removed from the equation, saving material used for containment and packaging as well as the reducing contamination risks of handling hazardous materials. Our design was built somewhat on the shoulders of previous year's successes, but this year we saw a much larger load that required new design considerations.

# Design Requirements

## Objectives & Goals

The objectives and goals of our design are to find a creative solution to the bulk material transporter. We wanted a robot that could achieve all of the high and low level design requirements without looking like the "garbage can on wheels" look of previous years. We also put a priority on speed and power, allowing our machine to make multiple faster runs with a lighter load (3 disks versus 5 or 6).

## Ramp Description

Our vehicle needs to transverse through the following ramp and reach the end to offload the lead disks into a collection bin. To do this we need to make sure we can go through the various slopes and turns of the ramp.

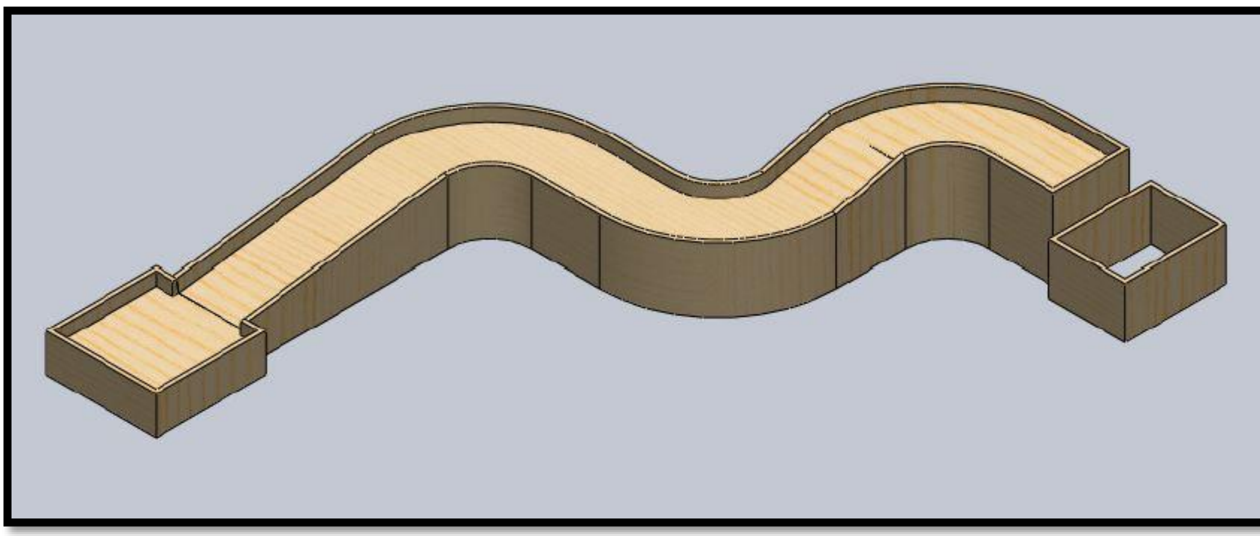


**Figure 2: The Spring 2013 Delivery Ramp**

Ramp description:

- Made of wooden boards
- Unloading collection bin is 3in. from the ramp.
- Slope of 14° for 16" sloped stretch and 7° for 48" sloped stretch
- Track width is 16" throughout
- Track has a total height change of 10"
- Starting box is 24" by 24"
- Unloading box is 16" by 24"
- Wall height is 3" throughout

Further dimension details are listed in the figure below.

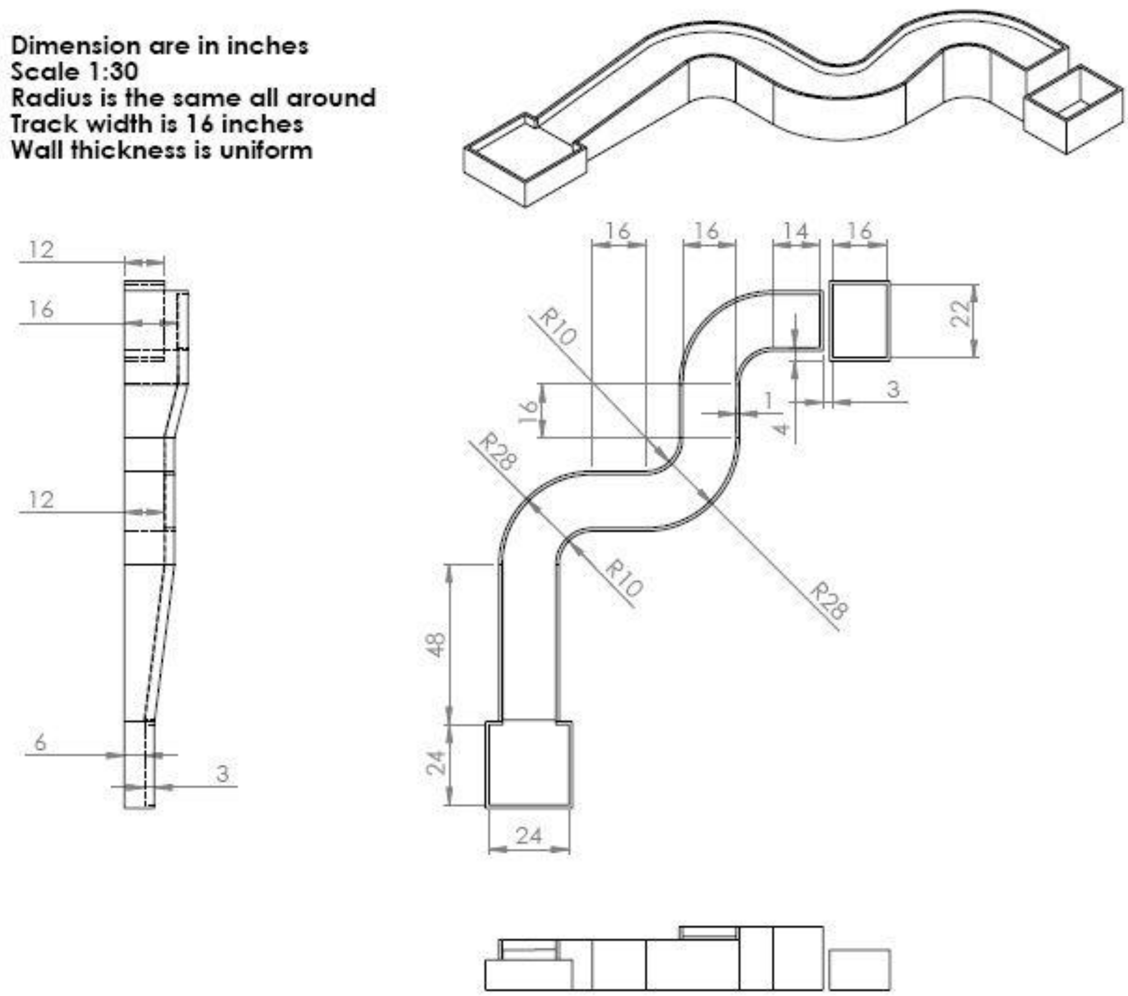



**Figure 3: Ramp dimension details [6]**

## High Level Design Requirements

The High Level Design Requirements are requirements that our team must adhere to. These type of requirements are what base the project, as in our projects low level designs will be based off the needs to satisfy the high level designs. The high level designs are as follows [7]:

1. Device must be no larger than 12x12x16 inches when fully assembled.

2. Vehicle may only be powered using ordinary and readily available rechargeable or disposable batteries. Battery types should not be mixed. Battery packs may be used as long as they comply with the requirements, and can easily be checked by the judges.

3. Disposable battery limit: 10 1.5 V (AAA,AA,C,D) and 3 9 volt batteries, making a total of 13 batteries.

4. Rechargeable battery limit: 12 1.2 V and 3 9 volt, making a total of 15.

5. No other power sources may be used, i.e. hydraulics, combustion and so on.

6. All powered devices must have a clearly labeled and readily accessible emergency kill switch to shut off the device.

7. 1 on/off switch may be installed, and can only be used in the starting/loading area.

8. Budget is 350 $, no outside money may be used, all receipts must be accounted for.

9. Ramp has set dimensions as stated in "Ramp Description" above, these are predefined and cannot be changed.

10. The payload will consist of a minimum of 3 lead discs, about 6 lb. each. The discs have predefined dimensions, outer diameter of 6", inner diameter of 25/64" and a thickness of 0.5".

11. Run time is 10 minutes for the demonstration with a 5 minute set up time. For the competition, run time is 5 minutes and set up time is 2 minutes.

## Low Level Design Requirements

The following are our groups design requirements that our team created to guide our decision making during the conceptual phase:

1. Deliver 3 disks per run (approx. 18 lb.)

2. Make a complete run in 45 seconds, requiring a speed of approximately 0.5 – 1 m/s, accounting for maneuvering time.

3. Simplicity in design - using gravity to aid in the delivery systems rather than battery powered sources or complicated sources.

4. Ability to reset payload delivery system for return trip (a bonus if done on the move)

5. Aesthetically appealing (attempt to avoid the trashcan on wheels look of previous years)

6. Use reusable batteries for practice runs to save money, and then use disposable batteries for the final runs and competition.

# 2. Design Description

## Design Concept Development

Through our initial team brainstorming we came up with three individual drive systems and three payload delivery systems. For our drive systems we have the three following:

**Three Wheels**: For this concept we have two drive wheels in the front with an unpowered omni-directional wheel in the back.

**Tracked**: This model uses a tank track system. These systems commonly have two motors, but sometimes have four.

**Four Wheels**: For this concept we have four drive wheels at each corner of the vehicle.

For each of these, no steering system is incorporated. Instead each uses a rotating method to turn where the left and right side drive system (wheels or tracks) spin in opposite directions. This should simpify our drive system and give us the option for 4WD.

The challenge in the payload delivery system is to find a method to transfer the plates across the 4" gap between the ramp and container. For the delivery system we have the following three ideas:

**Rear Door/Ramp:** In this method, the plates can be stored sideways and the rear door with a bottom hinge descends. Once descended, the door is now a ramp that the plates roll down into the container.

**Spindle Arm:** In this method, the plates are stored flat, secured with a vertical tube (spindle) running through their middle attached to a horizontal arm. In order to deliver, the arm extends. The spindle then rotates and the plates slide down the spindle into the container.

**Retractable/Extending Rear Ramp:** In this method, a ramp extends from the vehicle, down which the plates slide or roll. The plates can be secured in place with a rear door with a top hinge.

The intitial design concepts are combination of these different drive and payload delivery systems.

### Vehicle Type 1: - *Cheetara*- Three Wheeled with Rear Door/Ramp

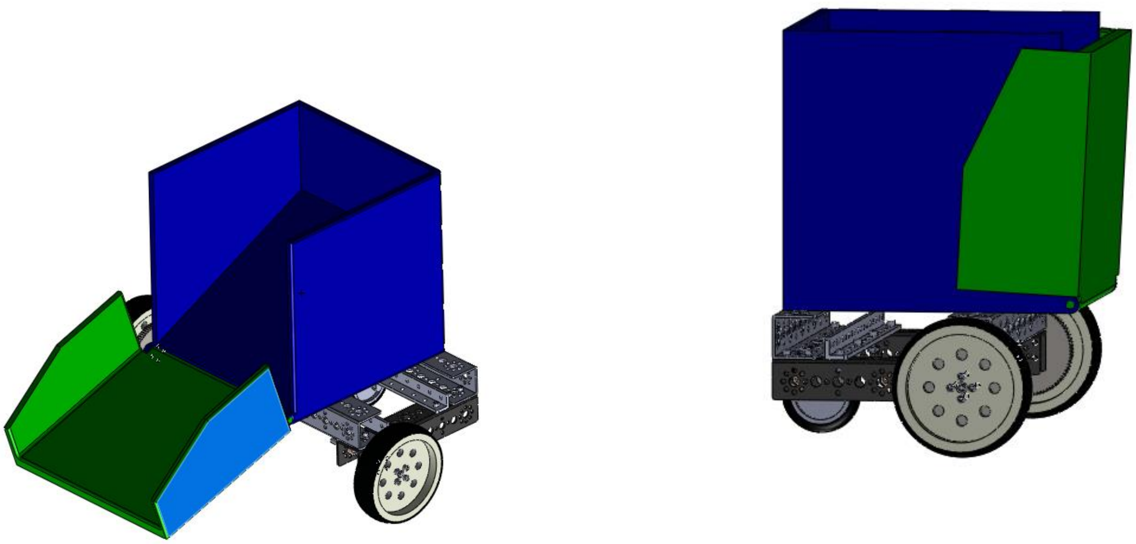


**Figure 4: *Cheetara* conceptual design**

The advantage of this vehicle lied in its simplicity. Its drive system relies on only two motors with a third non-drive multi-directional wheel. Because of the resulting small vehicle footprint, maneuverability should be improved as well. The payload delivery systems when under load is operated with the help of gravity (door opening downward), using it to help the plates down the ramp.

The disadvantages lie in its payload. With only two motors, the vehicle may not have enough power to deliver plates as quickly as needed. This might be solved with more powerful motors. Another issue with the bottom- hinged door is releasing the locking mechanism while loaded (with plates resting against the door). This may be solved with some creative engineering.

**Vehicle Type 2: - *Panthro* - Tracked with Spindle Arm**

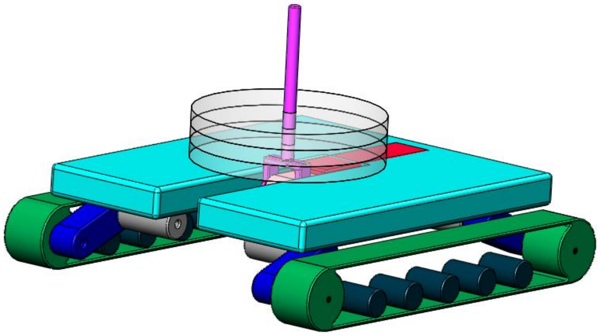


**Figure 5: *Panthro* conceptual design**

The advantage of this vehicle was in its payload and aesthetics. If provided four motors, it should have enough power to deliver a large payload with the high traction rubber tread. Speed may be a decisive factor. The spindle arm greatly improves aesthetics, giving the appearance of a true vehicle transporter and less that of a garbage can with wheels.

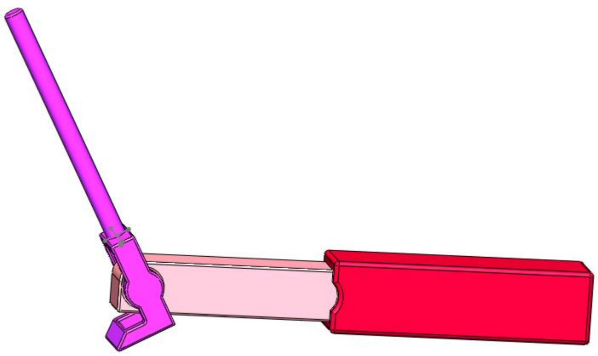


**Figure 6: Detail of *Panthro's* payload delivery system**

The delivery arm is the challenge in this design. The concept seen above has the ability to lock vertically when in the retracted position and then rotate to a downward angle when extended. Appropriate material and shapes that can handle the moment exerted by the three disks will require research and prototyping.

The disadvantage is the complexity. Timing the four motors may add difficulty. Most of the complexity is in the spindle arm along with the obvious counterbalance issues – as the arm extends out the vehicle may tip. This can possibly be solved with an extending pivot from the arm and some engineering ingenuity.

**Vehicle Type 3: -*Tygra* - Four Wheeled with Extending Rear Ramp.**

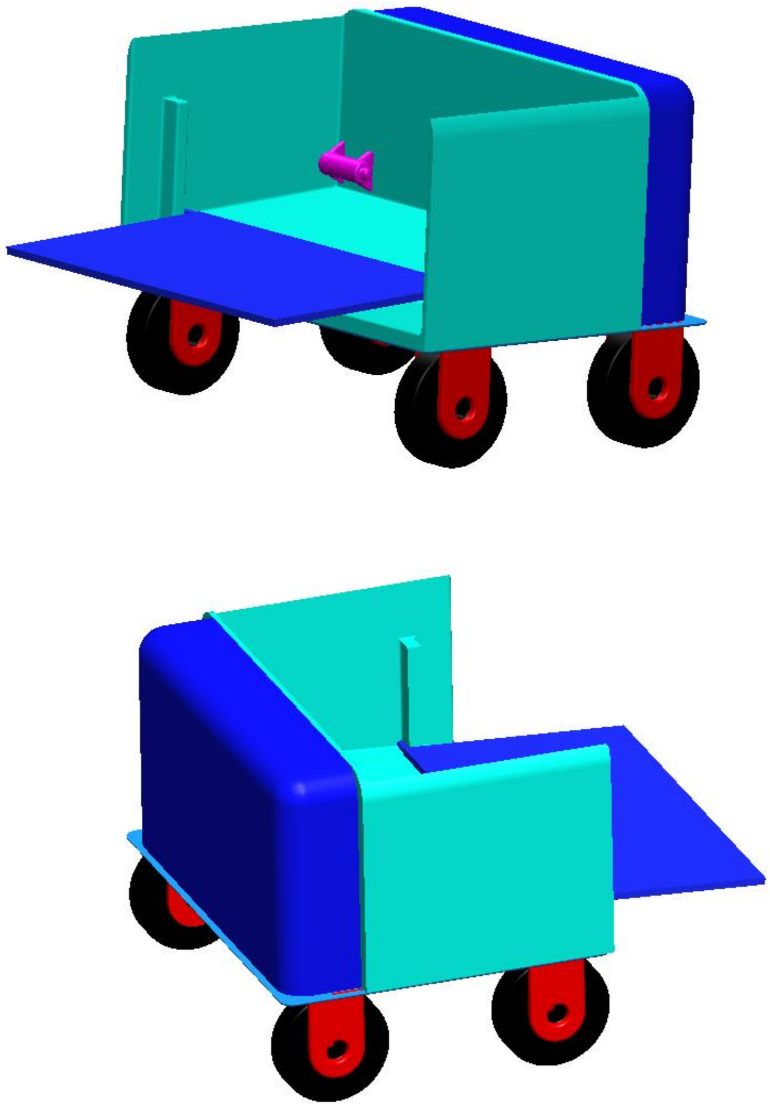
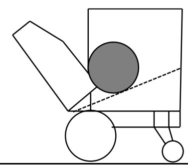
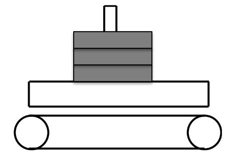
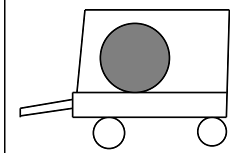


**Figure 7: *Tygra* conceptual design**

The four-wheeled drive system appeared a safe bet having been the winning choice for previous year's competitions. The payload delivery system only includes the moderately complex retractable ramp. By having a top hinged rear door to secure the plates, the reset of the system is aided by gravity. The design here is shown without the top hinged door, using instead a lock down system to secure the load.

The disadvantage is the lack of aesthetics and some complexity with the retractable ramp. One option is to retract the ramp horizontally into the hull, while another is to rotate back into its initial position (similar to the *Cheetara*) design.

**Table 1: Concept Design Tree**

| **Sub-function** | **Carrier** | **Task** | **Principle of Evaluation** | **Weight Factor** | **Type 1** ***Cheetara***  | **Type 2** ***Panthro***  | **Type 3** ***Tygra***  |
|---|---|---|---|---|---|---|---|
| Speed | Drive System | Optimal number of motors | Ability to perform run in <1 minute. Target speed of approx.. 0.5 – 1.0 m/s | 0.20 | 1 | 3 | 3 |
| Maneuverability | Frame, Drive System, Steering Method | Optimal form for vehicle. | Ability to maneuver track quickly and efficiently, maintaining sensor tracking as well as turn around. | 0.15 | 3 | 2 | 2 |
| Payload | Frame Suspension Motors Battery Pack | Optimal drive system and battery pack and frame. | Number of plates per run, ability to complete multiple runs | 0.18 | 1 | 3 | 3 |
| Simplicity | Wheels, Handlebars | Minimal Complexity | Simple methods to move vehicle and deliver payload, ease of troubleshooting | 0.11 | 3 | 1 | 2 |
| Creative Evaluation | | | | 0.09 | 1 | 3 | 1 |
| Cost Evaluation | | | | 0.18 | 2 | 2 | 2 |
| Aesthetic Evaluation | | | | 0.09 | 1 | 3 | 2 |
| Weighted Totals | | | | 1.0 | **1.70** | **2.27** | **2.29** |
| Order of Merit | | | | | **3rd** | **2nd** | **1st** |

Notes:
-Evaluation Marks:  0 - Unacceptable, 1 : Acceptable, 2 : Good, 3 : Optimal
-See Pair Wise Comparison Chart below for weighted scores.

**Table 2: Pair-Wise Comparison Chart**

| Subfunction | **Speed** | **Maneuverability** | **Payload** | **Creativity** | **Cost** | **Aesthetics** | **Simplicity** | **Total** | **Weight** |
|---|---|---|---|---|---|---|---|---|---|
| **Speed** | 5 | 8 | 5 | 8 | 4 | 8 | 6 | 44 | 0.20 |
| **Maneuverability** | 2 | 5 | 4 | 7 | 4 | 7 | 4 | 33 | 0.15 |
| **Payload** | 5 | 6 | 5 | 7 | 4 | 7 | 6 | 40 | 0.18 |
| **Creativity** | 2 | 3 | 3 | 5 | 2 | 5 | 4 | 20 | 0.09 |
| **Cost** | 6 | 6 | 6 | 8 | 5 | 8 | 7 | 39 | 0.18 |
| **Aesthetics** | 2 | 3 | 3 | 5 | 2 | 5 | 5 | 20 | 0.09 |
| **Simplicity** | 4 | 6 | 4 | 3 | 3 | 5 | 5 | 25 | 0.11 |
| | [Factor Scale: 10 – each vote counts 2 points] | | | | | | Totals: | 221 | 1.00 |

| | Design Scores: [out of 3] | | | Weighted Design Scores: | | |
|---|---|---|---|---|---|---|
| | **Type 1** | **Type 2** | **Type 3** | **Type 1** | **Type 2** | **Type 3** |
| **Speed** | 1 | 3 | 3 | 0.20 | 0.60 | 0.60 |
| **Maneuverability** | 3 | 2 | 2 | 0.45 | 0.30 | 0.30 |
| **Payload** | 1 | 2 | 3 | 0.18 | 0.36 | 0.54 |
| **Creativity** | 1 | 3 | 1 | 0.09 | 0.27 | 0.09 |
| **Cost** | 2 | 2 | 2 | 0.35 | 0.35 | 0.35 |
| **Aesthetics** | 1 | 3 | 2 | 0.09 | 0.27 | 0.18 |
| **Simplicity** | 3 | 1 | 2 | 0.34 | 0.11 | 0.23 |
| | | | | 1.70 | 2.27 | 2.29 |

| | |
|---|---|
| Type 1: | 3 wheel (2 powered) vehicle with bottom hinge rear ramp to deliver items. |
| Type 2: | Tracked vehicle with spindle arm to deliver weights |
| Type 3: | 4 wheel (4 powered) vehicle with retracting rear ramp and top hinge. |

Note: Each team member is given two votes to choose their favorite vehicles

**Final Design**

From our pairwise comparison and analysis, both the *Panthro* and *Tygra* scored very high. We decided on a combination of these two vehicles, designated *Panthra*. It would feature the payload delivery system of the *Panthro*, with the simpler, higher power drive system of the *Tygra*.

Though the spindle arm concept is more complicated that a simple "dump truck" style design, we thought the creativity and aesthetics gave our the design a distinct advantage over the others. The final design of the actual spindle arm has evolved through multiple iterations.

## Design Overview

The final design we came up with is called *Panthra* which is the combination of Panthro and Tygra as described above. The decision was base objectively on design uniqueness and power. The Panthro's spindle arm design was consider unique making it one of our most valued options for the unloading mechanism. The driving system was chosen based on torque power. The four wheel base direct drive provided the most torque without as much friction when compare to the track system. The diagram below shows our final design.

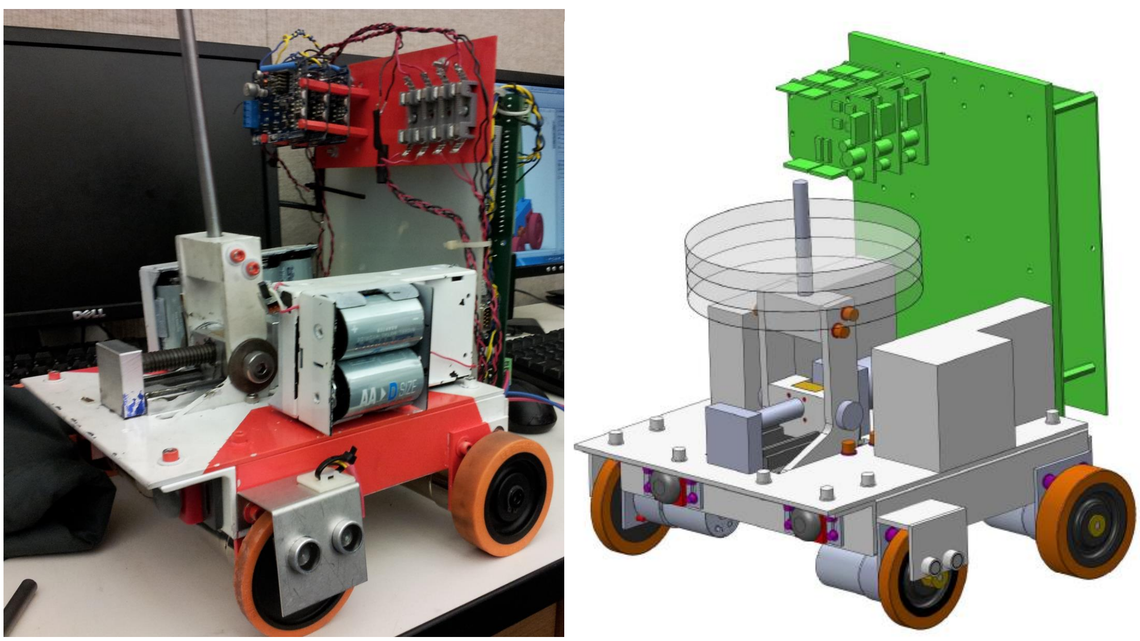


**Figure 8: Panthra final design physical design (left) Solidworks model (right).**

There are three main systems that help the device operate successfully when tested. There are more subsystems as described later but the main systems are the vehicle drive system, payload delivery system, and electronics and control system. During the motion up the ramp the four motor directive drives provide the necessary torque to drive up the ramp. Once reaching the end the payload delivery mechanism comes into pay and unloads the lead disks. This payload delivery mechanism move down and let the disk slip pass the receiver box edge during unloading. Throughout this process the whole vehicle is under the control of the electronics and control system. This system collects data from the sensors, process the data using pre-installed labview code, and transmit actions to the corresponding motors. This collection, processing, and transmission of data control the motors speed and direction.

## Systems Specifications

The following are our groups actual low level design requirements that are met by our physical transporter:

1. Deliver 3 disks per run. We can do 4 discs per run, but our time and steering is better with 3 discs so we've chosen to stick with that.

2. We make a complete run in about 70 seconds. This includes going up the ramp, delivering the load, turning around, going down the ramp, turning around again, and waiting for the discs to be reloaded. We are hopeful that we can do 4 runs in the 5 minutes we have for the competition (the last run doesn't need to wait for the discs to be reloaded which saves about 10 seconds).

3. Simplicity in design – our delivery arm works perfectly, and we take advantage of gravity (so that our discs slide off the arm without extra force).

4. We raise our delivery arm a little bit before we turn around. The delivery arm rises to its full reset position on the way down the ramp, which saves about 10 seconds.

5. Our robot looks very clean cut, basically a plate on wheels with our spindle arm. Unfortunately our batteries had to be mounted on the top plate which doesn't look as nice as we'd like, but the paint job makes it look more aesthetically appealing.

6. Throughout the quarter we have been using our own personal rechargeable AA batteries so save money. We will be using fresh disposable D batteries for the competition.

## Overall System Design

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 1 | VEHICLE SUPPORT STRUCTURE | 1 |
| 2 | 2 | ELECTRONICS AND CONTROLS SYSTEM | 1 |
| 3 | 3 | VEHICLE DRIVE SYSTEM | 1 |
| 4 | 4 | PAYLOAD DELIVERY SYSTEM | 1 |
| 5 | 5 | VEHICLE SENSOR ARRAY | 1 |
| 6 | Lead Disk weight 5.75lb | LEAD DISC, 5.75LBS, 6" DIAMETER | 3 |

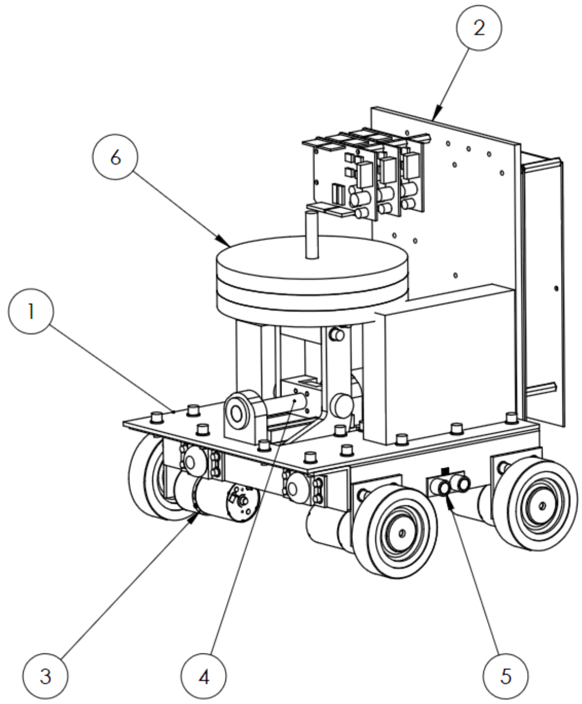



**Figure 9: Subassembly overview**

### Vehicle Drive System (VDS)

The VDS consists of 4 Tetrix Motors and 4 wheels. The two motors on each side will be run in parallel off of one motor driver. One motor driver will then control the left side motors with the other controlling the right side motors. There is no mechanical steering, the vehicle instead utilizes skid steering to turn.

### Payload Delivery System (PDS):

The PDS is composed of a lead screw drive system connected to a swinging spindle arm that carries the lead disks horizontally with a vertical shaft through their center holes. To offload, the lead screw moves the device forward, which is lowered steadily through a mechanical cam-roller to a below horizontal position. The retract, the lead screw reverses, the cam-roller action self rights the spindle arm. The curved portion of the spindle arm responsible for the self righting has been designated *The Fang* due to its sharp tooth-like appearance.

### Vehicle Support Structure (VSS)

This is the primary load distribution system onto which the other systems are mounted including wheels, motors, sensors, etc.

**Electronics and Control System (ECS)**

The ECS systems includes the National Instruments SBRio, motor drivers, as well as the battery packs.

**Vehicle Sensor Array (VSA)**

The VSA includes two front push sensors and two lateral ultrasonic sensors pointed outward from the left and right sides.

## Mechanical and Control System Operation

**Driving**: our drive system results in four powered wheels utilizing skid steering to turn. This requires a small wheel base and front wheels with lower friction. The motors are controlled through motor drivers using digital inputs for direction and pulse width modulation (PWM) for speed.

**Lane Control:** Our preliminary idea for lane control is utilizing two ultrasonic sensors on the left and right (possibly oriented forward oblique). These sensors have a minimum range of 3cm, but with the current width of our vehicle, we should maintain approximately 6-8 cm between the sides of the vehicle and the lane edge.

**Triggering Offload:** We plan on using two touch sensors on the front of the vehicle to recognize the end of the track. When the push sensors are compressed the spindle arm will unload the disk. During this process the control systems run the motor until the spindle is position at an angle. The motor will stop its motion when the SB-Rio reads a current from the closed switch the spindle creates at its unloading position. Afterward, we will be turning the vehicle around for the return trip.

**Spindle Arm:** In this method, the plates are stored flat, secured with a vertical tube (spindle) running through their middle attached to a horizontal arm. The Spindle Arm will extend forward using a power screw and motor. We have worked significantly on an arm design that only requires one linear actuator (all rotation occurs mechanically with gravity). Our current design, utilizing *The Fang*, mechanically eases the spindle into the down position and the uses a cam-roller system to return the spindle into the upright position on retraction. A significant challenge, though, is the difficulty in machining these parts, particularly *The Fang*.

# 3. Subsystems Design Description

The following is a more detailed description of the Vehicle Subsystems:

1. **Vehicle Drive System (VDS)**

a. As mentioned above, vehicle drive system is made up of 4 Tetrix 12V motors with stock

Tetrix gearboxes connected to Bane Bot 2.875" wheel. The motors' output is determined by the Electronics and Control System (ECS).

b. As shown in the following motor sizing section, the 4 tetrix motors should provide ample power to propel the *Panthra* up the ramp under a 3 disk load in the desired time.

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 3-101 | TETRIX DC MOTOR | 4 |
| 2 | 3-003 | BANEBOTS 2.875" WHEEL | 4 |
| 3 | 3-004 | AXLE SET COLLAR | 4 |
| 4 | 3-005 | MOTOR MOUNT PLATE | 4 |
| 5 | #4-0.75L | #4 SOCKET CAP SCREW | 16 |
| 6 | #4ss-0.25L | #4 SET SCREW | 4 |
| 7 | M3x0.5-0.375L | M3X0.5 SOCKET CAP SCREW | 8 |
| 8 | #4 WASHER | #4 FLAT WASHER | 16 |
| 9 | M3 WASHER | M3 WASHER | 8 |

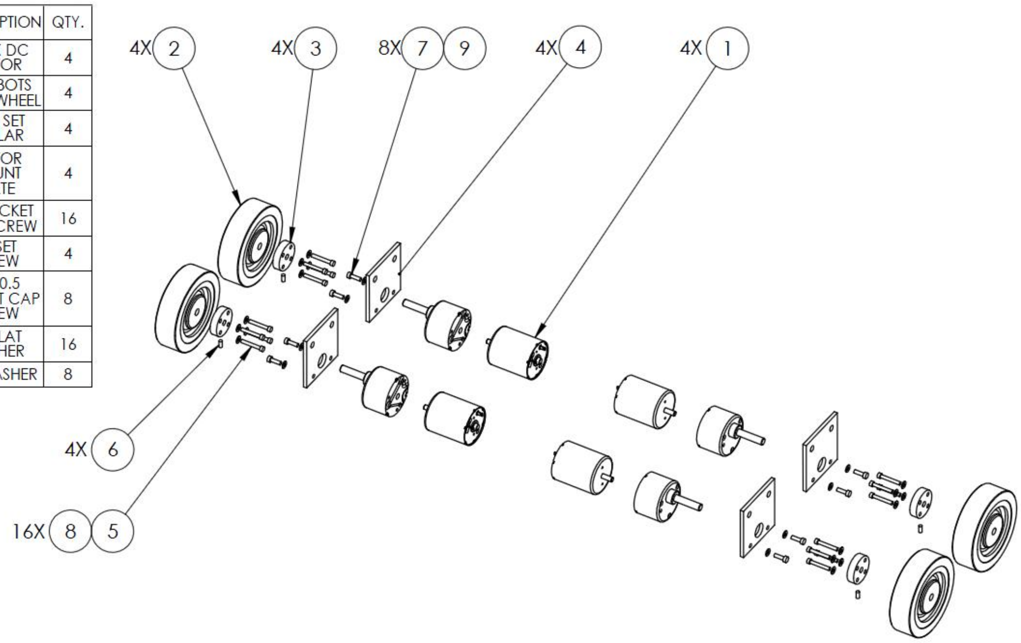



**Figure 10: Vehicle Drive System Subassembly Exploded View**

## 2. Payload Delivery System (PDS)

a. The PDS is made up of a Henkwell 12V DC motor connected to a lead screw. The spindle arm sits on a hinge connected on the lead screw, utilizing *The Fang*, a curved aluminum cam connected to a roller on the body of the vehicle. When the lead screw activates, *the Fang*, lowers the spindle arm in a controlled, static, until the arm is below horizontal. At this point, the lead discs slide off of the spindle arm into the receiving container below.

b. The spindle arm itself must be a strong enough material to not deform under the load of the lead discs while being narrow enough in diameter to fit into the disc center hole. By lowering the system in a static manner, we prevent kinetic energy from accumulating and having to be absorbed by the spindle arm and *Fang*.

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 4-010 | PAYLOAD CARRY ARM | 2 |
| 2 | 4-011 | PAYLOAD SPINDLE | 1 |
| 3 | 4-012 | SPINDLE MOUNT | 1 |
| 4 | #10-0.5L | #10-24 SOCKET CAP SCREW, 0.5" L | 4 |
| 5 | #10 WASHER | #10 FLAT WASHER | 4 |
| 6 | 4-102 | HENNKWELL DC MOTOR ASSEMBLY | 1 |
| 7 | 4-005 | 1/2"-10 LEAD SCREW NUT | 1 |
| 8 | 4-009 | LEAD SCREW NUT MOUNT | 1 |
| 9 | #4-0.75L | #4 SOCKET CAP SCREW | 4 |
| 10 | 4-001 | LINEAR ACTUATOR SLIDE | 2 |
| 11 | 4-002 | DRIVE SCREW BEARING MOUNT | 2 |
| 12 | 4-003 | DRIVE SCREW BEARING | 1 |
| 13 | 4-004 | ROLLER MOUNT | 2 |
| 14 | 4-006 | ROLLER | 1 |
| 15 | 4-007 | 0.5" SHOULDER SCREW | 2 |
| 16 | 4-008 | 0.5" LEAD SCREW, 4"L | 1 |
| 17 | .25-3.0L | 0.25" SOCKET CAP SCREW | 1 |
| 18 | .25 WASHER | 0.25" WASHER | 1 |
| 19 | 0.25-NUT | 0.25" HEX NUT | 1 |

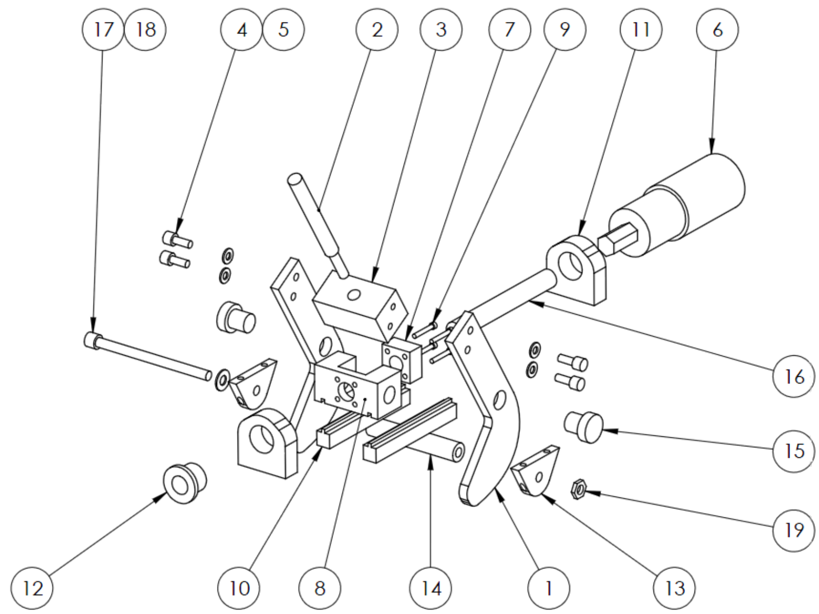



**Figure 11: Payload Delivery System Subassembly Exploded View**

### 3. Vehicle Support Structure (VSS)

a. The VSS consists of 4 aluminum L beams with a rectangular aluminum plate sitting flat on top.

b. The VSS distributes the load of all the mounted systems to maintain a center of gravity within the wheelbase of the vehicle. The VSS must also fit all components within the required dimensions as stated in the higher level requirements.

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 1-001 | CHASSIS | 1 |
| 2 | 1-002 | L-CHANNEL SUPPORT, SIDE | 2 |
| 3 | 1-003 | L-CHANNEL SUPPORT, FRONT | 1 |
| 4 | 1-004 | L-CHANNEL SUPPORT, REAR | 1 |
| 5 | #10-0.5L | #10-24 SOCKET CAP SCREW, 0.5" L | 12 |
| 6 | #10-NUT | #10 HEXNUT | 12 |
| 7 | #10 WASHER | #10 FLAT WASHER | 12 |

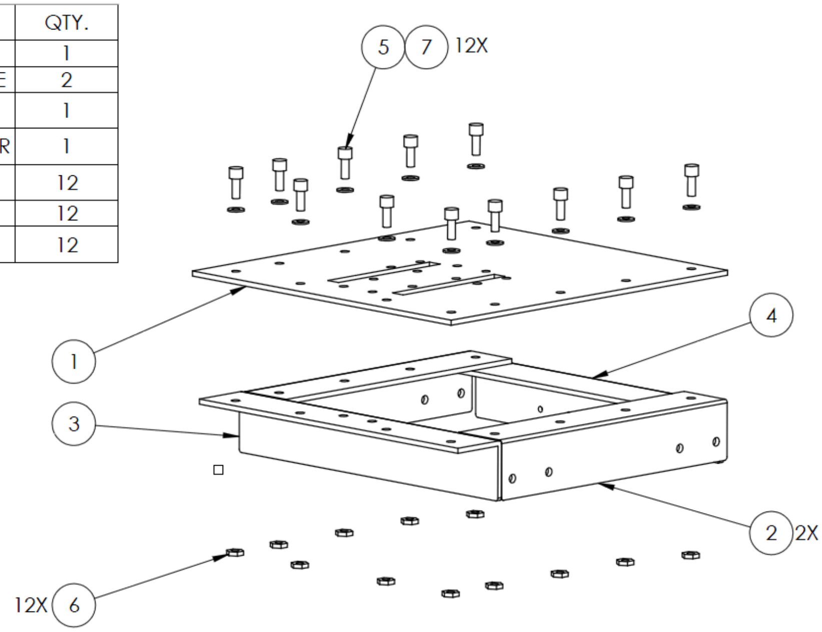



**Figure 12: Vehicle Support Structure Subassembly Exploded View**

### 4. Electronics and Control System (ECS)

a. The ECS consists of the National Instruments sbRIO, 3 Cytron motor controllers, the sbRIO battery pack, the batteries to power the VDS and PDS, and the voltage regulators to

b. The ECS must fit with the dimensional constraints, as well as provide the necessary amperage to drive the VDS.

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 2-101 | SB RIO ASSEMBLY | 1 |
| 2 | 2-006 | SB RIO BATTERY | 1 |
| 3 | 2-007 | BATTERY PACK, (4) D SIZE | 1 |
| 4 | 2-008 | BATTERY PACK, (6) D SIZE | 1 |
| 5 | 2-009 | CYTRON DC MOTOR CONTROLLER | 3 |
| 6 | 2-010 | BREADBOARD | 1 |
| 7 | #4-STANDOFF | HEX STANDOFF | 6 |

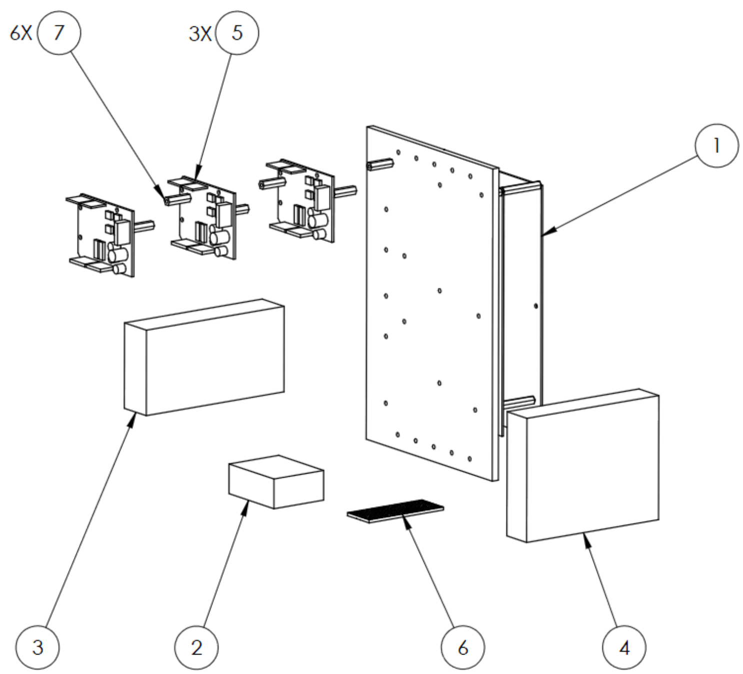



**Figure 13: Electronics and Control System Subassembly Exploded View**

## 5. Vehicle Sensor Array (VSA)

a. The VSA consists of 2 push sensors on the front of the vehile and 2 ultrasonic sensors – one on each side. When the vehicle reaches the end of the ramp the front push sensors are depressed, triggering offload. To trigger offload, the ultrasonic sensors must also be reading a close distance, indicating the vehicle is in the offload area and the push sensors were not accidently depressed during a turn.

b. The ultrasonic sensors must be able to detect a mimum distance of approximately 2 cm, so the lane control system can operate with in the 16" wide track. If necessary, the ultrasonic sensors can be mounted closer to the centerline of the vehicle to stay within the minimum sensor range.

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 5-001 | VEX BUMPER SENSOR | 2 |
| 2 | 5-002 | ULTRASONIC SENSOR | 2 |

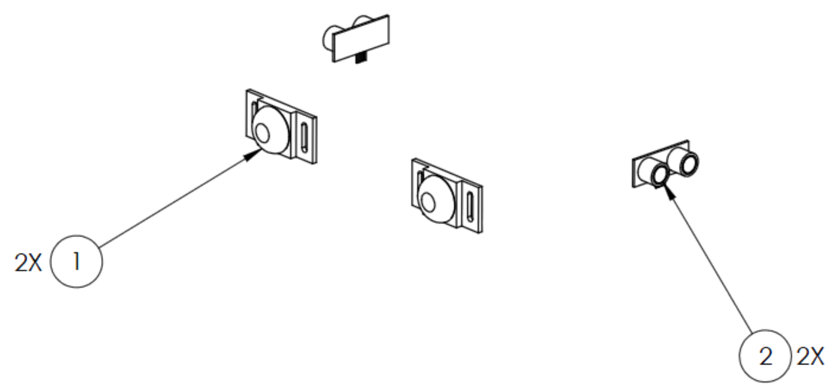



**Figure 14: Vehicle Sensor Array Subassembly Exploded View**

# 4. Design Analysis

## Power Requirements and Motor Sizing

### Part 1: Components Mass

The dimensions of our transporter are 12.0 in long x 12.2 in wide x 11.8 in tall. We are estimating that we will be able to carry 3 disks at a time. Including these in our model, our center of mass is located at (4.29 in, 5.37 in, 6.55 in). These distances are measured from the origin, which is aligned with the bottom of the wheels, the axel of the rear wheels, and the outer edge of the wheel. We have decided to use all wheel drive for our drive system.

**Table 3: List of components**

| Component | Weight (lb) | Multiplier | Total (lb) |
|---|---|---|---|
| Surface Plate | 1.57 | 1 | 1.57 |
| L-Channel | 0.37 | 2 | 0.74 |
| Wheel | 0.14 | 4 | 0.56 |
| Motor | 0.38 | 4 | 1.52 |
| Electronics | 1.88 | 1 | 1.88 |
| Batteries | 2.94 | 1 | 2.94 |
| Electronics Battery | 0.63 | 1 | 0.63 |
| Back Plate | 0.25 | 1 | 0.25 |
| Motor Mount | 0.05 | 4 | 0.2 |
| Bearing | 0.08 | 2 | 0.16 |
| Drive Nut | 0.15 | 1 | 0.15 |
| Drive Screw | 0.28 | 1 | 0.28 |
| Drive Nut Screw | 0.02 | 2 | 0.04 |
| Drive Bearing Mount | 0.08 | 2 | 0.16 |
| L-Channel Front | 0.07 | 2 | 0.14 |
| Payload Spring Standoff | 0.08 | 1 | 0.08 |
| Spindle Arm | 0.15 | 1 | 0.15 |
| | **Weight of Transporter** | | 11.45 |
| | **Weight of Disks** | | 17.27 |
| | **Combined Weight** | | 28.72 |

**Part 2: Friction Force Calculation**

a) Since we do not possess the BaneBot wheels yet, we cannot perform the coefficient of friction test. Therefore we still have to estimate the coefficient of friction. We estimate that μ is around .7, and worst case could be around .5. Therefore we are using μ = .6 for the majority of our calculations.

b to i) Once we know the variable from our CAD model, we can input them into the following excel sheet to solve for normal forces, tractive forces, and the force of gravity along the ramp:

**Table 4: Force calculations**

| Inputs: | | | Outputs: | (in lb) |
|---|---|---|---|---|
| $F_m$ = | 28.72 lb | | $N_f$ = | 12.30 |
| L = | 5.87 in | | $N_r$ = | 15.51 |
| $L_c$ = | 4.29 in | | $F_{Tf}$ = | 7.38 |
| $h_c$ = | 6.55 in | | $F_{Tr}$ = | 9.30 |
| θ = | 14.5 deg | | $F_T$ = | 16.68 |
| μ = | 0.6 | | $F_w$ = | 7.19 |

Since the total tractive force is greater than the force of gravity along the ramp (16.16 > 7.19), our transporter will climb the ramp.

j) Since our drive system is all wheel drive, the minimum coefficient of friction does not depend on transporter design. The minimum coefficient of friction is :

$$\textbf{(eq. 4-1)}\ \boldsymbol{\mu = \tan(\theta)}$$

The largest ramp angle is 14.5 degrees, so the minimum coefficient of friction is .26.

**Part 3: Move/Velocity Profile**

a)

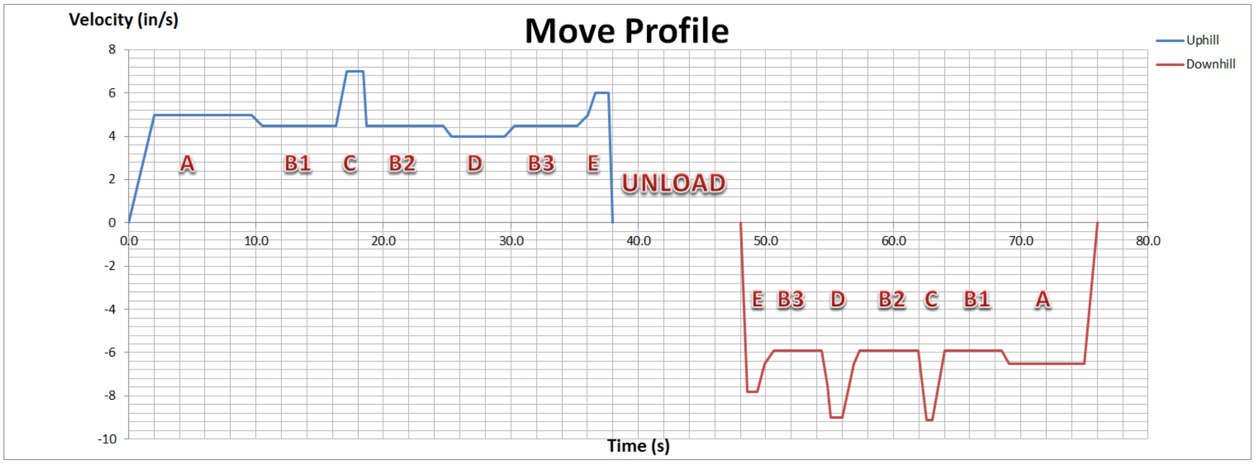



**Figure 15: Round-trip move profile**

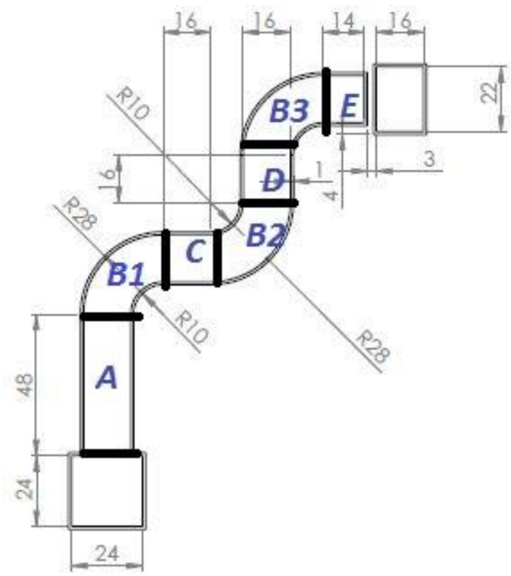



**Figure 16: Labeling of track used in move profile**

b)

**Table 5: Maximum velocities of move profile**

| Section | Uphill (in/s) | Downhill (in/s) |
|---|---|---|
| A | 5 | -6.5 |
| B | 4.5 | -5.9 |
| C | 7 | -9.1 |
| D | 4 | -9 |
| E | 6 | -7.8 |

c)

**(eq. 4-2)** $\beta_f = \frac{L_c * \cos(\theta) - h_c * \sin(\theta)}{L}$

**(eq. 4-3)** $\beta_r = \frac{(L - L_c) * \cos(\theta) + h_c * \sin(\theta)}{L}$

**Table 6: Beta for uphill**

| Section | $\beta_f$ | $\beta_r$ | θ |
|---|---|---|---|
| A | 0.587 | 0.413 | 7.1° |
| B,C,E | 0.731 | 0.269 | 0° |
| D | 0.439 | 0.561 | 14° |

**Table 7: Beta for downhill**

| Section | $\beta_f$ | $\beta_r$ | θ |
|---|---|---|---|
| A | 0.159 | 0.841 | 7.1° |
| B,C,E | 0.274 | 0.726 | 0° |
| D | 0.044 | 0.956 | 14° |

Note: When going downhill, the rear wheels are the lead wheels, as it is moving backwards.

d) The total propulsion force is:

**(eq. 4-4)** $F_{prop} = F_m + F_T + F_{rol} + F_{Inertia}$

**(eq. 4-5)** $F_{Inertia} = M * a$

**(eq. 4-6)** $F_{rol} = \mu_{rol} * mgcos(\theta)$

**(eq. 4-7)** $F_f = \mu * mgcos(\theta)$

**(eq. 4-8)** $F_{m,v} = mgsin(\theta)$

The units are in lbf.

**Table 8: Required propulsion force for uphill**

| Section | $F_{inertia}$ | $F_{rol}$ | $F_f$ | $F_{m,v}$ | $\mathbf{F_{prop}}$ |
|---|---|---|---|---|---|
| A | 0.186 | 0.570 | 17.100 | 3.550 | 21.406 |
| B,C,E | 0.232 | 0.574 | 17.232 | 0.000 | 18.038 |
| D | 0 | 0.557 | 16.72 | 6.948 | 24.225 |

Inertia acceleration was estimated using the assumption of constant acceleration for changes in velocity. To estimate, acceleration is taken as the velocity change over a section divided by the time it takes to cross the section. Rolling friction was taken as a car tire on asphalt, which is a decent estimate.

**Part 4: Power Requirement Calculations**

a) The following is the vehicle data used in the torque calculations. Propulsion Force was calculated in our previous report:

**Table 9: Torque calculations data**

| **Wheel Make** | BaneBots 20A Tread |
|---|---|
| Diameter: | $2\frac{7}{8}$" |
| Width: | 0.8" |
| Estimated $\mu_s$: | 0.7 |
| **WheelBase** | 5.87in (L), 9.16 in (W) |
| **Rear Wheel dist. To CG** | |
| horizontal: | 4.29 in |
| vertical: | 6.55 in |
| **Estimated $\mu_s$** | 0.7 |
| **Ramp Slopes** | Propulsion Force |
| A: 7.125° | 21.406 lb |
| B, C, E: 0° | 18.038 lb |
| D: 14.5° | 24.225 lb |

b) To calculate the required propulsion torque for each section we use the following equation:

**(eq. 4-9)** $\boldsymbol{T_{Propulsion} = F_{Propulsion} \times r_{Drivewheels}}$

$$T_{Propulsion} = 24.225 \text{ lb} \times 1.438 \text{ in}$$

$$T_{Propulsion} = 34.84 \text{ lb} \cdot \text{in} = 40.18 \text{ kgf} \cdot \text{cm}$$

(Note that 1.0 kgf · cm = 0.867 lb · in.)
For each ramp section we get the following, with the minimum required highlighted:

**Table 10: Required propulsion torque**

| Ramp Section | $T_{Propulsion}$ | $T_{Propulsion}$ |
|---|---|---|
| A | 30.78 lb · in | 35.50 kgf · cm |
| B, C, E | 24.94 lb · in | 29.92 kgf · cm |
| D | 34.84 lb · in | 40.18kgf · cm |

**Part 5: Torque Calculation**

We decided to build our robot with the direct drive system (note: Tetrix motor has an internal gearbox, but information is not given so we assume that the output torque provided by the company have already taken the gearbox into account). Below is the collection of data for calculating the required torque for our robot. To find the required torque we used the following torque equation:

**(eq. 4-10)** $$T_{req} = J_t \alpha_{acc} + T_f = (J_l + J_m)\alpha_{acc} + T_f$$

We first have to find the individual moment of inertia before we can find the $T_{req}$. The data of the inertia and $T_f$ calculation are listed in color code

**Table 11: Required torque for direct drive**

| $J_L$ | $J_m$ | $\alpha$ | $T_f$ | $T_{req}$ |
|---|---|---|---|---|
| 3.73E-04 | 1.33E-03 | 2.10 | 23.94 | 23.94 |
| lb-in-s^2 | lb-in-s^2 | rad/s^2 | lb-in | lb-in |

**Table 12: Load inertia**

| | | |
|---|---|---|
| $J_L$ | 3.73E-04 | lb-in-s^2 |
| Weight_wheel | 0.14 | lb |
| R_wheel | 1.435 | in |
| G | 386 | in/s^2 |

**Table 13: Motor inertia**

| | | |
|---|---|---|
| $J_m$ | 1.33E-03 | lb-in-s^2 |
| m_shaft | 2.22E-02 | lb |
| R_shaft | 0.12 | in |
| p_density | 0.28 | lb/in^3 |
| V_volume | 7.92E-02 | in^3 |
| Shaft_length | 1.75 | in |

**Table 14: Friction Torque**

| | | |
|---|---|---|
| $T_f$ | 0.22 | lb-in |
| $T_{f(max)}$ | 23.94 | lb-in |
| $F_s$ | 16.68 | lb-in-s^2 |
| Robot Weight | 28.72 | lb |
| µ (Friction) | 0.6 | unitless |
| R_wheel | 1.435 | in |

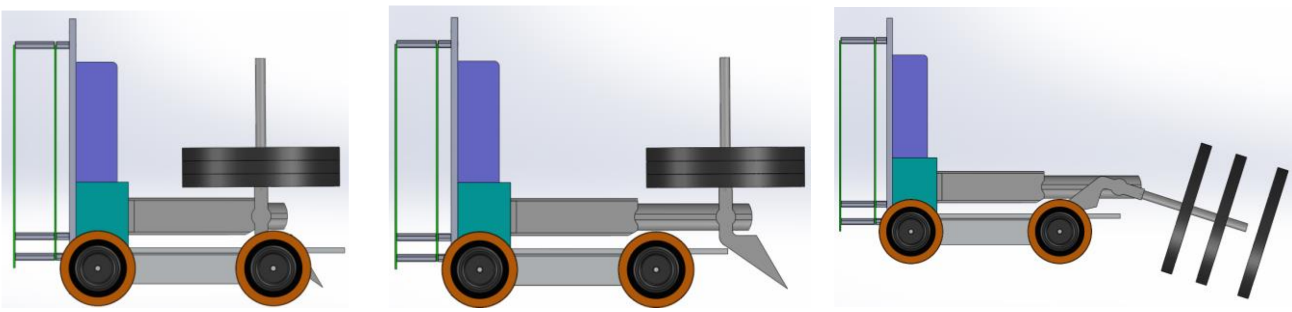
From our previous calculation with 4 Tetrix Motor we achieve a 40.65 lb-in of torque. This means that the require torque 23.94 lb-in is less than the motor drive torque. In conclusion this means that the vehicle can move up the ramp without significant problem since the require torque is about 1/2 the drive torque.

**(eq. 4-11)** $$\boxed{\mathbf{T_{req} = 23.94\ lb\text{-}in < T_{Drive\_Torque} = 40.65\ lb\text{-}in}}$$

## Part 6: Unloading Mechanisms

The payload, as previously described, uses a linear actuator to move the payload forward to a point at which a mechanism touches the sidewall of the ramp. At this point, the mechanism which holds the payload tips forward, and allows the payload disks to slide off into the collection box. The linear tipping mechanism uses gravity and some form of angular damper, but the linear actuator requires power. The estimated power is derived below.

The *Panthra* vehicle must transport a minimum of 3 disks (18lb) up the ramp. As shown in the diagram below, the drive screw (linear actuator) will only need to move the payload horizontally, so the only load on the actuator will be due to friction in the drive screw.



(a) (b) (c)

**Figure 17: a,b,c: (a) transport configuration, (b) delivery configuration with extended actuator, (c) delivery configuration with extended actuator and tipped payload**

In the above figures, the vehicle is shown in (a) the transport configuration, (b) the delivery configuration with extended actuator, and (c) the delivery configuration with extended actuator and tipped payload. The drive screw must provide the force to extend the payload horizontally for approximately 3”. For a ½” – 10 drive screw, the lead angle is given by

$$\textbf{(eq. 4-12)}\ \boldsymbol{\lambda = \tan^{-1}\left(\frac{1}{10}\Big/0.5\pi\right) = \tan^{-1}\left(2/10\pi\right) = 3.64°}$$

For a drive screw in various nut materials, kinetic friction coefficients are in the range of 0.11-0.17 if oiled. A friction coefficient of 0.15 will be assumed. For a stainless steel ACME drive screw with a metallic nut, common efficiencies are in the range of 35-55%. The torque required to overcome friction in moving a load by a drive screw is given by:

$$\textbf{(eq. 4-13)}\ \boldsymbol{T = \frac{F_{\mu}}{2\pi pe} = \frac{\mu F_N}{2\pi pe}}$$

For a normal force of 18lbf, a pitch of 10 (assuming a ½”-10 drive screw), and an efficiency of 45%, the required torque is 0.0955 in-lb.

Additionally, some torque is required to overcome the rotational inertia of the lead screw. For a 5 inch steel lead screw with ½” diameter

$$\textbf{(eq. 4-14)}\ \boldsymbol{T = J = \frac{\pi L\rho R^4}{2} = 0.1424\ in - lb}$$

Thus, the final torque required is

$$T = 0.0955 in - lb + 0.1424\ in - lb = 0.2378 \text{ in-lb}$$

If the same motor is used as for the wheels (TETRIX DC Gear Motor, PN 739023), a stall torque of 20kg-cm = 17.36in-lb can be provided, which is far more than enough. At peak efficiency, the motor supplies 4.85 kg-cm of torque, which translates to 4.21 in-lb, at 128 RPM. If the motor directly drives the lead screw, this would translate to a linear speed of 0.213 in/sec. If the torque curve was provided in an equation form or as an array of values, the differential equation of motion for this problem could be solved. Based on this information alone, however, we can reason that the motor will be able to move the payload in near 15 seconds.

**Spindle Arm Stress Analysis:**

The following is a preliminary analysis for the viability of the spindle arm delivery system. As the spindle rotates into the downward delivery position large impact forces can be generated. Also, as the weights slide outward on the arm towards the receptacle, large forces and moments are generated on the rod. For these calculations I have made the spindle 1/16th inch smaller than the hole in the lead disk.

The first analysis is finding the stresses generated on the rod angled $\theta$ degrees below horizontal with the weights at the end. To simplify the model, we will maintain standard horizontal and vertical axis, while taking the gravitational force as $F_G \cos\theta$.

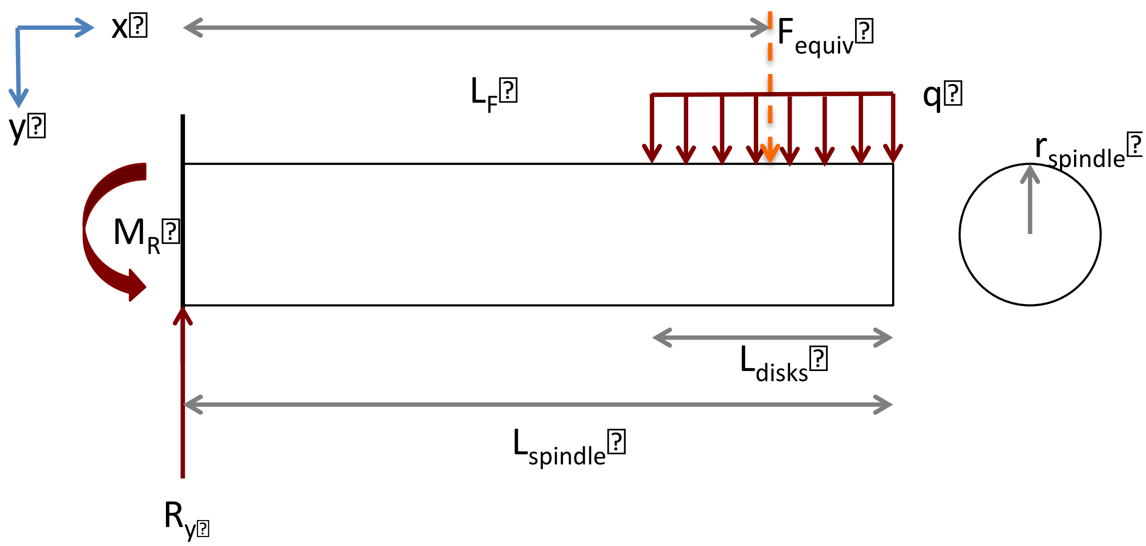



**Figure 18: Free body diagram of spindle arm**

$$\text{(eq. 4-15)} \quad \textbf{Load: } q = \frac{F_G \cos\theta}{L_{disks}}$$

**Table 15: Properties of spindle arm**

| | | | |
|---|---|---|---|
| $F_G$ | 18 lb | **Steel, High Strength ASTM-A242** | |
| $F_{equiv}$ | 18 cos θ lb | Yield Strength: | |
| Q | $10.67\ \frac{lbs}{in}$ | Tension | 50ksi |
| $L_{disks}$ | 1.5 in | Shear | 30 ksi |

| | | | |
|---|---|---|---|
| $L_{spindle}$ | 6.0 in | Modulus of Rigidity (G): | 11.5E6 psi |
| $L_F$ | 5.25 in | | |
| $r_{spindle}$ | 21/128 in | | |
| $I_x$ | 5.690E-4 $in^4$ | | |
| V | 0.1268 $in^3$ | | |

By balancing moments we get that:

$$\textbf{(eq. 4-16)}\ \mathbf{M_R = = F_{equiv} \cdot \left(L_{spindle} - {}^{L_{disks}}/_{2}\right)}$$

$M_R = 84.02 \cos\theta$ lb·in

Solving for max stress:

$$\textbf{(eq. 4-17)}\ \boldsymbol{\sigma}_{\mathbf{max}} = \frac{\mathbf{M_R r_{spindle}}}{\mathbf{I_x}}$$

$$\sigma_{max} = 24.2 \cos\theta \ \text{ksi}$$

We then find our safety factor, if using High Strength Steel ASTM-A242:

$$\textbf{(eq. 4-18)}\ \frac{\boldsymbol{\sigma}_{\mathbf{yp}}}{\mathbf{n}} = \sqrt{\boldsymbol{\sigma}_{\mathbf{max}}{}^{2} + 4\boldsymbol{\tau}_{xy}{}^{2}}$$

$$n = \frac{1.24}{\cos\theta}$$

This analysis puts us under the yield strength of High Strength Steel with a factor of safety of 1.24. This would be with the spindle horizontal. By increasing the angle below horizontal we would expect less stress and a higher factor of safety.

To analyze the initial impact of the rotating spindle we use shear impact:

$$\textbf{(eq. 4-19)}\ \boldsymbol{\tau}_{impact} = 2\sqrt{\frac{KE \cdot G}{V}}$$

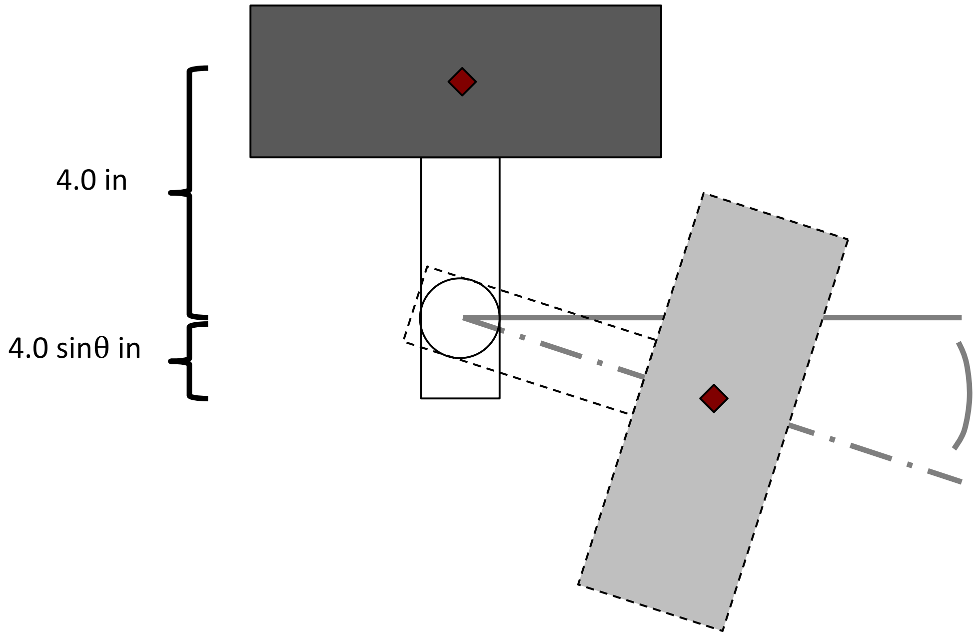



**Figure 19: Rotation of Spindle Arm**

We computed the Kinetic Energy as the energy transformed from Potential Energy from the lead disks' initial height, to its final height.

$$\textbf{(eq. 4-20)}\ \mathbf{KE = 18lbs \cdot 4in\ (1 + \sin\theta)}$$

To simplify this analysis, we'll use $\theta = 30°$

$$\mathrm{KE} = 108\ \mathrm{lb \cdot in}$$

This results in a shear impact of:

$$\textbf{(eq. 4-21)}\ \boldsymbol{\tau_{impact}} = \mathbf{198\ ksi}$$

This value is much too high for the steel spindle to absorb, but also represents a worst case scenario of the lead disks freely falling into the down position. The process could still be viable by instituting some method of dampening, or a mechanical method to ease the spindle into the down position.

**Lead Screw Calculations:**

For our unloading mechanism we decided to use the lead screw mechanism to push our load to the edge of the robot and let gravity unload the lead disk. To make sure it actually work we performed some basic calculation. The governing equation we use for this calculation is:

$$\textbf{(eq. 4-22)}\quad T_{req} = J_t \alpha_{acc} + T_f = \left(J_l + J_{LS} + J_m\right)\alpha_{acc} + T_f$$

We first have to find the individual moment of inertia before we can find the $T_{req}$. The data of the inertia and $T_f$ calculation are listed in color code.

**Table 16: Required torque for lead screw, μ = 0.15**

| $J_L$ | $J_{LS}$ | $J_M$ | alpha | $T_f$ | $T_{req}$ |
|---|---|---|---|---|---|
| 4.6382E-05 | 0.00875 | 0.00133 | 40 | 0.21092 | 0.615976 |
| lb-in-s^2 | lb-in-s^2 | lb-in-s^2 | rad/sec | lb-in-s^2 | lb-in-s^2 |

Assumed μ (Friction) to be **0.15** (steel on steel lubricated)

**Table 17: Required torque for lead screw, μ = 0.58**

| $J_L$ | $J_{LS}$ | $J_M$ | alpha | $T_f$ | $T_{req}$ |
|---|---|---|---|---|---|
| 4.6382E-05 | 0.00875 | 0.00133 | 40 | 0.815558 | 1.220614 |
| lb-in-s^2 | lb-in-s^2 | lb-in-s^2 | rad/sec | lb-in-s^2 | lb-in-s^2 |

Assumed μ (Friction) to be **0.58** (steel on steel lubricated

**Table 18: Load inertia and lead screw inertia**

| | | | | | |
|---|---|---|---|---|---|
| $J_L$ | 4.64E-05 | lb-in-s^2 | $J_{LS}$ | 8.75E-03 | lb-in-s^2 |
| Weight_load | 17.67 | lb | mass | 0.28 | lb |
| P (pitch) | 5 | rev/in | radius | 0.25 | in |

**Table 19: Friction torque for two different μ's**

| | | | | | | |
|---|---|---|---|---|---|---|
| $T_f$ | 2.11E-01 | lb-in-s^2 | | $T_f$ | 8.16E-01 | lb-in-s^2 |
| μ (Friction) | ***0.15*** | Unitless | | μ (Friction) | ***0.58*** | unitless |
| Weight_load | 17.67 | lb | | Weight_load | 17.67 | lb |
| e (efficiency) | 0.4 | Unitless | | e (efficiency) | 0.4 | Unitless |

It turns out that the $T_{req}$ is quite small. Again if we choose to use the Tetrix Motor for this screw as well it will perform fine in general since the drive torque is significantly higher than the required torque for the unloading mechanism. Note: We choose the 0.816 lb-in since this will be the max torque the motor will have to go against in the worst case scenario.

**(eq. 4-23)** $\boxed{\mathbf{T_{req} = 0.816\ lb\text{-}in < T_{Drive\_Torque} = 10.16\ lb\text{-}in}}$

## FEM-Analysis of PDS

To verify that the delivery arm can withstand the load we performed an FEA. In our analysis we chose to do an analysis when the PDS is horizontal. During its horizontal position the PDS experienced the most stress and torque. Due to this condition, we decided to perform a test during this position. Any other positions we believe should experience less stress or torque because the weight of the disk is not perpendicular to the loading arm; therefore, resulting in a lower torque.

**Table 20: PDS assumptions for FEA**

| | |
|---|---|
| **Analysis type** | Static Analysis |
| **6 Disks** | Place until it reach the end of the rod (Not shown in diagram) |
| **Mesh type** | Solid Mesh |
| **Solver type** | FFEPlus |
| **Incompatible bonding options** | Automatic |
| **Fixtures** | Screw mount to drive screw (Green) |
| **Gravity** | Y-direction both direction has same result (direction in red) |

In this analysis we chose the horizontal position. Our PDS is symmetric making it have similar stress on both sides so applying gravity in either y-direction makes no difference in magnitude of stress, displacement, or FOS. As shown below the fixtures are chosen there because it's the only possible fixtures and point of contact connected to the moving block driven by the lead screw.

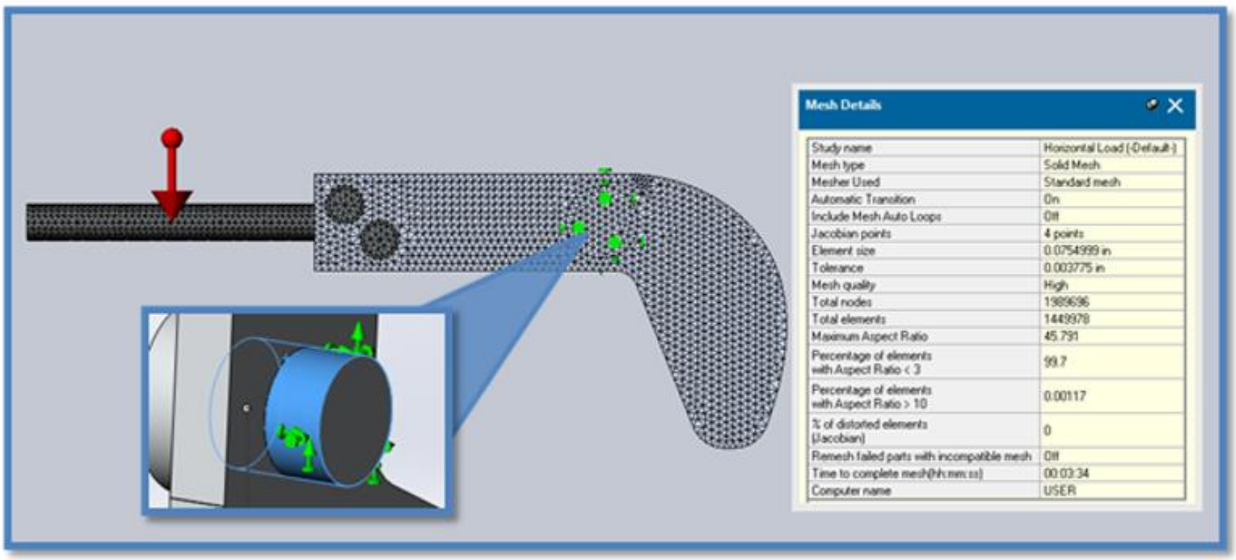



**Figure 20: Mesh and fixtures detail. (Fixtures are green and gravity direction in red)**

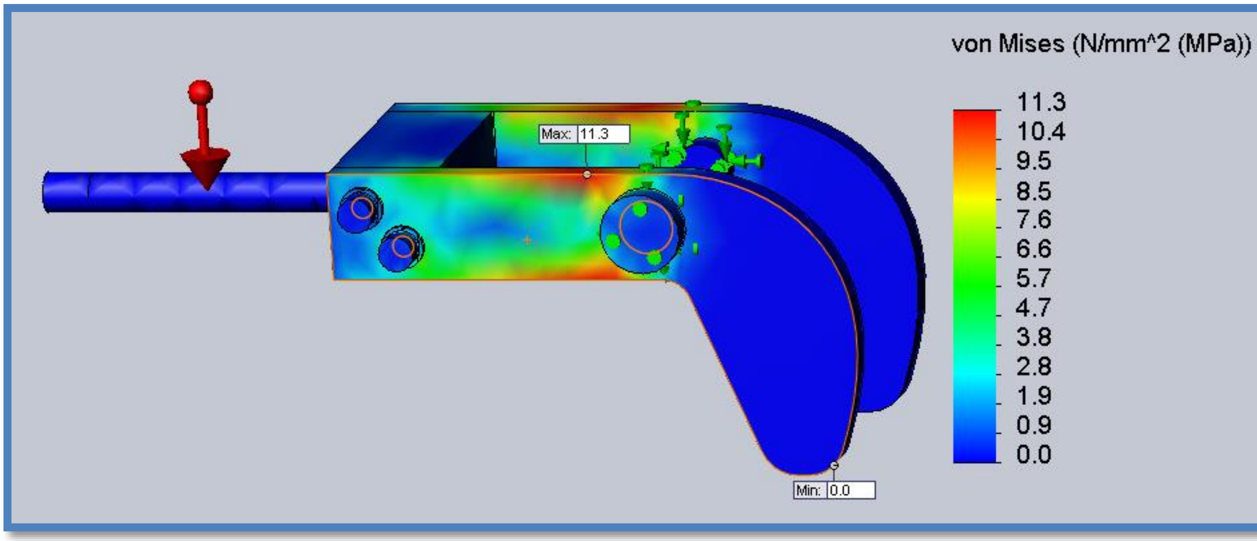



**Figure 21: PDS stress analysis during horizontal position.**

From the stress analysis there are a few materials that are present and playing a major role in the FEM analysis. The material are Carbon Steel and Al 6061-T6 having a yield stress of 220 MPa and 275 MPa respectively. As we expect both yield stress are greater than the stress supplied by the load. This means that the PDS is safe from failure.

When observing the FEA for displacement the largest displacement is about 0.1mm. In cases like this the results does not amount to much displacement as we would expect since the stress has not approach anywhere near the yield strength.

The Factor of Safety (FOS) test still has a FOS over 19 with 6 disks on. Even during this case the PDS provide prove that we could support up to six disks. In our current situation there is a chance only 3 or 4 disks will be driven up during each run due to battery power.

The only results that these FEA fail to provide detail information on are the joints that are threaded. Due to insufficient information at the joints the FEA cannot provide us with that information. So we would have to perform an actual physical test. During the actual physical test the PDS was able to hold the disk perfectly fine satisfying the requirements to hold the disks without failures.

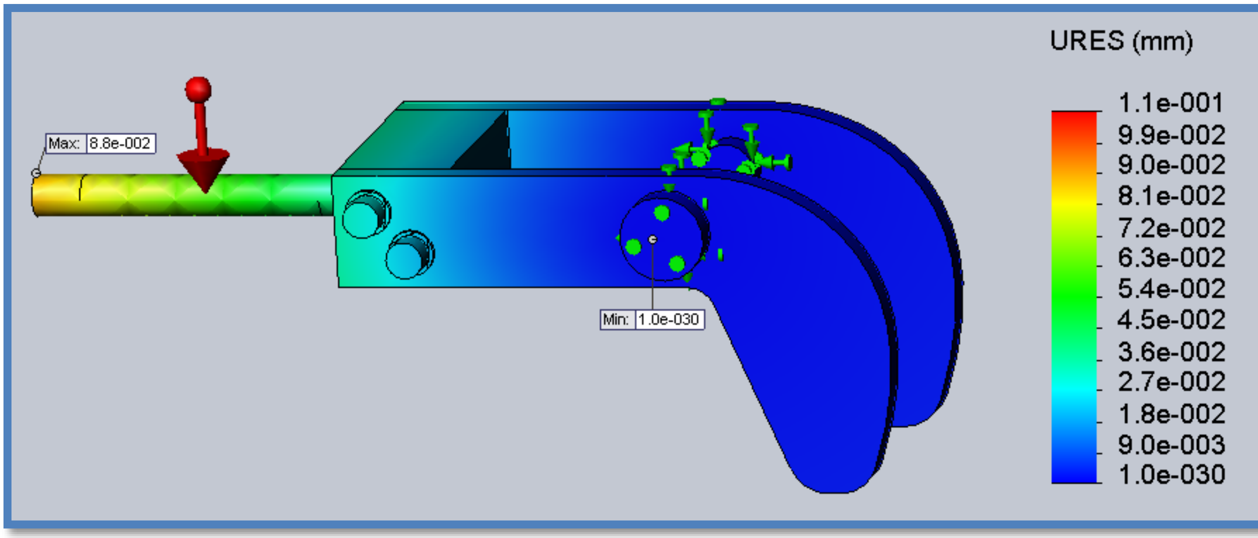



**Figure 22: PDS displacement analysis during horizontal position.**

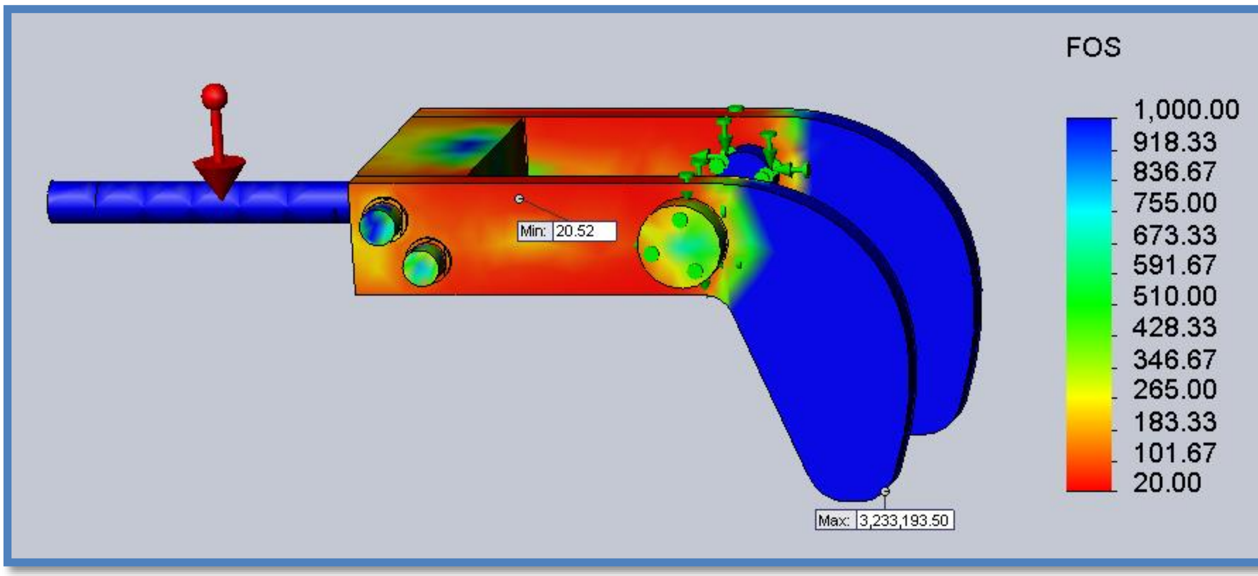



**Figure 23: PDS FOS during horizontal position.**

# 5. Control System Design

The following is a more detailed description of the Electronics and Control System (ECS) Design:

## Motor Selection

### Motor Details

We have selected the following motor as a candidate: Tetrix DC Drive Motor

**Table 21: Tetrix DC Drive Motor Specs**

| | |
|---|---|
| **Test Voltage:** | 12 V DC |
| **Gear Ratio:** | 1:52 |
| | |
| **At No Load** | |
| Speed: | 146 RPM |
| Current: | 0.17 Amps |
| **At Stall Extrapolation** | |
| Torque | 20 kgf · cm |
| Current | 4.55 Amps |
| **At Max Efficiency** | |
| Efficiency | 50% |
| Speed | 128 RPM |
| Torque | 4.85 kgf · cm |
| Current | 1.05 Amps |
| Output | 6.38 Watts |
| **At Max Output** | |
| Efficiency | 36.22 % |
| Speed | 89 RPM |
| Torque | 11.72 kgf · cm |
| Current | 2.46 Amps |
| Output | 10.7 Watts |

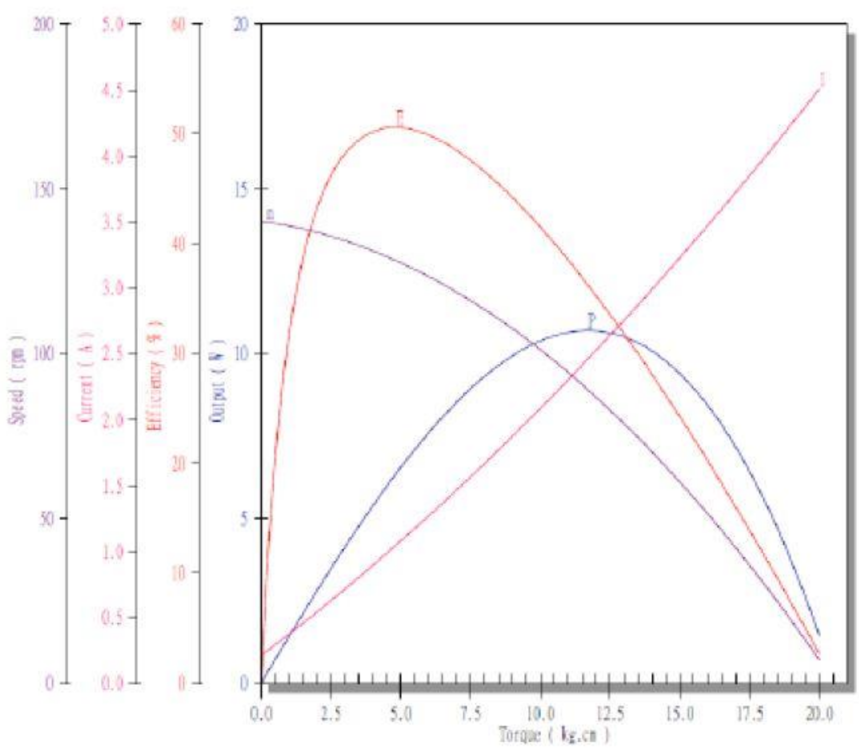



**Figure 24: Tetrix DC Motor Performance Curve**

a) Relying on 4 Tetrix Motors (1 powering each wheel), we could theoretically achieve a maximum output torque of:

**(eq. 5-1)** $\boldsymbol{T_{Propulsion,Max}} = \mathbf{4 \times 11.72\ kgf \cdot cm = 46.88\ kgf \cdot cm\ or}\ \boxed{\mathbf{40.64\ lb \cdot in}}$

Drive Torque: Our current design does not utilize any gearing between the motor and wheels.

b) Running the motors at max efficiency will not result in the necessary output torque for the steepest ramp section. From the plot, an output torque of 10.05 kgf · cm (our minimum required Torque, divided by 4) will result in approximately 40% efficiency. With 50% being the motor's max attainable efficiency, this is reasonable. Running the 4 motors at a 10 kgf · cm at 80 RPM will result in an output of 10 Watts, with a motor efficiency of 40%.

c) Motor circuit diagram are provide in later section.

**Motor Driver Selection**

The motor drive we chose is: 10A DC Motor Driver Ardiuno Shield 7-15V
From Plot for the Tetrix Motor:

$$\textbf{(eq. 5-2)}\ K_T = \frac{T_{MAX}}{I_{MAX}} = \frac{20\ kg \cdot cm}{4.55\ A} = 4.396\ \frac{kg \cdot cm}{A}$$

Using Propulsion Torque per Motor = 46.88 $kg \cdot cm$ / 4 = 11.72 $kg \cdot cm$

$$\textbf{(eq. 5-3)}\ I_{PROP} = \frac{T_{PROP}}{K_T} = \frac{11.72\ kg \cdot cm}{4.396 \frac{kg \cdot cm}{A}} = 2.67A$$

Using Acceleration Torque per Motor = 5.985 $kg \cdot cm$

$$\textbf{(eq. 5-4)}\ I_{ACCEL} = \frac{T_{ACCEL}}{K_T} = \frac{5.985\ kg \cdot cm}{4.396 \frac{kg \cdot cm}{A}} = 1.361\ A$$

**Figure 25: Motor Driver**

Price: $19.06
Peak Load: 15A
Continuous Load: 10A
Operation: PWM input for speed and DI for direction

This motor driver can operate at 10A continuous load; therefore, making it a safe candidate for two motors driven in parallel.

## Unloading Mechanism

### Motor Details

a)
We have selected the following motor as a candidate for the PDS:
Hennkwell 12V DC Motor

**Table 22: Hennkwell 12V DC Motor Specs**

| Model | Rated Voltage | Reduction Ratio | 1/264 |
|---|---|---|---|
| 2100 | 12V | No Load Speed(rpm) | 38 |
| | | No Load Current (mA) | 1000 |
| | | Rated Torque (kg-cm) | 12.00 |
| | | Rated Speed (rpm) | 36.5 |
| | | Rated Current (mA) | 5000 |
| 9100 | 24V | No Load Speed(rpm) | 36 |
| | | No Load Current (mA) | 440 |
| | | Rated Torque (kg-cm) | 12.00 |
| | | Rated Speed (rpm) | 34.5 |
| | | Rated Current (mA) | 770 |

PK32K3SP2100-264 (12V)

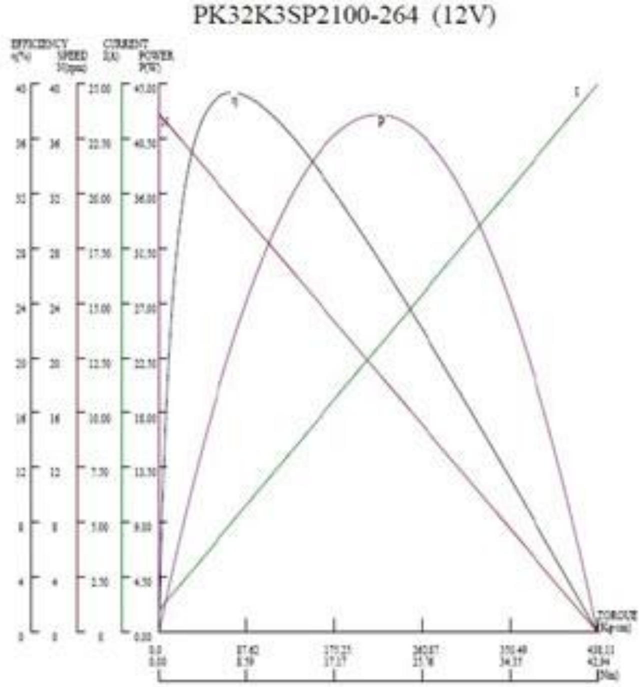


**Figure 26: Hennkwell 12V DC Motor Performance Curve**

b) The main purpose of this motor is to drive the lead screw. When a current is passed to drive the motor the lead screw is also driven as well because the motor is connected directly to the lead screw. So by controlling the motor rotation the lead screw is drive at the same angular velocity as the motor shaft. As it turns out the operating current is pretty low so the same motor drivers is used for the PDS and VDS.

c) PDS (same as motor) circuit diagram are provide in later section.

**Motor Driver Selection**
The chosen motor driver for the PDS is the same as the VDS (for more information look at the Motor Driver Selection above). This is because the current is low and this motor driver was sufficient to support the necessary current.

From Plot for the Hennwell Motor:

$$\textbf{(eq. 5-5)}\ K_T = \frac{T_{MAX}}{I_{MAX}} = \frac{12\ kg{\cdot}cm}{5\ A} = 2.4\,\frac{kg{\cdot}cm}{A}$$

$$\textbf{(eq. 5-6)}\ I_{REQ} = \frac{T_{REQ}}{K_T} = \frac{1.407\ kg{\cdot}cm}{2.4\frac{kg{\cdot}cm}{A}} = 0.586\ A$$

## Sensors and Theory of Operation

### Push Sensors

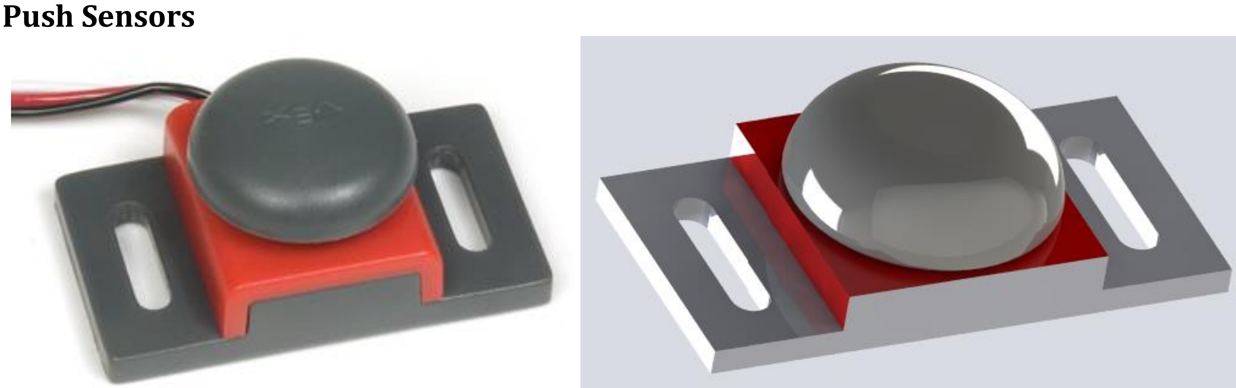


**Figure 27: Vex Robotics Push Sensors (left-physical) (right-Solidworks)**

a) These Vex Robotics push sensors are best used to detect solid surface contact. This is due to the way the push sensors are designed. Depending on whether the sensors are pushed or not this create an open or close switch that controls whether current flows or not.
b) These sensors are used to detect the ending location wall to unload and the starting location wall on its way down. To detect the wall the vehicle needs to drive into the wall and push both the buttons.
c) Circuit diagram are provide in the circuit section.

d)

**Table 23: Pros/Cons of a push sensor**

| Pros | Cons |
|---|---|
| Simple trigger mechanism | Require surface contact and switch compression |
| Easy installation | Limited operation |
| Mechanical mechanism | |

**Ultrasonic Sensor**

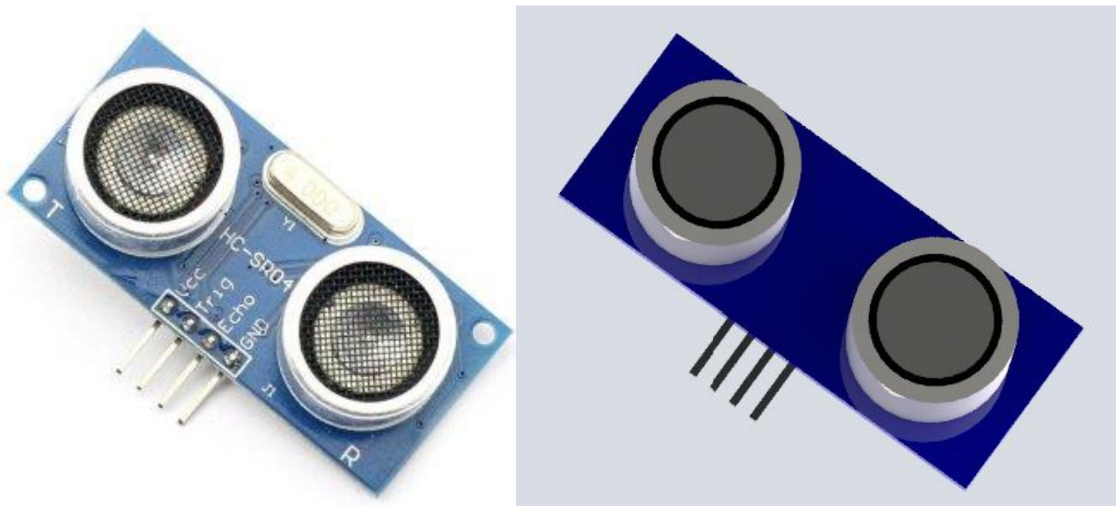



**Figure 28: Ultrasonic Module HC-SR04 (left-physical) (right-Solidworks)**

a) These ultrasonic sensors are best used to detect solid surface. This is due to the way the sensor is design. The sensors works by sending and receiving sound waves at a target. The effect is similar to radar or sonar used to interpret an object location or distance.
b) These sensors are used to detect the walls distance. There are two ultrasonic sensors mounted on each side used to detect the distance from each wall. By knowing the distance from each wall the vehicle can then be kept centered. The sensors are also used to help with the wall following. The sensors transmit a sound wave and receive it back. This data is converted to distance and used to calculate for possible action taken by the vehicle.
c) Circuit diagram are provide in the circuit section.
d)

**Table 24: Pros/Cons of a ultrasonic sensor**

| Pros | Cons |
|---|---|
| Good precision (1mm) for our application | Surface must easily reflect sound wave |
| Good distance measurement (up to 1m) | Measured voltage changes when distance is below 2cm from sensor |
| Works for most solid surface | Depends on speed of sound |
| Surface and wall detection | Depend on medium sound is propagating through |
| Quick responses due to sound speed | Shape of surface or material (foam) |

## Circuit Design Description

The following is a detailed description of the robot's circuit design:

### Motor Drivers Circuit

a. In the motor driver circuit design we used 3 Arduino motor drivers to power 5 motors on our robot. The VDS motors are power in parallel on each side. The circuit design of the left and right motors are exactly the same (below).

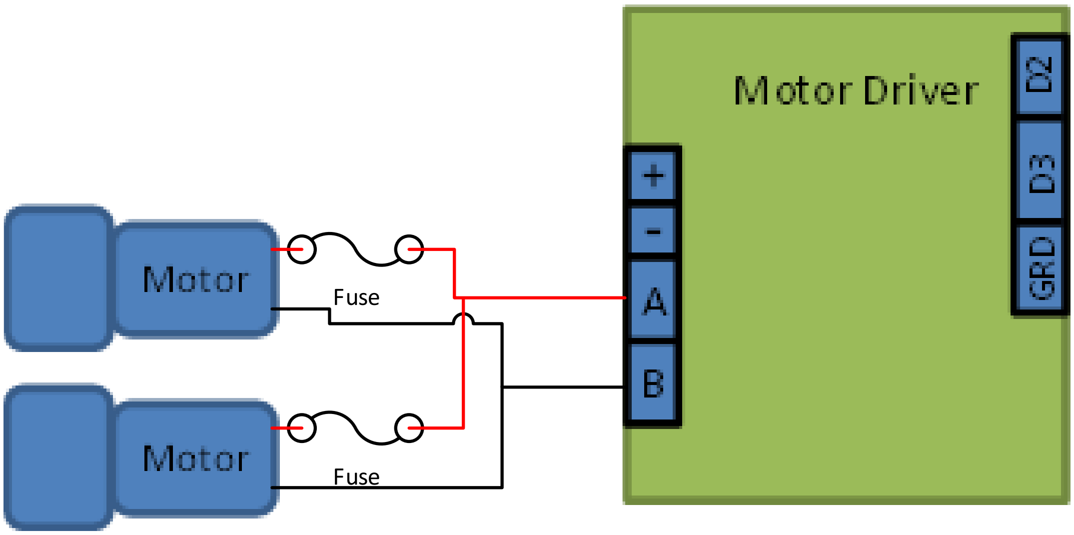



**Figure 29: Motors and motor drivers circuit design for VDS (PDS has only one motor).**

b. There are fuses added to the input of the motor to prevent too much current from passing through the opposite motor when one of the motor is stalled.
c. Fuses are also added before the motor drivers to prevent sudden current surges from frying the motor drivers. As display below the motors are all connected to the external battery supply all in parallel.
d. The parallel connection of the drivers is used to provide 12V to the motors.
e. The PWM signal the drivers receive from the circuit board is not directly connected to the SB-Rio to prevent possible current from surging back to the SB-Rio.
f. D3 is the PWM connection. A resistor is place between the board and motor driver PWM signal to prevent possible high current from surging back to the SB-Rio. The higher the resistor's resistance the lower the current is passed through. But if the resistor is too high almost no current is passed through and therefore to weak a signal. So in this case we chose 10kΩ resistors.
g. All of the connections are integrated together on one breadboard hidden below the vehicle.
h. The switch is added after the battery to turn on/off the motors without influencing the SB-Rio signal. This will prevent us from using the emergency stop.

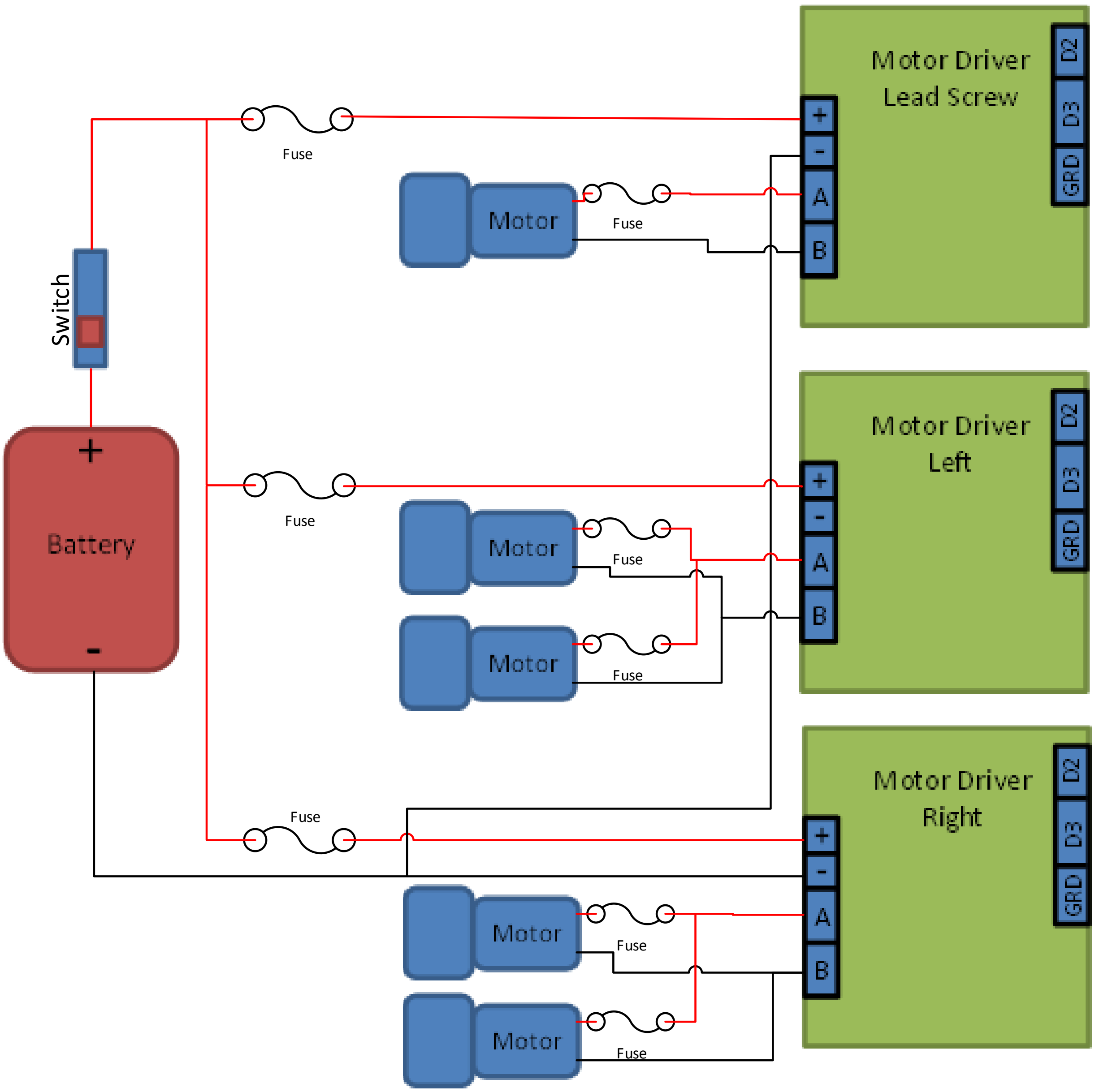



**Figure 30: VDS and PDS integrated circuit design.**

### Sensor Circuits

a. To power the sensors we needed to lower the voltage to 5V using the voltage regulator. Adding a capacitor right after the voltage regulator stabilized the voltage.
b. To power the ultrasonic sensors only a parallel connection is sufficient to power it.
c. For the lead screw and push button they are very similar in design. They are all basically a switch that sends a current when shorted. The lead screw switch sends a current signal when in contact to stop the motor from driving the lead screw forward.
d. The switches needed resistors to prevent high current when the circuit is shorted. Higher resistors also prevent the battery from being drained too quickly.

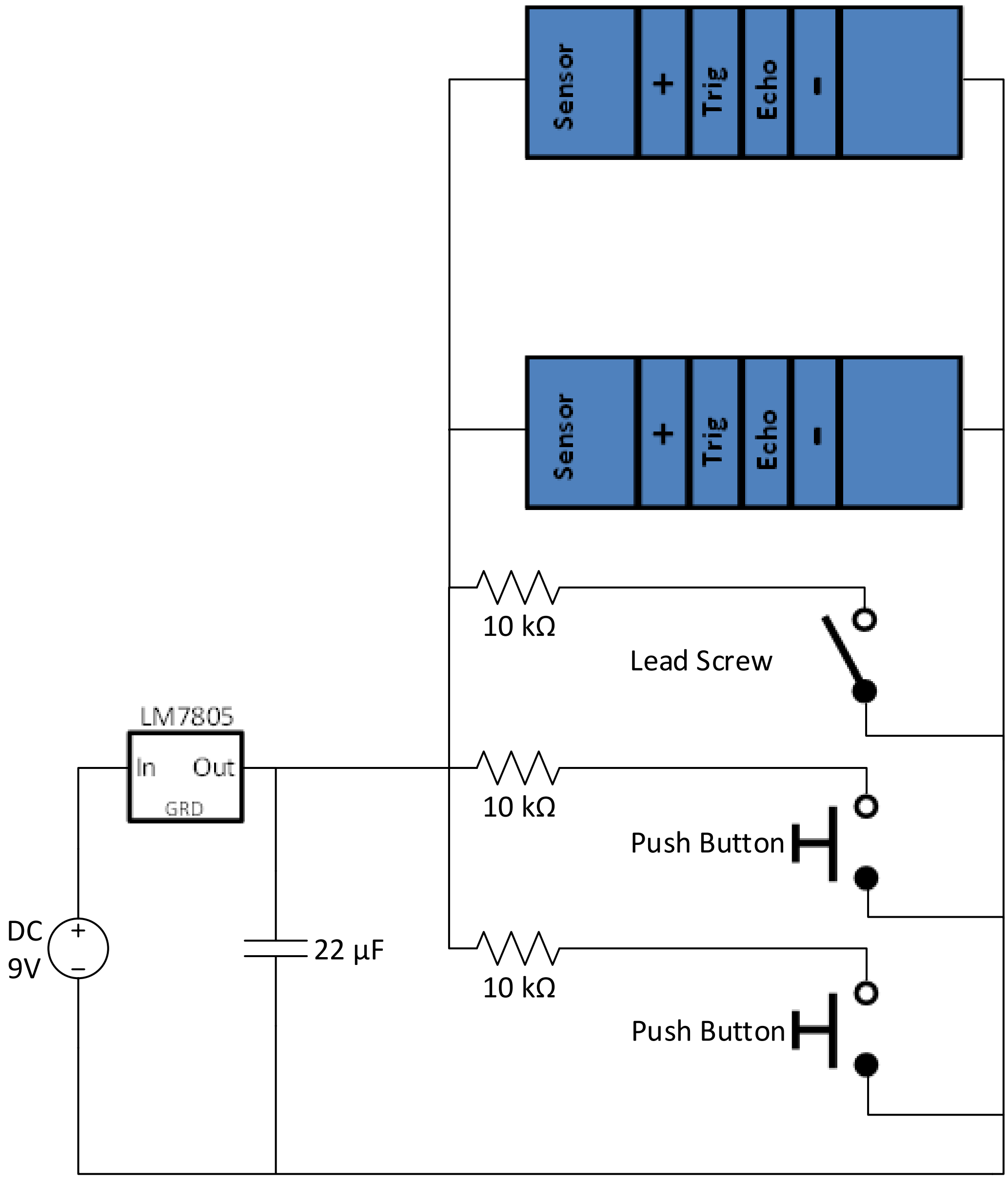



**Figure 31: Sensors and PDS's switch circuit design.**

### Overall Circuit Wire Diagram

a. The overall circuit design requires the ultrasonic sensors to be connected to the respective echo and trigger port in the SB-Rio.
b. All the push button and lead screw switch are connected to digital inputs.
c. The motor driver ports D3 are connected to the respective SB-Rio PWM port to provide speed signal.
d. The motor driver ports D2 are connected to the respective SB-Rio digital input port to give the direction of the motor rotation.

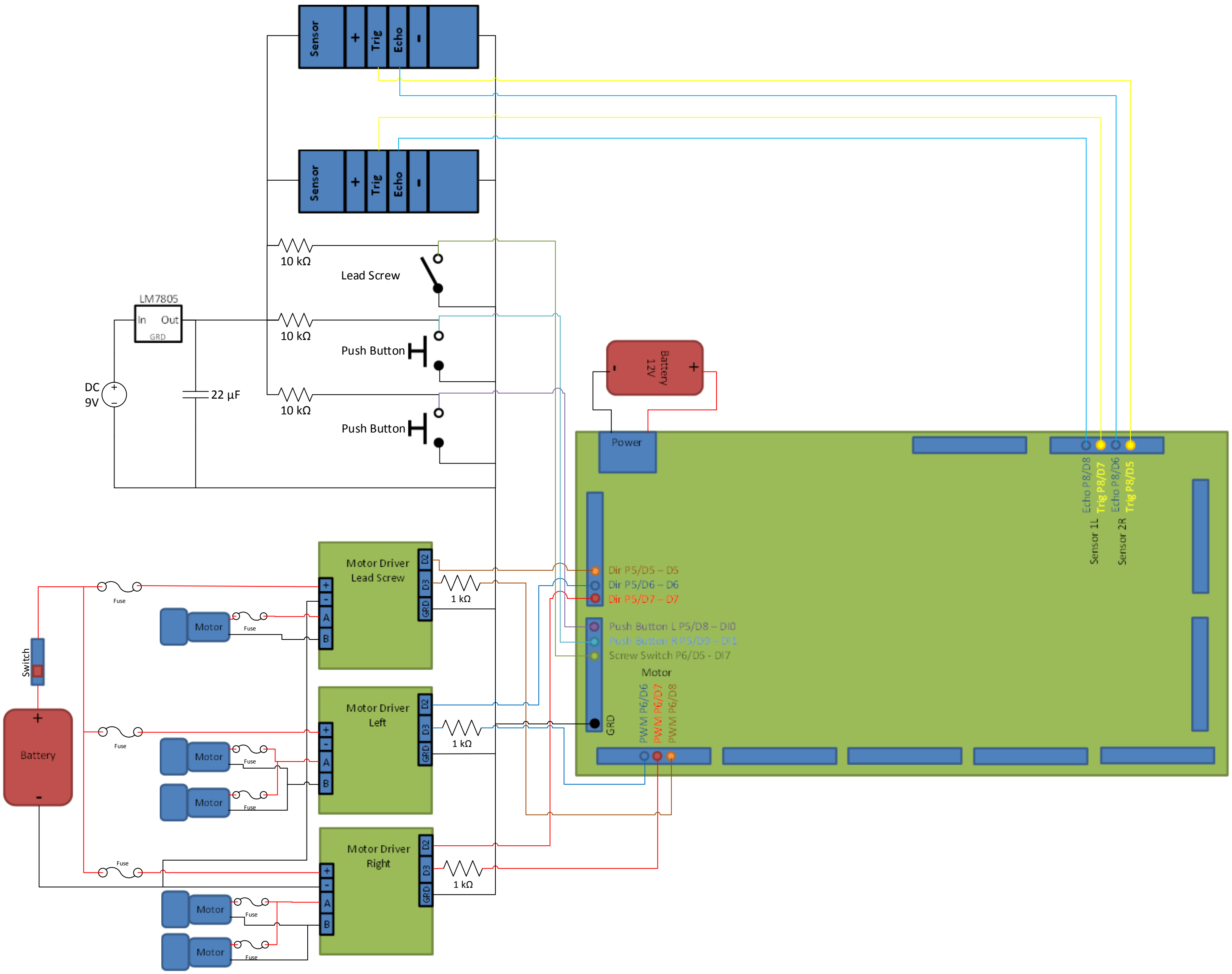

Sensor
+
Trig
Echo
-
Sensor
+
Trig
Echo
-
10 kΩ
Lead Screw
LM7805
In
Out
GRD
10 kΩ
Push Button
DC
9V
22 µF
10 kΩ
Push Button
Battery
12V
Power
Echo P8/D8
Trig P8/D7
Echo P8/D6
Trig P8/D5
Sensor 1L
Sensor 2R
Motor Driver
Lead Screw
D2
D3
GRD
1 kΩ
Dir P5/D5 – D5
Dir P5/D6 – D6
Dir P5/D7 – D7
Push Button L P5/D8 – DI0
Push Button R P5/D9 – DI1
Screw Switch P6/D5 - DI7
Motor
PWM P6/D6
PWM P6/D7
PWM P6/D8
GRD
Fuse
Motor
Fuse
Switch
Battery
Motor Driver
Left
1 kΩ
Motor
Motor
Motor Driver
Right
1 kΩ
Motor
Motor
A
B

**Figure 32: Complete wire diagram with VDS, PDS, and Sensor circuits.**

## State Diagram

Our percept sequence is based on distance measurements from two ultrasonic sensors, each mounted to a fender on the front wheel. We can then find how far off-center the vehicle is by the formula:

$$d = L - R$$

We then set a threshold, $\epsilon$, and have our lane control activate when the vehicle is off-center enough that $d > \epsilon$.

We also implemented a spin state where if during a turn one sensor lost its signal (such as a reflection from a convex surface) the robot would drive forward, spin, then drive forward again and attempt to regain the signal.

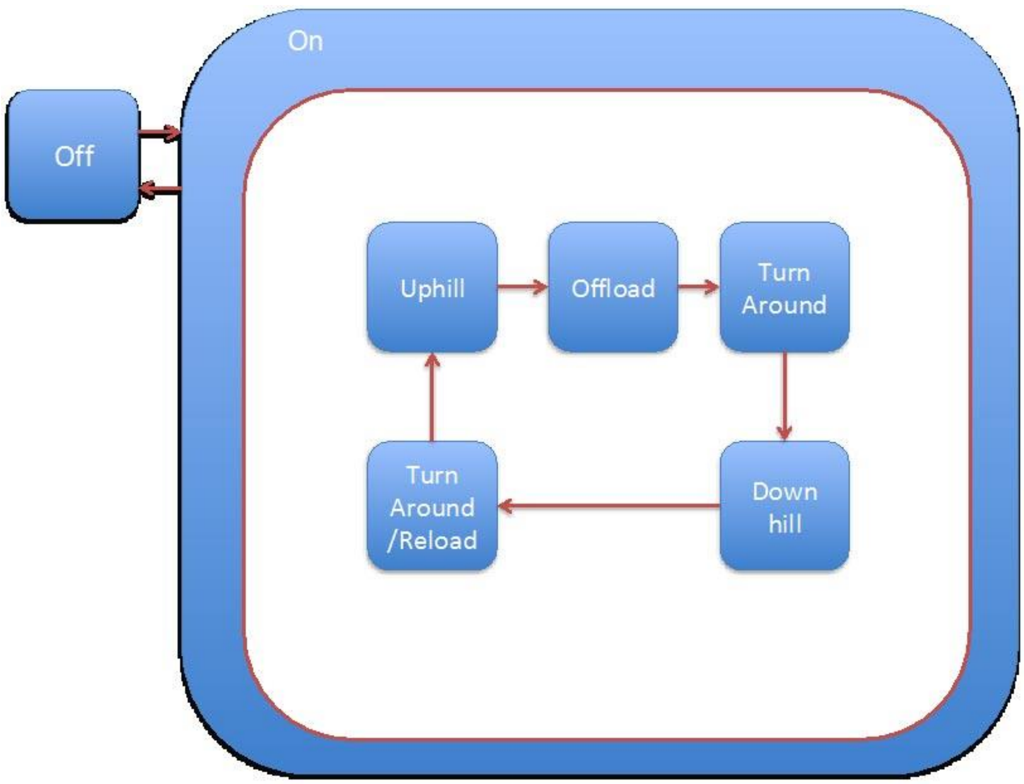



**Figure 33: General Regions State Chart**

Figure 33 shows the general regions of the state chart diagram. *Off* is accessible from any state to allow resetting of the delivery program. The *On* state loops through the delivery algorithm resetting all boolean flags before repeating *Uphill*. The different *Turn Around* states differ only slightly, with the second adding an extra pause to allow reloading of disks. *Uphill* and *Downhill* are identical except for a power dampening applied to *Downhill* to reduce motor power (since the vehicle weight is much lighter).

*Uphill*
The default state within *Uphill* is straight and the vehicle will enter turn left or turn right once it is off-center enough to cross the threshold discussed earlier.

Once the robot has enter the *Turn Left/Right* state, the outboard and inboard motors are sent multipliers based on how far off-center it is. If the vehicle is 4cm off-center, the outboard motors would be multiplied by 2.5, if only 1.5cm off, the outboard motors would be multiplied by 1.1. This allows for more aggressive correction as the robot becomes more off track.

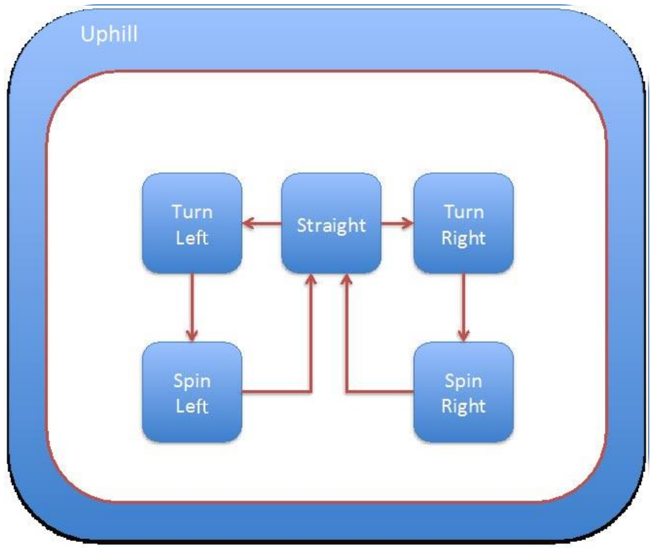


**Figure 34: Uphill Statechart**

-> *Straight*
**Action:** Left and Right motors forward at front panel setpoint.

*Straight -> Turn Left/Turn Right*
**Guard**: d > $\epsilon$
**Action**: Multiply outboard and inboard wheels by constant $c_o$ and $c_i$

*Turn Left/Right -> Spin*
**Guard**: Outboard sensor reads less than 10cm, inboard sensor reads above 50cm
**Action:** Drive Forward for a count, spin for a count, drive forward for a count, return to *Straight*.

*Offload*
The robot enters offload when the two front buttons are depressed. If only one button is depressed, the motors on the opposite side power up to straighten the vehicle against the wall. The initial state is screw forward.

-> *Screw Forward*
**Action:** Linear drive screw turns forward
*Screw Forward -> Dump*
**Guard:** Contacts touch, indicating delivery

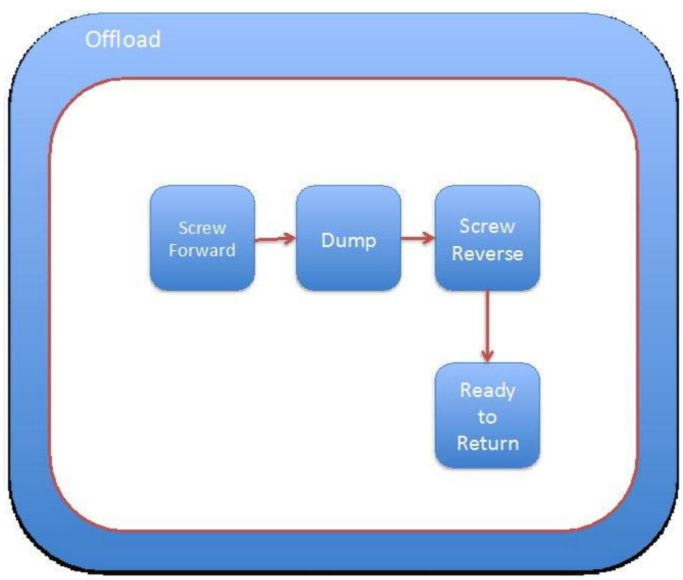


**Figure 35: Offload Statechart**

system in lowered position.
**Action:** Stop linear drive screw

*Dump->Screw Reverse*
**Guard:** Counter
**Action:** Linear Drive Screw turns reverse

*Screw Reverse -> Ready to Return*
**Guard:** Counter
**Action:** Stop linear drive screw, set boolean flag to allow entering *Turnaround*

*Turnaround*
Turn around backs up the vehicle with a slight right turn, then implementing a left spin. After spinning the vehicle picks up the wall and heads downhill. The boolean flags for *Ready to Return* and *Ready for Downhill* were added to prevent premature entering of *Downhill* and the *Turnaround 2/Reload*.

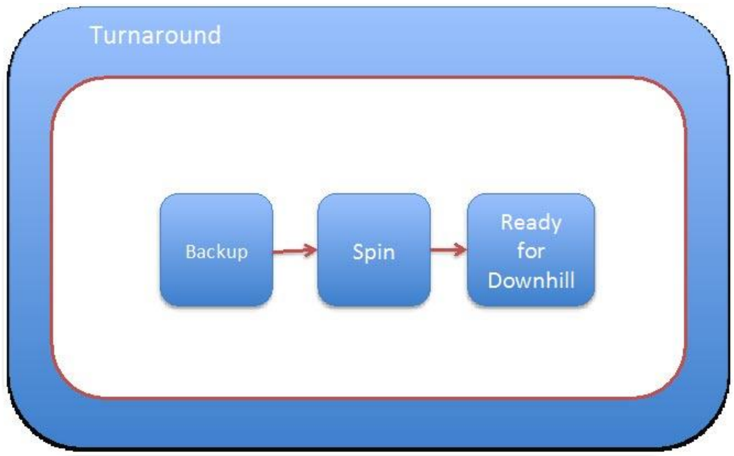


**Figure 36: Turnaround Statechart**

*-> Backup*
**Action:** Both motors reverse, left motors have a power increase.

*Backup->Spin*
**Guard:** Counter
**Action:** Right motors forward, left motors reversed

*Spin->Ready for Downhill*
**Guard:** Counter
**Action:** Set boolean flag to allow entering *Downhill*.

*Downhill*
*Downhill* is then a minor variation on *Uphill* but all motor values are multiplied by a constant set at the front panel (typically 0.8)

*Turnaround/Reload*
Similar to *Turnaround* but with a straight *Backup* and a counted pause before returning to *Uphill*.

The advantage of using the two wall inputs is not needing a different state between the wider loading area and the main 16 inch ramp section. This would give our robot the flexibility of handling varying widths of ramps. Taking two inputs did cause more problems, where if the robot was severely oblique it would not get correct readings and would produce undesirable behavior.

# 6. Product Fabrication

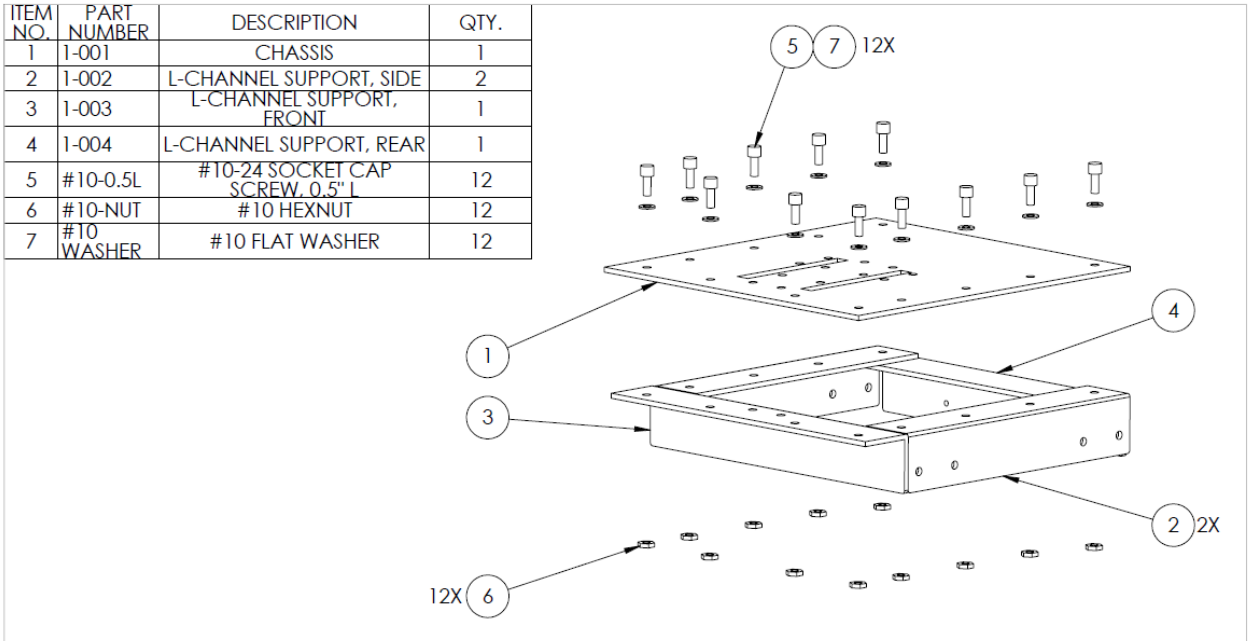
## Overview

All components of the Panthra are purchased or made in house (none are custom made by professional machinists). Due to the nature of the project, all custom parts are required to be machined by the project team in the UCLA Student/Faculty Machine Shop with traditional machining equipment and tools. For this reason, Design for Manufacturability and Assembly (DFMA) was a critical aspect of the Panthra design. At every step of detailed design, thought for easy manufacturability with traditional machines was taken into account into order to speed fabrication with minimal chances of rework necessary.

As previously mentioned, the Panthra Robot is divided into five primary subsystems. Of these subsystems, the Payload Delivery System (PDS) and Vehicle Support System (VDS) required the most custom made parts. The other subsystems primary contained purchased parts and small mounts. The components for these systems were fabricated and assembled first as they represented the integral structural members and functional parts of the vehicle. After their fabrication, the smaller mounts and accessory parts of the other systems were manufactured. Any error in fabricating the main components could be compensated in the manufacture of the smaller components.

## Vehicle Support Structure (VSS) Fabrication

The VSS establishes the chassis of the robot and is composed of 6061 aluminum L-channel extrusions and an 1/8" thick 6061 T6 aluminum plate. 6061 aluminum was chosen for its excellent strength to weight ratio and machinability. The benefit of a high strength to weight ratio is an overall weight reduction of the entire vehicle which decreases motor load and increases battery life. The L-channel extrusions serve as wheel/component mounts and stiffening members of the chassis while the plate serves as the primary mounting structure for the PDS. Manufacturing the L-channel components required the use of a vertical bandsaw and a drill press alone, while the plate required the bandsaw, drill press, and a jigsaw. Rough edges were deburred with a belt sander and a file.



| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 1-001 | CHASSIS | 1 |
| 2 | 1-002 | L-CHANNEL SUPPORT, SIDE | 2 |
| 3 | 1-003 | L-CHANNEL SUPPORT, FRONT | 1 |
| 4 | 1-004 | L-CHANNEL SUPPORT, REAR | 1 |
| 5 | #10-0.5L | #10-24 SOCKET CAP SCREW, 0.5" L | 12 |
| 6 | #10-NUT | #10 HEXNUT | 12 |
| 7 | #10 WASHER | #10 FLAT WASHER | 12 |



**Figure 37: Vehicle Support Structure Engineering Drawing, Exploded View**

## Payload Delivery System (PDS) Fabrication

The PDS serves as the functional delivery system for the lead disks. Designing the PDS for manufacturability presented a difficulty as the creative nature of the system demands complexity and low tolerances. In order to perform its function, the PDS utilizes a linear actuator. The actuator requires contact between part faces with minimal normal forces between them. Care was taken to machine parts to tolerances of 0.010”, and in some instances, 0.005”. All components of the PDS were made from 6061 T6 aluminum for the same reasons as above, except for the spindle rod, which was made from 416 Stainless Steel for additional strength and stiffness. Most components were fabricated on the mill and drill press, while the spindle rod was fabricated on the lathe. Fabrication also involved deburring, tapping, threading, and chamfering.

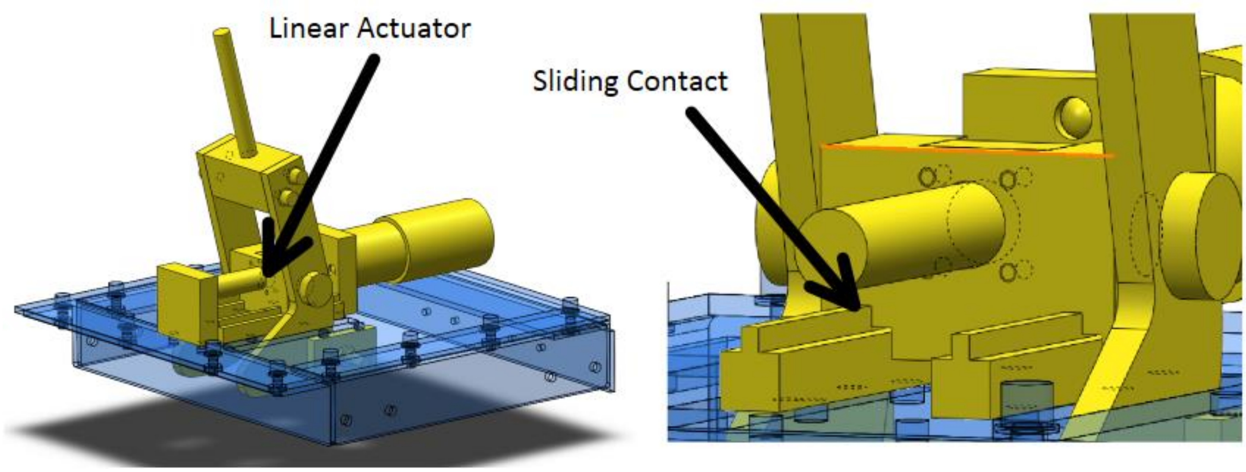



**Figure 38: Vehicle Delivery System: Low Tolerance Sliding Contacts Emphasized**

During manufacture of these parts, some small adjustments were made to the design of the actuator slides and drive screw bushing mounts. The team realized that the front drive screw bushing mount should not contain a through-hole, but a flat bottomed hole to constrain the drive screw from moving forward. This relieved the torque needed on the set screw holding the drive screw in place in the motor coupler. Other adjustments were small dimensional changes necessary to compensate for small dimension errors in other components.

# Assembly

Lastly, assembly was taken into account in the design of the Panthra. Aside from cases where purchased components required a specific fastener, #10-32 fasteners were used throughout the construction of the Panthra in order to guard against improper fastener installation and to reduce costs (by allowing bulk purchase). Furthermore, the Panthra was designed for easy access to and removal of the SB RIO, sensors, motor drivers, breadboard, and batteries. Each of these components can be removed from the Panthra without removing any structural components. This allows for quick and simple electrical debugging as well as quick battery exchange.

The following table lists every custom made part, its material, and machines used in its manufacture:

**Table 25: Parts and Machines**

| *Subsystem* | *Part Description* | *Mill* | *Lathe* | *Drill Press* | *Bandsaw* | *Belt Sander* | *Other* |
|---|---|---|---|---|---|---|---|
| **Vehicle Drive System (VDS)** | | | | | | | |
| | *Motor Mount* | | | x | x | x | |
| **Payload Delivery System (PDS)** | | | | | | | |
| | *Delivery Arm* | | | x | x | x | |
| | *Spindle* | | x | | | | Die |
| | *Spindle Mount* | x | | x | x | x | Tap |
| | *Drive Nut Mount* | x | | | x | x | Tap |
| | *Actuator Slide* | x | | x | x | x | Tap |
| | *Drive Screw Bushing Mount* | x | | | x | x | |
| | *Drive Motor Mount* | x | | | x | x | Counterbore |
| | *Drive Screw* | x | x | | x | | |
| | *Roller Mount* | | | x | x | x | Tap |
| **Vehicle Support Structure (VSS)** | | | | | | | |
| | *L-Channel Members* | | | x | x | x | |
| | *Chassis Plate* | | | x | x | | Jigsaw |
| **Electronics and Control System (ECS)** | | | | | | | |
| | *Motor Driver Mount* | | | x | x | x | |

# 7. Product Testing and Evaluation

The goal for our team from the get-go was to transport and unload three lead discs autonomously. While transporting three discs is a disadvantage competitively, our decision to use a unique unloading mechanism overweighed winning the competition. Due to the uniqueness of the unloading mechanism, carrying more than three discs seemed like a long shot.

The balance between stability and speed was at the forefront of product testing. With a full load of three discs, at one hundred percent power, the robot can probably drive in a straight line smoothly at a high speed; however, the robot cannot perform a skid steering turn at this speed. A fine line had to be drawn to decide how much speed to give up for stability. At twenty five percent motor effort, the robots steering performed great. The slow speed allowed skid steering to occur quickly enough relative to the robots speed. Unfortunately, at twenty five percent motor effort, the robot cannot drive up the fourteen degree incline with three discs loaded. After testing, a balance was found between stability and speed. Thirty eight percent motor power was the optimum output to reach our goal.

At thirty eight percent motor effort, the total runtime is seventy seconds. This is a little slower than our goal of sixty seconds, but will suffice. At forty five percent motor effort, a full run can be completed in sixty five seconds, however, the robots steering responds poorly. With seventy second runs, we expect to successfully complete four runs carrying three discs.

Four discs were tested with mixed results. The run was completed successfully at forty five percent motor effort. Driving on the ramp with the extra disc slowed the uphill portion by five seconds, as well as the unloading by one second. While the run was completed successfully, turning posed a problem. It took a lot of fine tuning to get the turning stable with three discs. With four discs, it would take countless hours to perfect the turning. The instability of four discs causes the robot to jerk when driving straight and not turn tight enough, due to the added friction on the skid turn. The benefits of using the bonus disc do not outweigh stability for us, therefore, we are comfortable using three discs, and aim to complete four solid runs.

**Table 26: Breakdown of average run times**

| # of Discs | Uphill time (s) | Unload time (s) | Downhill time (s) | reload time (s) |
|---|---|---|---|---|
| 3 | 35 | 5 | 30 | 5 |
| 4 | 40 | 6 | 30 | 6 |

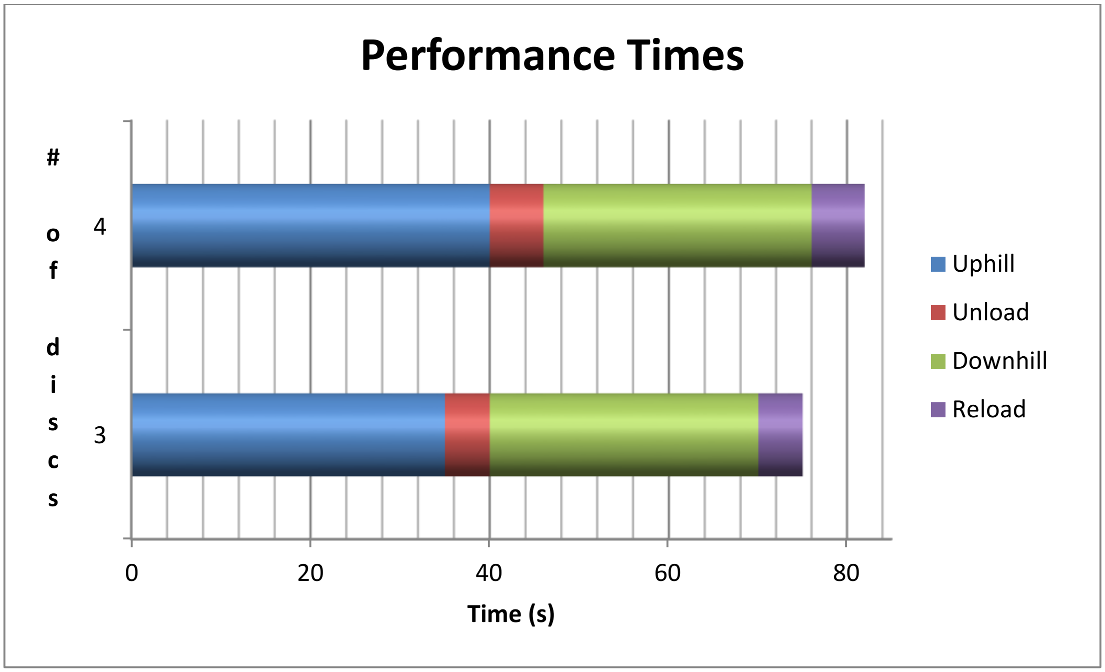



**Figure 39: Performance Times**

The increased time while carrying four discs is due to the heavier load. The motor power can be increased to compensate for the heavier, however, steering is not sufficient. Unloading increses by a second due to the fact the lead screw motor is slowed by the heavier load, this is not a negative impact. Reload time also adds a second, it takes about a second a disc, with a two second safety window based on averages during testing.

Unloading time can be sped up by increasing the lead screw's motor effort. If the discs are unloaded too fast, a risk of tipping arises from the impulsive torque, we do not want to risk this. From testing, sixty percent unloading power delivered the load smoothly in 5 seconds.

# 8. Work Breakdown Schedule

## Work Breakdown Schedule Dictionary

**Table 27: Work Breakdown Schedule Dictionary**

| WBS Element | Description |
|---|---|
| **Panthra Transporter** | Project title, main deliverable (transporter) |
| **1. Design** | Design of transporter, complete CAD model |
| 1.1 Mechanical Systems | Drive and delivery systems |
| 1.1.1 Analysis | Force, torque, FEM analysis |
| 1.2 Electrical System | Includes SB rio board, sensors, etc. |
| 1.2.1 Analysis | Circuit analysis |
| **2. Material Procurement** | Self explanatory |
| 2.1 Bill of Materials | Get from CAD model |
| 2.2 Prices | Research best prices |
| 2.3 Purchasing | Purchase all materials |
| **3. Manufacturing** | Self explanatory |
| 3.1 Create drawings | Create using CAD model |
| 3.2 Machining | Machine all metal parts |
| 3.2.1 Distribute work | Split up work load |
| **4. Assembly of Mechanical Parts** | Self explanatory |
| **5. Test Electrical Components** | Self explanatory |
| 5.1 SB Rio Board | Test battery, board, connectors |
| 5.2 Sensors | Test connectors |
| 5.3 Motor Controllers | Test connectors |
| **6. Circuit Diagrams** | Self explanatory |
| 6.1 Data sheets | Look up data sheets for electrical components |
| 6.2 Draw circuit diagrams by hand | Self explanatory |
| 6.3 Draw circuit diagrams on computer | Self explanatory |
| **7. Assemble Electrical Components** | Self explanatory |
| 7.1 Mount components on transporter | Self explanatory |
| 7.2 Route all wires using circuit diagrams | Self explanatory |
| 7.3 Clean up/organize wires | Clean up wires using zipties or other method |
| **8. Programming** | Program transporter to move, deliver load autonomously |
| **9. Testing/Fine Tuning** | Self explanatory |
| 9.1 Test mechanical parts | Test mechanical parts, replace broke parts |
| 9.2 Test and fine turn programming | Fine tune programming for best results |
| **10. Demo/Competition** | Successfully deliver load and return to starting point |

### Gantt Chart

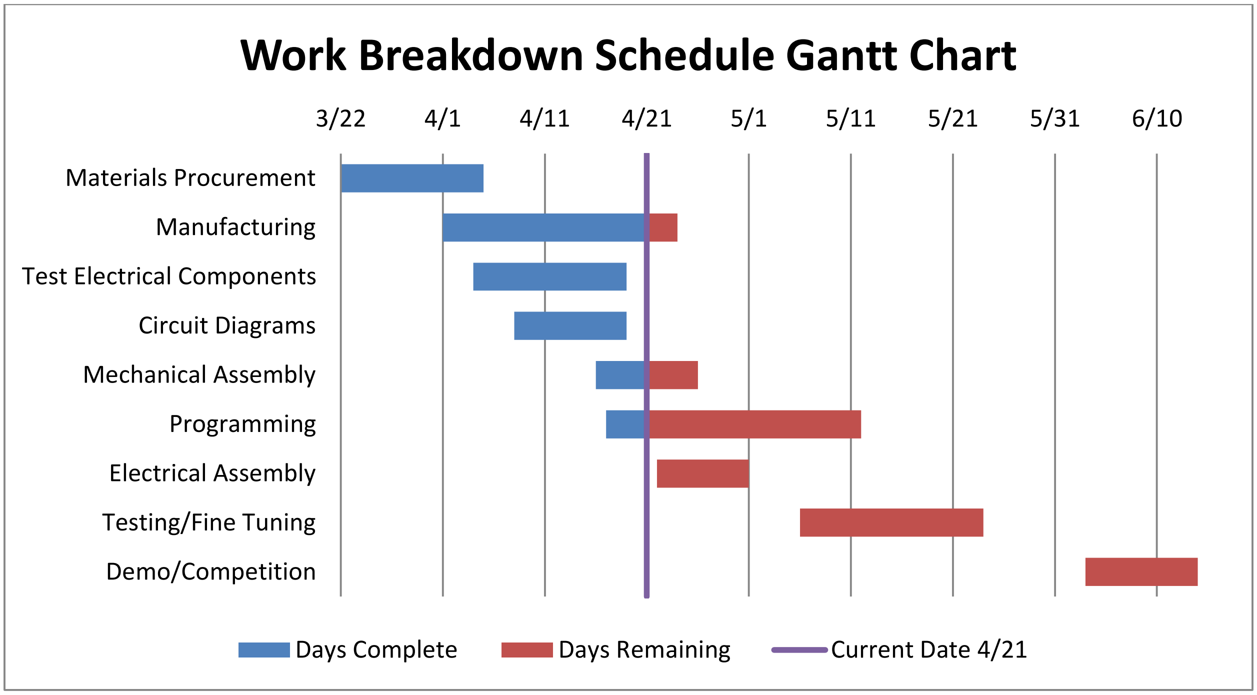



**Figure 40: Schedule Gantt chart. See work breakdown schedule dictionary for more detail on these milestones**

The Gantt Chart provides a good portrayal of our location throughout the project. This was mostly due to the fact that most things where done consistently each day. The group members tasks where distributed in an organized matter such that everyone always have certain tasks to accomplish. Throughout the whole process the steps that makes this possible is the determination of the individual group member that made this possible.

## 9. Bill of Materials and Procurement

Our CAD model has been broken up into the system subassemblies:

1- Vehicle Support Structure
2- Electronics and Control System
3- Vehicle Drive System
4- Payload Delivery System
5- Vehicle Sensor Array

The part numbers are broken up and numbered according to these subassemblies.

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 1-001 | CHASSIS | 1 |
| 2 | 1-002 | L-CHANNEL SUPPORT, SIDE | 2 |
| 3 | 1-003 | L-CHANNEL SUPPORT, FRONT | 1 |
| 4 | 1-004 | L-CHANNEL SUPPORT, REAR | 1 |
| 5 | #10-0.5L | #10-24 SOCKET CAP SCREW, 0.5" L | 36 |
| 6 | #10-NUT | #10 HEXNUT | 12 |
| 7 | #10 WASHER | #10 FLAT WASHER | 36 |
| 8 | 2-001 | SB RIO BASE PLATE | 1 |
| 9 | 2-002 | HEX STANDOFF, .48" | 4 |
| 10 | 2-003 | SB RIO BOARD | 1 |
| 11 | 2-004 | HEX STANDOFF, 1.48" | 4 |
| 12 | 2-005 | SB RIO ADD-ON BOARD | 1 |
| 13 | 2-006 | SB RIO BATTERY | 1 |
| 14 | 2-007 | BATTERY PACK, (4) D SIZE | 1 |
| 15 | 2-008 | BATTERY PACK, (6) D SIZE | 1 |
| 16 | 2-009 | CYTRON DC MOTOR CONTROLLER | 3 |
| 17 | 2-010 | BREADBOARD | 1 |
| 18 | #4-STANDOFF | HEX STANDOFF | 6 |
| 19 | 3-001 | TETRIX DC MOTOR BASE | 4 |
| 20 | 3-002 | TETRIX DC MOTOR HEAD | 4 |
| 21 | 3-003 | BANEBOTS 2.875" WHEEL | 4 |
| 22 | 3-004 | AXLE SET COLLAR | 4 |
| 23 | 3-005 | MOTOR MOUNT PLATE | 4 |
| 24 | #4-0.75L | #4 SOCKET CAP SCREW | 20 |
| 25 | #4ss-0.25L | #4 SET SCREW | 4 |
| 26 | M3x0.5-0.375L | M3X0.5 SOCKET CAP SCREW | 8 |

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 27 | #4 WASHER | #4 FLAT WASHER | 16 |
| 28 | M3 WASHER | M3 WASHER | 8 |
| 29 | 4-010 | PAYLOAD CARRY ARM | 2 |
| 30 | 4-011 | PAYLOAD SPINDLE | 1 |
| 31 | 4-012 | SPINDLE MOUNT | 1 |
| 32 | 4-102 | HENNKWELL DC MOTOR ASSEMBLY | 1 |
| 33 | 4-005 | | 1 |
| 34 | 4-009 | | 1 |
| 35 | 4-001 | LINEAR ACTUATOR SLIDE | 2 |
| 36 | 4-002 | DRIVE SCREW BEARING MOUNT | 2 |
| 37 | 4-003 | DRIVE SCREW BEARING | 1 |
| 38 | 4-004 | ROLLER MOUNT | 2 |
| 39 | 4-006 | ROLLER | 1 |
| 40 | 4-007 | 0.5" SHOULDER SCREW | 2 |
| 41 | 4-008 | 0.5" LEAD SCREW, 4"L | 1 |
| 42 | .25-3.0L | 0.25" SOCKET CAP SCREW | 1 |
| 43 | .25 WASHER | 0.25" WASHER | 1 |
| 44 | 0.25-NUT | 0.25" HEX NUT | 1 |
| 45 | 5-001 | VEX BUMPER SENSOR | 2 |
| 46 | 5-002 | ULTRASONIC SENSOR | 2 |
| 47 | Lead Disk weight 5.75lb | LEAD DISC, 5.75LBS, 6" DIAMETER | 3 |
| 48 | #6-.5L | #6-32 SOCKET CAP SCREW | 13 |
| 49 | #6-NUT | #6 HEX NUT | 13 |
| 50 | #6 WASHER | #6 FLAT WASHER | 13 |

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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL N/A
FINISH N/A
DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | C.UNDERHILL | 03/20/2013 |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

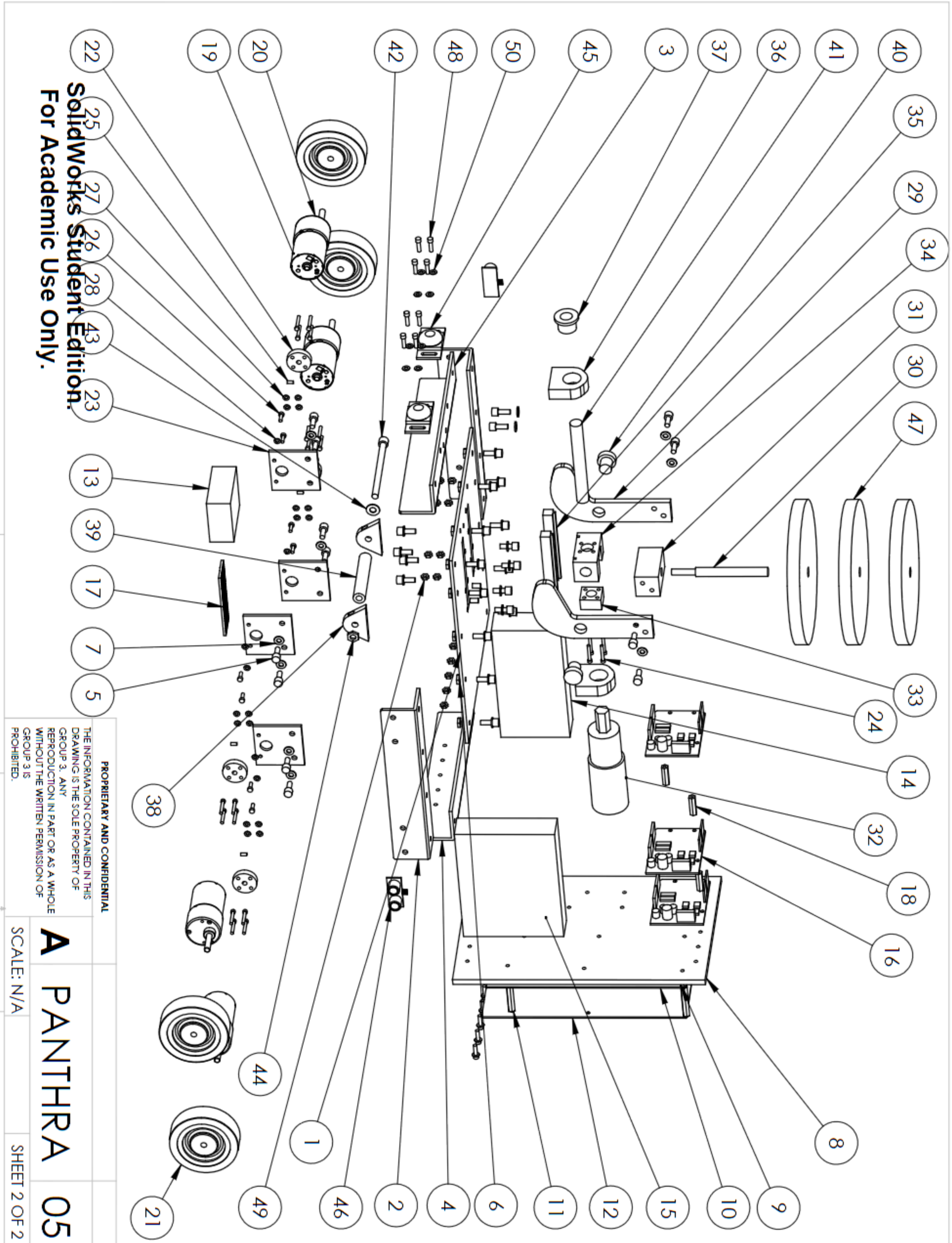
COMMENTS:

MAE 162D - GROUP 3

TITLE:
AUTONOMOUS BULK TRANSPORTER

SIZE A DWG. NO. PANTHRA REV 05

SCALE: N/A WEIGHT: N/A SHEET 1 OF 2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A
PANTHRA
05
SCALE: N/A
SHEET 2 OF 2

We bought all of the parts ourselves. We have done a lot of research on vendors and believe our parts are reasonably prices. Some of these parts will be ordered online and some will be purchased in person. We came in just under the $350 budget.

# 10. Design Requirement Satisfaction

| Subsystem | Requirements | Result |
|---|---|---|
| VDS | Sufficient motor output to propel vehicle up ramp and through course with desired speed and a 3 disk payload. | The motor calculations in Part 3 show that the 4 Tetrix motors provide ample power to drive the vehicle under load with a run time of approximately 40 seconds. |
| PDS | Strong enough material not to deform under requisite load.<br><br>Lower load quasi-statically to offload position and self righting of spindle.<br><br>Sufficient motor output to advance arm. | Calculations in Part 6 show that a spindle made of High Strength ASTM-A242 Steel should not deform under the load of 3 disks<br><br>The curved design of *the Fang* will lower the arm quasi-statically and return the arm to the upright position through use of only a lead screw drive system.<br><br>The motor calculations in Part 6 show that the Henkwell 12V motor provides ample power to advance the PDS under load. |
| VSS | Sufficient strength to hold on subassemblies in within the requisite size constraints and a center of gravity (CG) somewhat centered and the ability to remain upright in the offload position. | The vehicle falls within the requisite dimensional constraints with a CG within the wheelbase. In the offload position, the vehicle will utilize a lip on the front to rest on the maze wall and prevent flipping.<br><br>Since we have not yet learned the FEA in Solidworks, our strength analysis in this area is incomplete until next quarter. Using common sense and machining experience, our structure should be strong enough to handle all necessary loads. |
| ECS | Must fit within dimensional constraints. | The current configuration of the vehicle fits within the requisite dimensional constraints. |

| | | |
|---|---|---|
| | Provide requisite current and stored power to handle multiple runs | By selecting D batteries for the final run, the ECS should provide enough amp-hours to conduct several runs. |
| VSA | Ultrasonic sensors must have minimum range to detect walls at close proximity | The ultrasonic sensors have a minimum range of 2cm. Even with that case, by placing two sensors on each side let us read distance from both wall. This will always give us good results from one sensor and provide smooth turns. |

# 11. Conclusion

From our original three designs we have narrowed it down to a combination of the *Panthro* and *Cheetara* base on the analysis we did with the conceptual tree. Our conceptual design from these two combinations creates the *Panthra*. This robot has met the requirements for our needs based on our initial calculations. *Panthra* is distinct from the other two designs because it incorporates the innovative spindle arm with the four wheel drive system for maneuverability. The spindle arm is a plus, because we wanted a design that uses the force of gravity to help drop the disks and be able to extend and retract to move our center of gravity only when we are unloading. As for the four wheel base, we chose this mostly for maneuverability. From our knowledge and objective tree we avoided the track system since it has more friction when turning when compared to the four wheel vehicle turning. From this analysis we have *Panthra*.

During the manufacturing process of *Panthra we* smoothly create the necessary parts for the VSS and PDS without many problems. We also perform a FEM analysis and find out that the stress was an order of magnitude below the yielding stress making the PDS safe enough to operate without failure. Following the Gantt chart schedule we finished the base as planned assemble the circuits and begin the programming. The schedule where exactly followed due to the fact that the group was extremely organized and workload were distributed evenly.

The lessons we mostly learn where picked up during the programming and organization. These lesson for programming where techniques to improve the smoothness in wall following. For organization we learn to keep work distributed and time managed. We started the programming early and worked on it consistently giving us enough time to have a tune up.

With this our successful “Panthra Project” has finally come to an end accomplishing the high level requirements we set out to perform. Overall, *Panthra* is a huge success completing the run smoothly as we desire.

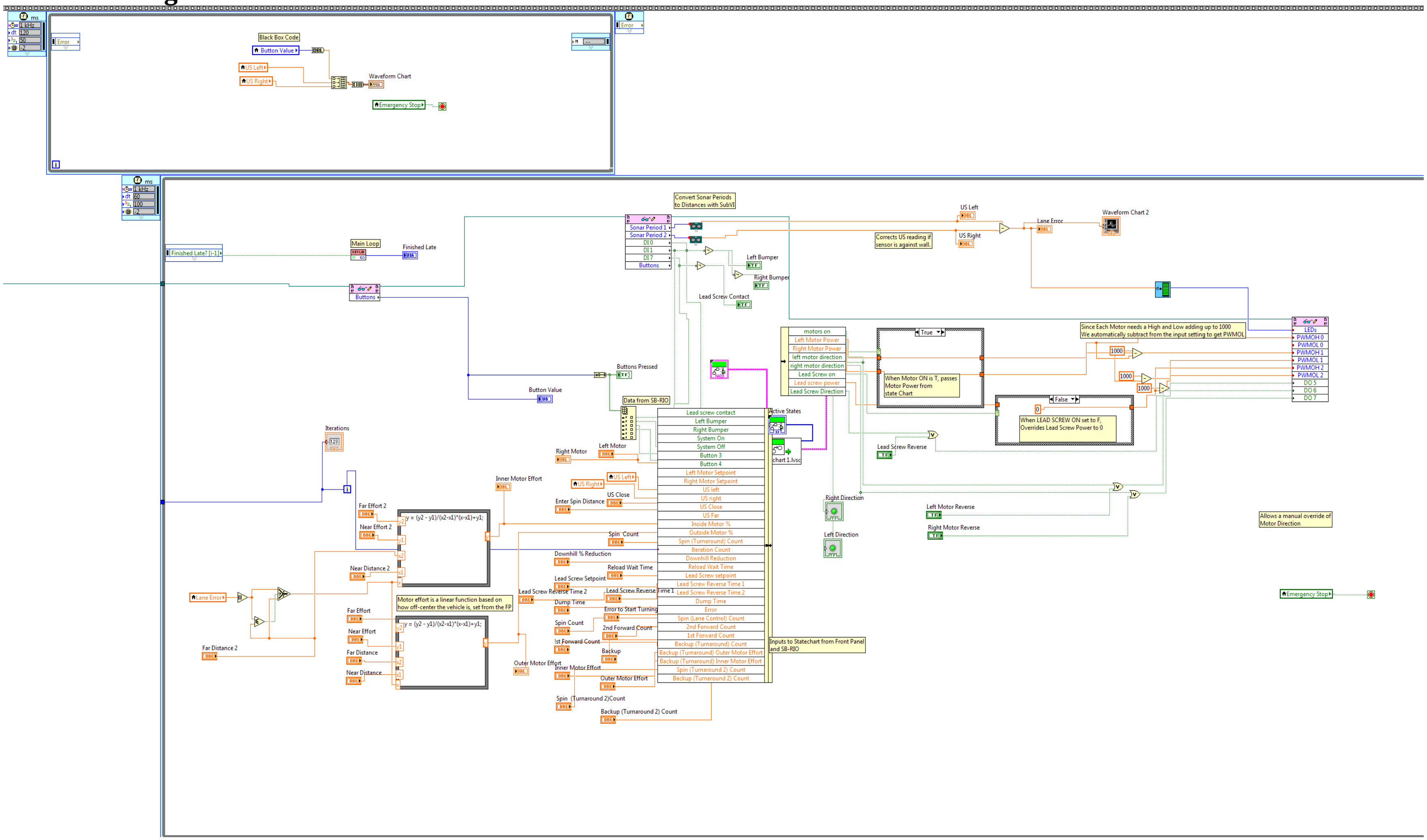
# 12. Reference

[1] Ugural, A. *Advanced Mechanics of Materials and Applied Elasticity* (5th ed.). Prentice Hall 2012.
[2] *BaneBots Wheel.* (2013, March 1). Retrieved from http://banebots.com
[3] *General Specifications for Tetrix DC Drive Motor.* (2011, January 1). Retrieved February 5, 2013
[4] International Atomic Energy Agency (IAEA). (2006). *The Safe Transport of Radioactive Materials 4th Edition.*
[5] Klesov, A. A. (2007). *Wood-plastic Composites.* Hoboken, NJ: Wiley-Interscience.
[6] Schaefer, R. (2013, Winter). Mechanical and Aeropace Engineering 162 Ramp Detail.
[7] Schaefer, R. (2013, Winter). Mechanical And Aerospace Engineering 162D Lecture 2 Mechanical Engineering Based Design Approach to the Transporter.
[8] Schaefer, R. (2013, Winter). Mechanical And Aerospace Engineering 162D Lecture 5A – Smart Motor Sizing.
[9] Rolling Friction and Rolling Resistance. (n.d.). *The Engineering Toolbox* . Retrieved March 1, 2013, from http://www.engineeringtoolbox.com/rolling-friction-resistance-d_1303.html

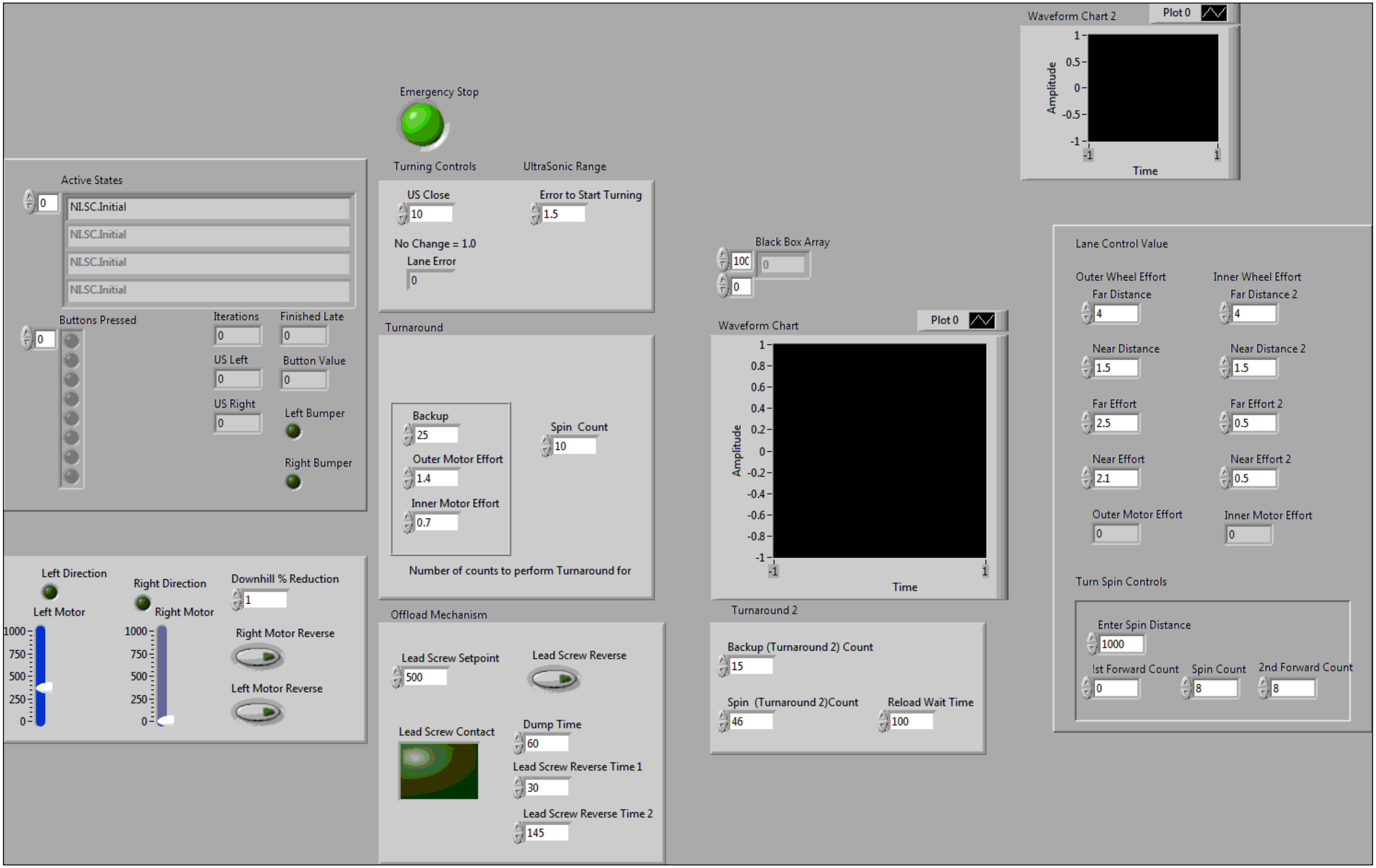
# 13. Appendix

## Labview Code

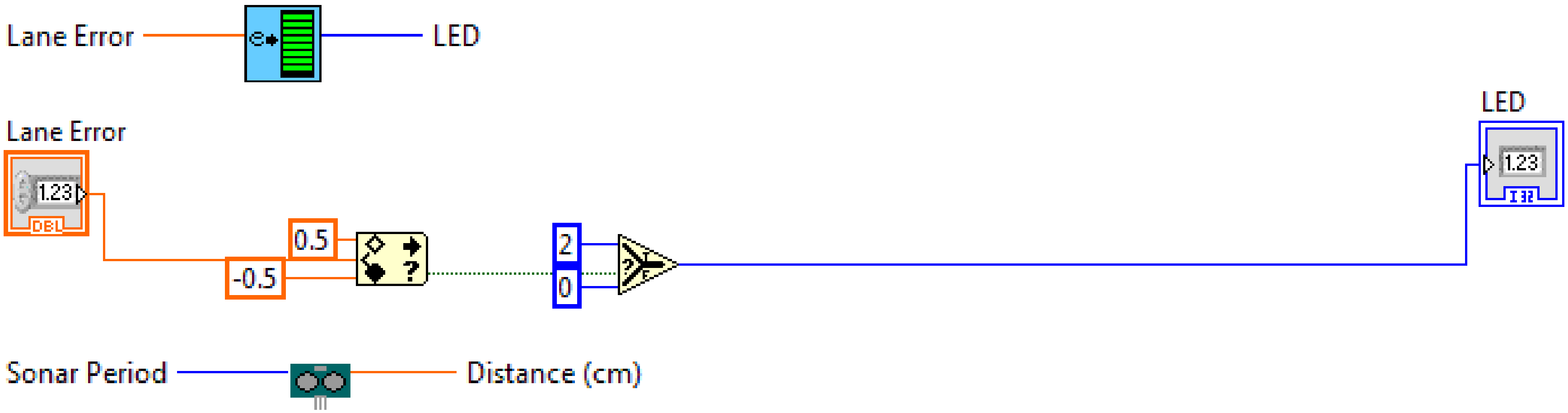
### Block Diagram



## Front Panel

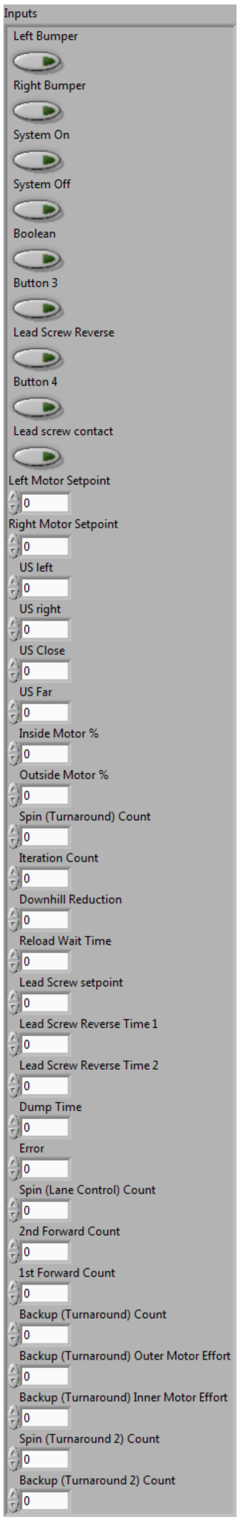

Emergency Stop
Waveform Chart 2
Plot 0
Amplitude
Time
Active States
NI.SC.Initial
NI.SC.Initial
NI.SC.Initial
NI.SC.Initial
Buttons Pressed
Iterations
Finished Late
US Left
Button Value
US Right
Left Bumper
Right Bumper
Turning Controls
UltraSonic Range
US Close
10
Error to Start Turning
1.5
No Change = 1.0
Lane Error
Turnaround
Backup
25
Outer Motor Effort
1.4
Inner Motor Effort
0.7
Spin Count
10
Number of counts to perform Turnaround for
Black Box Array
Waveform Chart
Plot 0
Amplitude
Time
Lane Control Value
Outer Wheel Effort
Inner Wheel Effort
Far Distance
4
Far Distance 2
4
Near Distance
1.5
Near Distance 2
1.5
Far Effort
2.5
Far Effort 2
0.5
Near Effort
2.1
Near Effort 2
0.5
Outer Motor Effort
Inner Motor Effort
Turn Spin Controls
Enter Spin Distance
1000
Ist Forward Count
Spin Count
8
2nd Forward Count
8
Left Direction
Right Direction
Downhill % Reduction
1
Left Motor
Right Motor
Right Motor Reverse
Left Motor Reverse
Offload Mechanism
Lead Screw Setpoint
500
Lead Screw Reverse
Lead Screw Contact
Dump Time
60
Lead Screw Reverse Time 1
30
Lead Screw Reverse Time 2
145
Turnaround 2
Backup (Turnaround 2) Count
15
Spin (Turnaround 2)Count
46
Reload Wait Time
100

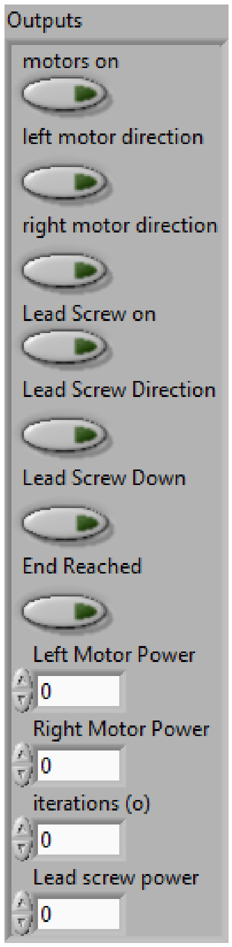
**Sub Vis**

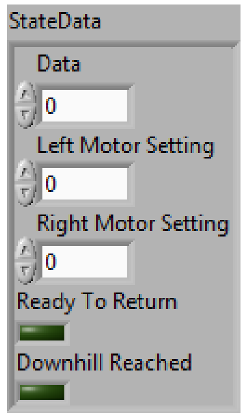

Lane Error
LED
Lane Error
1.23
DBL
0.5
-0.5
2
0
LED
1.23
I32
Sonar Period
Distance (cm)

## State Chart

Inputs Outputs StateData



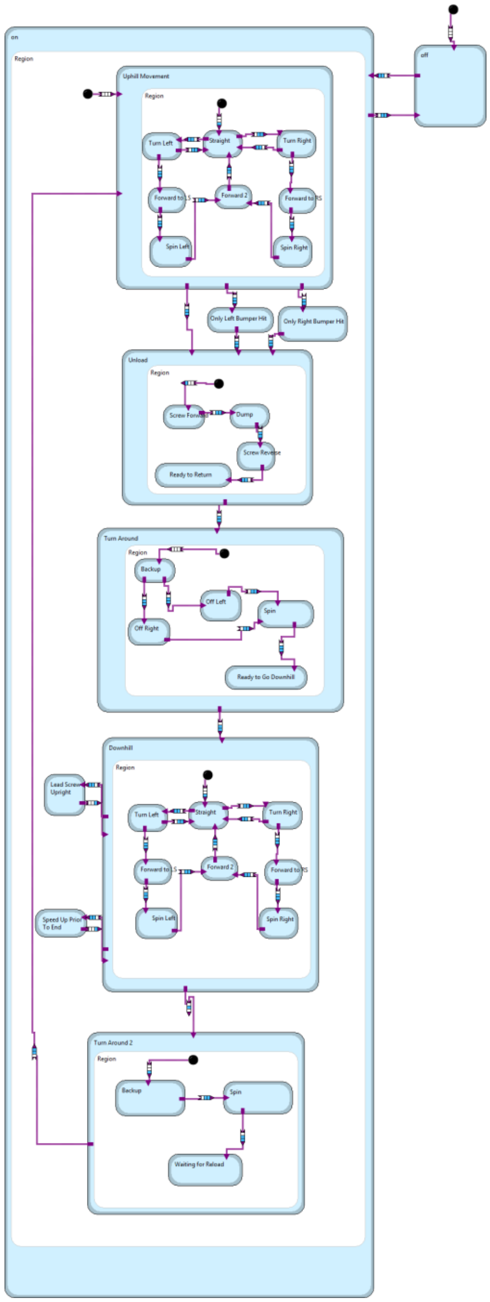



## Code Generation Properties

| | |
|---|---|
| **Execution Target** | Real Time |
| **Usage** | Synchronous |
| **Queue Settings** | Not Applicable |
| **Internal trigger queue size** | 10 |
| **Debugging** | Disabled |
| **Reset output values after each iteration** | FALSE |
| **Guard or Action VI reentrancy** | Preallocate clone for each instance |

## Statechart Diagram

**Main Diagram**

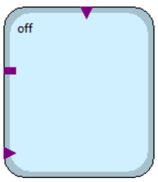

on
off
Region
Uphill Movement
Turn Left
Straight
Turn Right
Forward 2
Spin Left
Spin Right
Only Left Bumper Hit
Only Right Bumper Hit
Unload
Dump
Ready to Return
Turn Around
Backup
Off Left
Spin
Off Right
Ready to Go Downhill
Downhill
Turn Around 2
Waiting for Reload

| | |
|---|---|
| **Contained Objects** | Initial, off, on |
| **Contained Transitions** | Transition, Transition, Transition |

**A Initial**

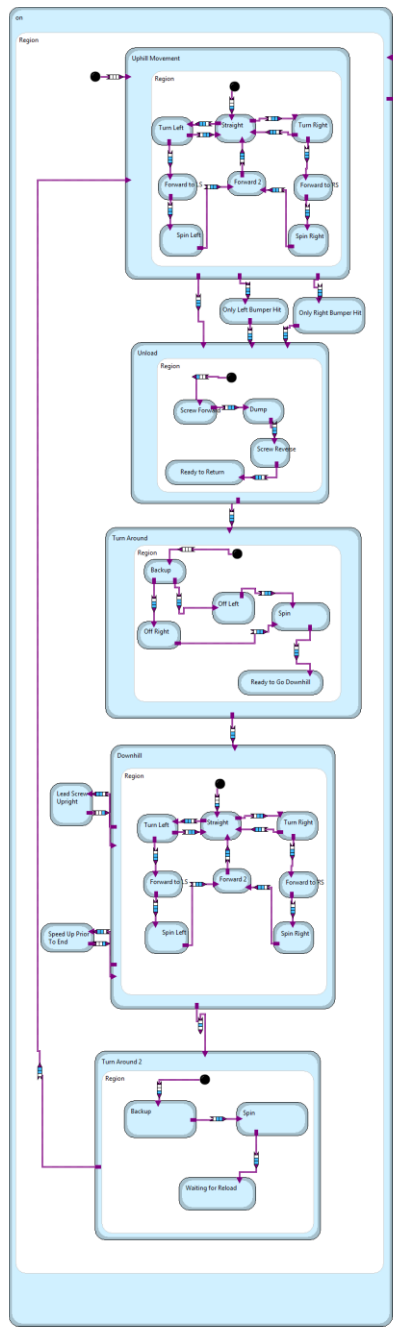
| | |
|---|---|
| **Description** | - |
| **Destination** | Transition ->off |
| **Containing Region** | Main Diagram |

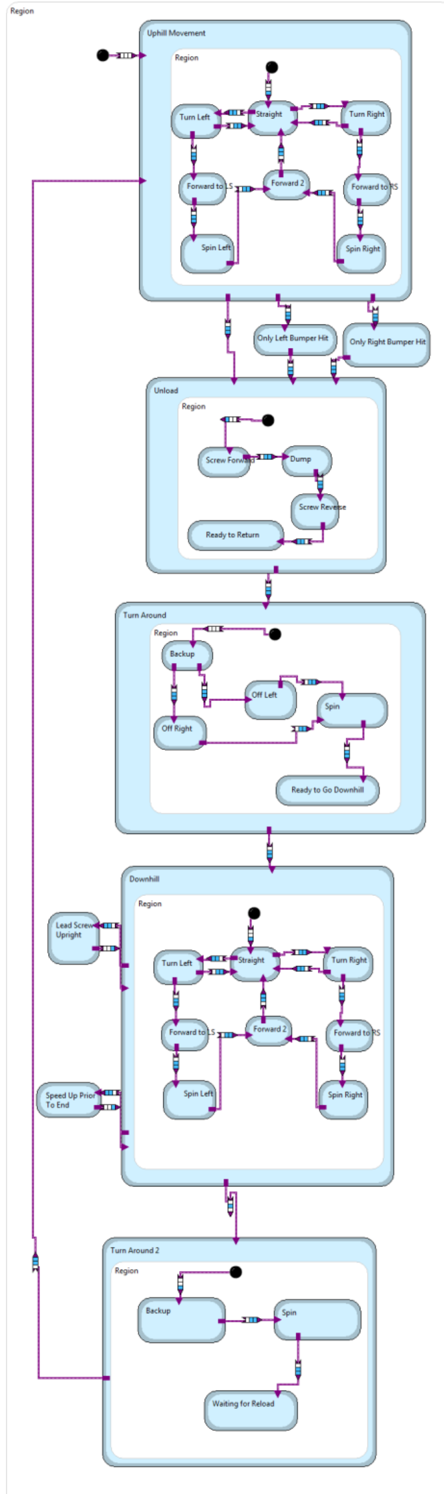
**B off**




| | |
|---|---|
| **Description** | - |
| **Source** | Initial ->Transition, on ->Transition |
| **Destination** | Transition ->on |
| **Containing Region** | Main Diagram |

**C on**






| Description | - |
|---|---|
| Source | off ->Transition |
| Destination | Transition ->off |
| Containing Region | Main Diagram |
| Contained Regions | Region |

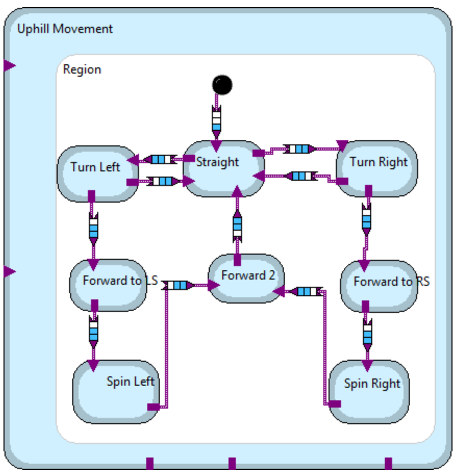
**C.1 Region**

| | |
|---|---|
| **Description** | - |
| **Containing State** | on |
| **Contained Objects** | Uphill Movement, Unload, Turn Around, Turn Around 2, Initial, Downhill, Lead Screw Upright, Speed Up Prior To End, Only Left Bumper Hit, Only Right Bumper Hit |
| **Contained Transitions** | Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition |

#### C.1.A Initial

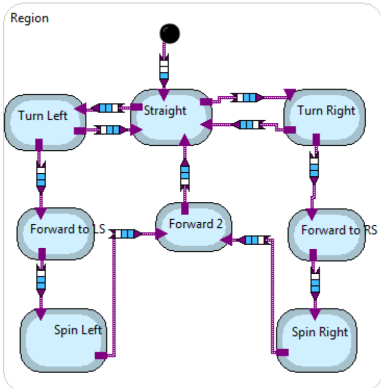
| | |
|---|---|
| **Description** | - |
| **Destination** | Transition ->Uphill Movement |
| **Containing Region** | Region |

#### C.1.B Uphill Movement




| | |
|---|---|
| **Description** | - |
| **Source** | Initial ->Transition, Turn Around 2 ->Transition |
| **Destination** | Transition ->Unload, Transition ->Only Left Bumper Hit, Transition ->Only Right Bumper Hit |
| **Containing Region** | Region |
| **Contained Regions** | Region |

##### C.1.B.1 Region

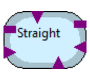



| | |
|---|---|
| **Description** | - |
| **Containing State** | Uphill Movement |
| **Contained Objects** | Straight, Turn Right, Turn Left, Initial, Spin Left, Spin Right, Forward 2, Forward to LS , Forward to RS |
| **Contained Transitions** | Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition |

#### C.1.B.1.A Initial

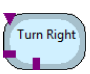
| | |
|---|---|
| **Description** | - |
| **Destination** | Transition ->Straight |
| **Containing Region** | Region |

#### C.1.B.1.B Straight



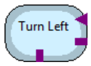

| | |
|---|---|
| **Description** | - |
| **Source** | Initial ->Transition, Turn Left ->Transition, Turn Right ->Transition, Forward 2 ->Transition |
| **Destination** | Transition ->Turn Left, Transition ->Turn Right |
| **Containing Region** | Region |

#### C.1.B.1.C Turn Right




| | |
|---|---|
| **Description** | - |
| **Source** | Straight ->Transition |
| **Destination** | Transition ->Straight, |
| **Containing Region** | Region |

#### C.1.B.1.D Turn Left




| | |
|---|---|
| **Description** | - |
| **Source** | Straight ->Transition |
| **Destination** | Transition ->Straight, |
| **Containing Region** | Region |

### C.1.B.1.E Spin Left


| | |
|---|---|
| **Description** | - |
| **Source** | Forward to LS ->Transition |
| **Destination** | Transition ->Forward 2 |
| **Containing Region** | Region |

### C.1.B.1.F Spin Right


| | |
|---|---|
| **Description** | - |
| **Source** | Forward to RS ->Transition |
| **Destination** | Transition ->Forward 2 |
| **Containing Region** | Region |

### C.1.B.1.G Forward 2


| | |
|---|---|
| **Description** | - |
| **Source** | Spin Left ->Transition, Spin Right ->Transition |
| **Destination** | Transition ->Straight |
| **Containing Region** | Region |

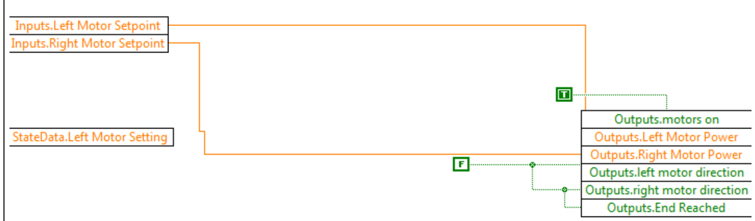
### C.1.B.1.H Forward to LS


| | |
|---|---|
| **Description** | - |
| **Source** | Turn Left ->Transition |
| **Destination** | Transition ->Spin Left |
| **Containing Region** | Region |

### C.1.B.1.I Forward to RS

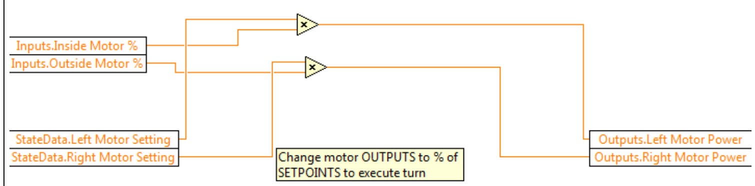
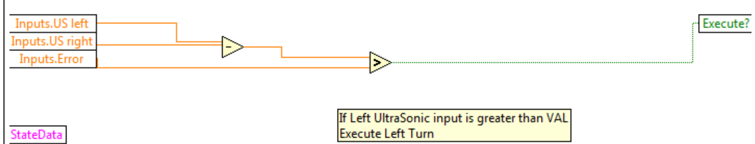
| | |
|---|---|
| **Description** | - |
| **Source** | Turn Right ->Transition |
| **Destination** | Transition ->Spin Right |
| **Containing Region** | Region |

#### C.1.B.1.J Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Initial |
| **Destination** | | | Straight |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | {Responds to all triggers} |
| | **Action** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

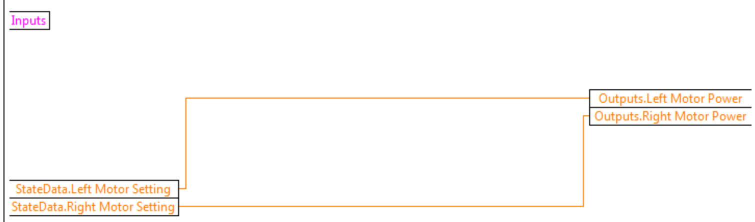
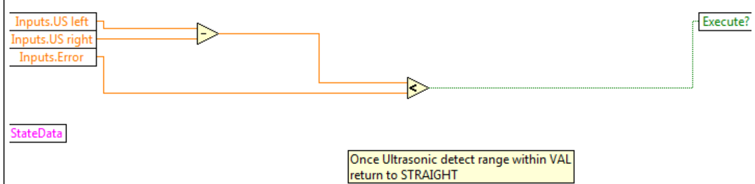
#### C.1.B.1.K Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Straight |
| **Destination** | | | Turn Left |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

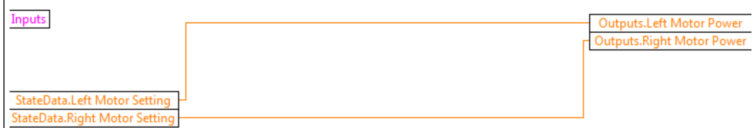
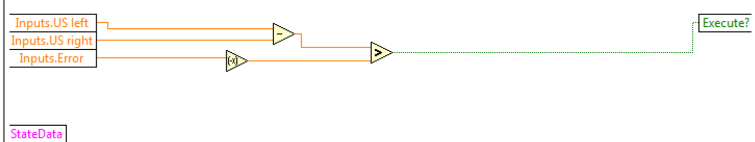
**C.1.B.1.L Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Turn Left |
| **Destination** | | | Straight |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

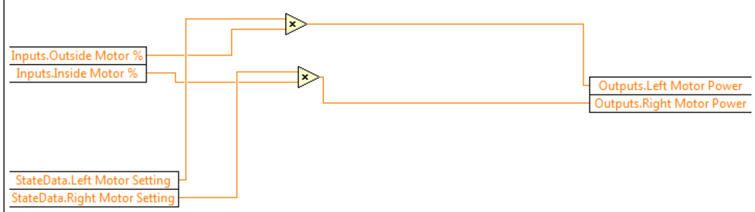
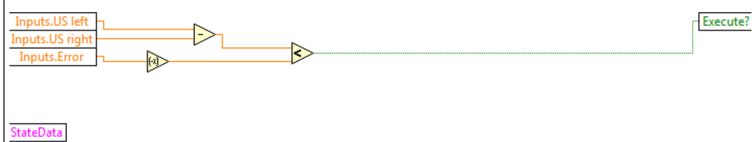
#### C.1.B.1.M Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Turn Right |
| **Destination** | | | Straight |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

#### C.1.B.1.N Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Straight |
| **Destination** | | | Turn Right |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

<table>
<tr><td rowspan="6"></td><td rowspan="3"></td><td></td><td>
</td></tr>
<tr><td>Disable</td><td>FALSE</td></tr>
<tr><td>AutoPreAllocate</td><td>FALSE</td></tr>
<tr><td rowspan="3">Guard</td><td>Code</td><td>
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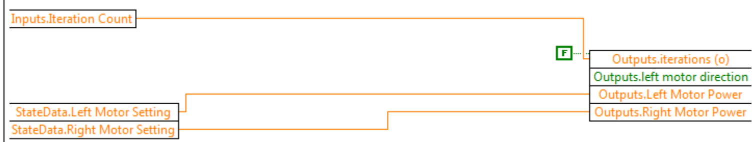
<tr><td>Disable</td><td>FALSE</td></tr>
<tr><td>AutoPreAllocate</td><td>FALSE</td></tr>
</table>

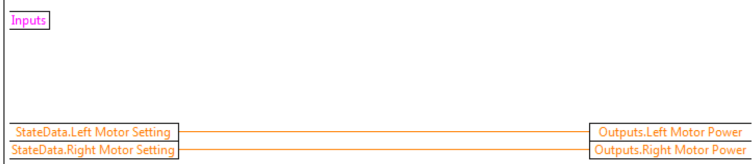
#### C.1.B.1.O Transition

<table>
<tr><td colspan="3">Description</td><td>-</td></tr>
<tr><td colspan="3">Source</td><td>Spin Left</td></tr>
<tr><td colspan="3">Destination</td><td>Forward 2</td></tr>
<tr><td colspan="3">Containing Region</td><td>Region</td></tr>
<tr><td rowspan="3">Transition Code</td><td colspan="2">Description</td><td></td></tr>
<tr><td colspan="2">Trigger List</td><td>NULL</td></tr>
<tr><td>Action</td><td>Code</td><td></td></tr>
</table>

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

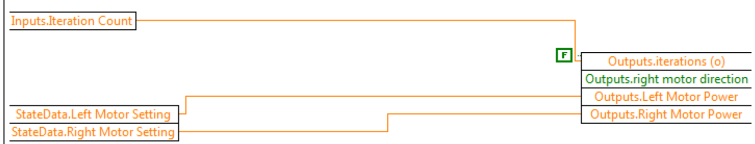
#### C.1.B.1.P Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Forward 2 |
| **Destination** | | | Straight |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

<table>
<tr><td rowspan="6"></td><td rowspan="3"></td><td></td><td>
</td></tr>
<tr><td>Disable</td><td>FALSE</td></tr>
<tr><td>AutoPreAllocate</td><td>FALSE</td></tr>
<tr><td rowspan="3">Guard</td><td>Code</td><td>
</td></tr>
<tr><td>Disable</td><td>FALSE</td></tr>
<tr><td>AutoPreAllocate</td><td>FALSE</td></tr>
</table>

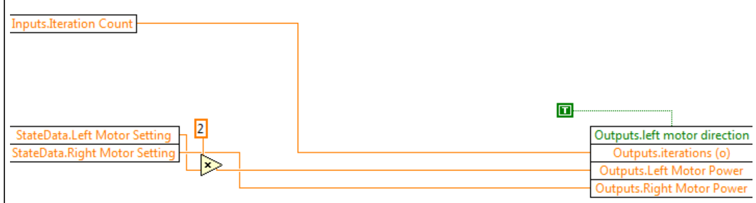
### C.1.B.1.Q Transition

<table>
<tr><td colspan="3">Description</td><td>-</td></tr>
<tr><td colspan="3">Source</td><td>Spin Right</td></tr>
<tr><td colspan="3">Destination</td><td>Forward 2</td></tr>
<tr><td colspan="3">Containing Region</td><td>Region</td></tr>
<tr><td rowspan="3">Transition Code</td><td colspan="2">Description</td><td></td></tr>
<tr><td colspan="2">Trigger List</td><td>NULL</td></tr>
<tr><td>Action</td><td>Code</td><td></td></tr>
</table>

<table>
<tr><td rowspan="6"></td><td rowspan="3"></td><td></td><td>
</td></tr>
<tr><td>Disable</td><td>FALSE</td></tr>
<tr><td>AutoPreAllocate</td><td>FALSE</td></tr>
<tr><td rowspan="3">Guard</td><td>Code</td><td>
</td></tr>
<tr><td>Disable</td><td>FALSE</td></tr>
<tr><td>AutoPreAllocate</td><td>FALSE</td></tr>
</table>

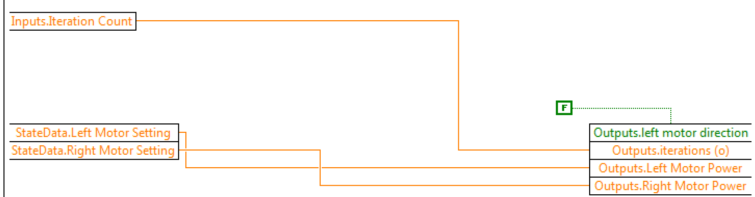
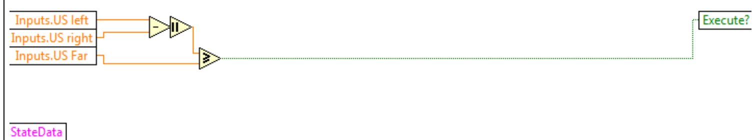
#### C.1.B.1.R Transition

<table>
<tr><td colspan="3">Description</td><td>-</td></tr>
<tr><td colspan="3">Source</td><td>Forward to LS</td></tr>
<tr><td colspan="3">Destination</td><td>Spin Left</td></tr>
<tr><td colspan="3">Containing Region</td><td>Region</td></tr>
<tr><td rowspan="3">Transition Code</td><td colspan="2">Description</td><td></td></tr>
<tr><td colspan="2">Trigger List</td><td>NULL</td></tr>
<tr><td>Action</td><td>Code</td><td></td></tr>
</table>

| | | | |
|---|---|---|---|
| | | |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

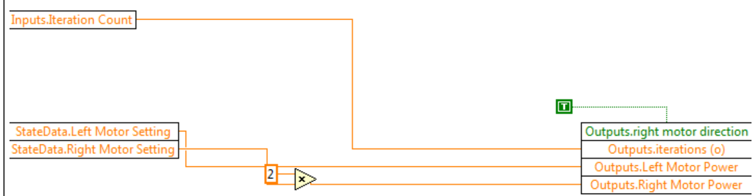
**C.1.B.1.S Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Turn Left |
| **Destination** | | | Forward to LS |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | | |
|---|---|---|---|---|
| | | | |  |
| | | | Disable | FALSE |
| | | | AutoPreAllocate | FALSE |
| | | Guard | Code |  |
| | | | Disable | FALSE |
| | | | AutoPreAllocate | FALSE |

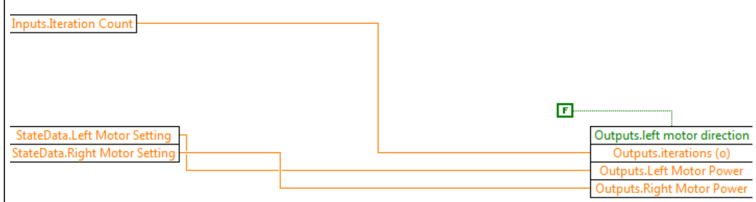
#### C.1.B.1.T Transition

| | | | |
|---|---|---|---|
| Description | | | - |
| Source | | | Forward to RS |
| Destination | | | Spin Right |
| Containing Region | | | Region |
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code | |

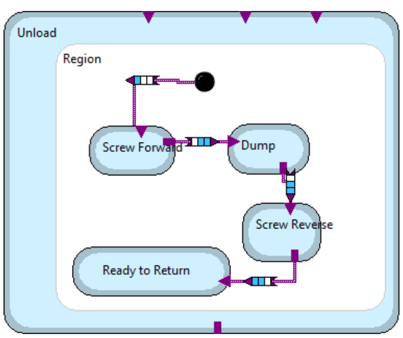
| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

**C.1.B.1.U Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Turn Right |
| **Destination** | | | Forward to RS |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

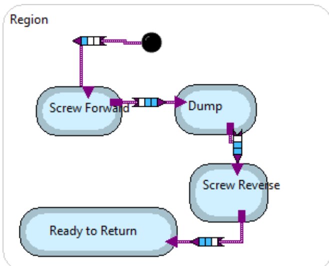
| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

**C.1.C Unload**



| | |
|---|---|
| **Description** | - |
| **Source** | Uphill Movement ->Transition, Only Left Bumper Hit ->Transition, Only Right Bumper Hit ->Transition |
| **Destination** | Transition ->Turn Around |
| **Containing Region** | Region |
| **Contained Regions** | Region |

#### C.1.C.1 Region

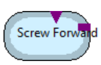



| | |
|---|---|
| **Description** | - |
| **Containing State** | Unload |
| **Contained Objects** | Initial, Screw Forward, Dump, Screw Reverse, Ready to Return |
| **Contained Transitions** | Transition, Transition, Transition, Transition |

#### C.1.C.1.A Initial

| | |
|---|---|
| **Description** | - |
| **Destination** | Transition ->Screw Forward |
| **Containing Region** | Region |

#### C.1.C.1.B Screw Forward




| | |
|---|---|
| **Description** | - |
| **Source** | Initial ->Transition |
| **Destination** | Transition ->Dump |
| **Containing Region** | Region |

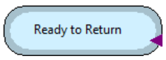
#### C.1.C.1.C Dump


| | |
|---|---|
| **Description** | - |
| **Source** | Screw Forward ->Transition |
| **Destination** | Transition ->Screw Reverse |
| **Containing Region** | Region |

#### C.1.C.1.D Screw Reverse


| | |
|---|---|
| **Description** | - |
| **Source** | Dump ->Transition |
| **Destination** | Transition ->Ready to Return |
| **Containing Region** | Region |

#### C.1.C.1.E Ready to Return




| | |
|---|---|
| **Description** | - |
| **Source** | Screw Reverse ->Transition |
| **Destination** | |
| **Containing Region** | Region |

#### C.1.C.1.F Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Initial |
| **Destination** | | | Screw Forward |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | {Responds to all triggers} |
| | **Action** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

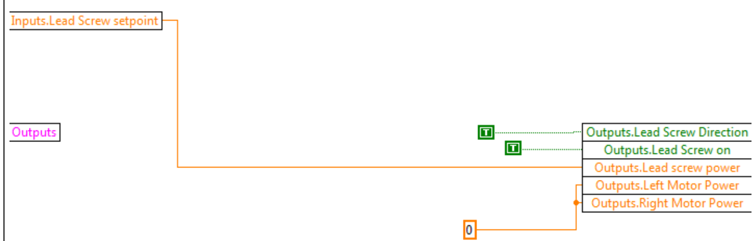
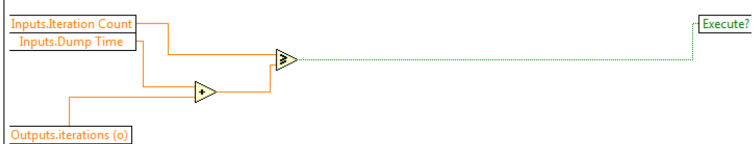
#### C.1.C.1.G Transition

| | |
|---|---|
| **Description** | - |

| | | | |
|---|---|---|---|
| **Source** | | | Screw Forward |
| **Destination** | | | Dump |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

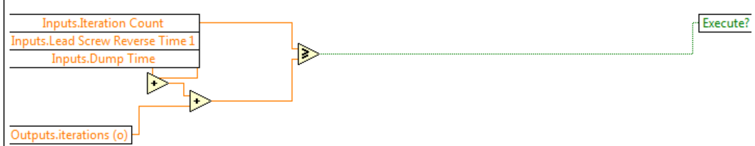
**C.1.C.1.H Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Dump |
| **Destination** | | | Screw Reverse |
| **Containing Region** | | | Region |

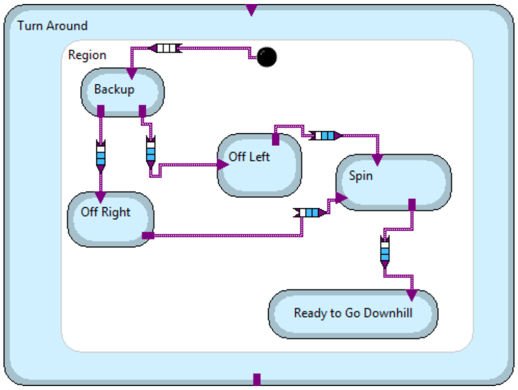
| | | | |
|---|---|---|---|
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

#### C.1.C.1.I Transition

| | | | |
|---|---|---|---|
| Description | | | - |
| Source | | | Screw Reverse |
| Destination | | | Ready to Return |
| Containing Region | | | Region |
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code | |

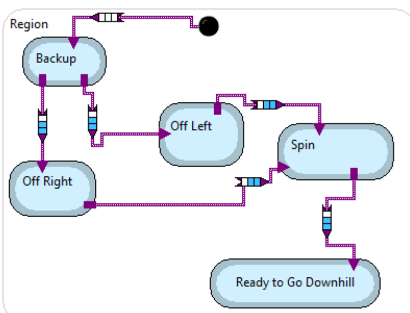
| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

**C.1.D Turn Around**




| | |
|---|---|
| **Description** | - |
| **Source** | Unload ->Transition |
| **Destination** | Transition ->Downhill |
| **Containing Region** | Region |
| **Contained Regions** | Region |

### C.1.D.1 Region




| | |
|---|---|
| **Description** | - |
| **Containing State** | Turn Around |
| **Contained Objects** | Initial, Backup, Spin, Off Right, Off Left, Ready to Go Downhill |
| **Contained Transitions** | Transition, Transition, Transition, Transition, Transition, Transition |

#### C.1.D.1.A Initial

| | |
|---|---|
| **Description** | - |
| **Destination** | Transition ->Backup |
| **Containing Region** | Region |

#### C.1.D.1.B Backup


| | |
|---|---|
| **Description** | - |
| **Source** | Initial ->Transition |
| **Destination** | Transition ->Off Right, Transition ->Off Left |
| **Containing Region** | Region |

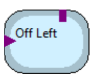
### C.1.D.1.C Spin


| | |
|---|---|
| **Description** | - |
| **Source** | Off Right ->Transition, Off Left ->Transition |
| **Destination** | Transition ->Ready to Go Downhill |
| **Containing Region** | Region |

### C.1.D.1.D Off Right

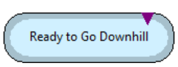

| | |
|---|---|
| **Description** | - |
| **Source** | Backup ->Transition |
| **Destination** | Transition ->Spin |
| **Containing Region** | Region |

### C.1.D.1.E Off Left




| | |
|---|---|
| **Description** | - |
| **Source** | Backup ->Transition |
| **Destination** | Transition ->Spin |
| **Containing Region** | Region |

### C.1.D.1.F Ready to Go Downhill



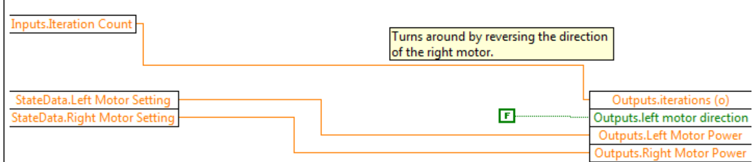
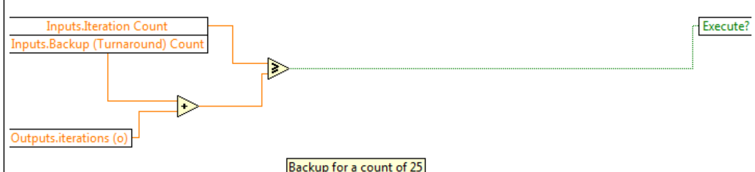

| | |
|---|---|
| **Description** | - |
| **Source** | Spin ->Transition |
| **Destination** | |
| **Containing Region** | Region |

### C.1.D.1.G Transition

| | |
|---|---|
| **Description** | - |

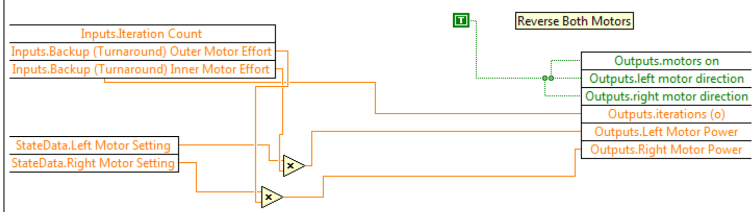
| | | |
|---|---|---|
| Source | | [Initial] |
| Destination | | [Backup] |
| Containing Region | | [Region] |
| Transition Code | Description | |
| | Trigger List | {Responds to all triggers} |

#### C.1.D.1.H Transition

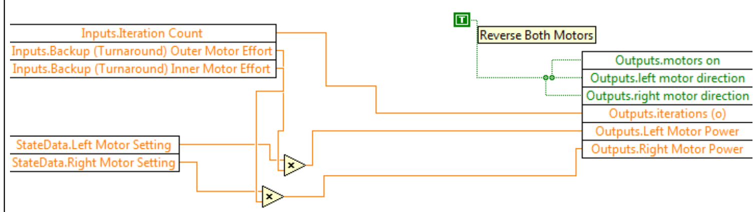
| | | | |
|---|---|---|---|
| Description | | | - |
| Source | | | Off Right |
| Destination | | | Spin |
| Containing Region | | | Region |
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code |  |
| | | Disable | FALSE |
| | | | |

| | | | |
|---|---|---|---|
| | | AutoPreAllocate | FALSE |

#### C.1.D.1.I Transition

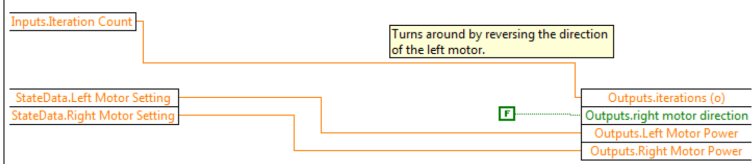
| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Backup |
| **Destination** | | | Off Right |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

#### C.1.D.1.J Transition

<table>
<tr><td colspan="3">Description</td><td>-</td></tr>
<tr><td colspan="3">Source</td><td>Backup</td></tr>
<tr><td colspan="3">Destination</td><td>Off Left</td></tr>
<tr><td colspan="3">Containing Region</td><td>Region</td></tr>
<tr><td rowspan="8">Transition Code</td><td colspan="2">Description</td><td></td></tr>
<tr><td colspan="2">Trigger List</td><td>NULL</td></tr>
<tr><td rowspan="3">Action</td><td>Code</td><td>
</td></tr>
<tr><td>Disable</td><td>FALSE</td></tr>
<tr><td>AutoPreAllocate</td><td>FALSE</td></tr>
<tr><td rowspan="3">Guard</td><td>Code</td><td>
</td></tr>
<tr><td>Disable</td><td>FALSE</td></tr>
<tr><td>AutoPreAllocate</td><td>FALSE</td></tr>
</table>

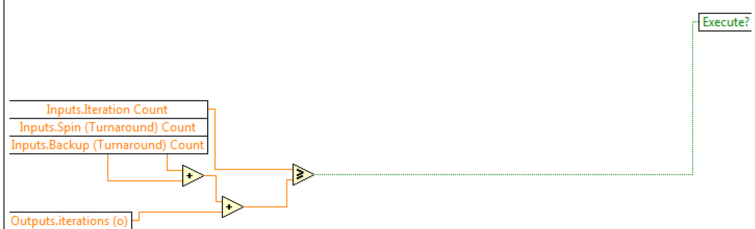
#### C.1.D.1.K Transition

| | |
|---|---|
| **Description** | - |
| **Source** | Off Left |
| **Destination** | Spin |

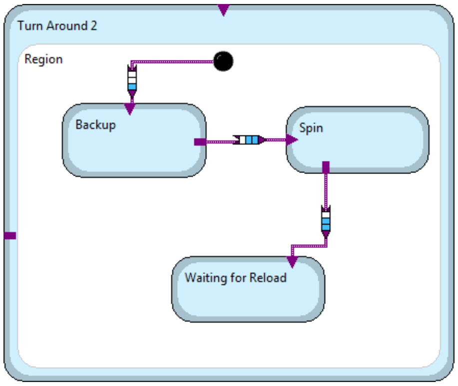
| | | | |
|---|---|---|---|
| Containing Region | | | Region |
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

#### C.1.D.1.L Transition

| | | | |
|---|---|---|---|
| Description | | | - |
| Source | | | Spin |
| Destination | | | Ready to Go Downhill |
| Containing Region | | | Region |
| Transition Code | Description | | |
| | Trigger List | | NULL |

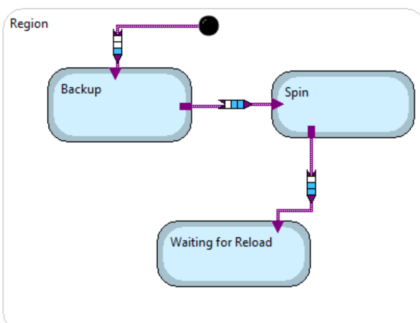
| | | | |
|---|---|---|---|
| | **Action** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

**C.1.E Turn Around 2**




| | |
|---|---|
| **Description** | - |
| **Source** | Downhill ->Transition |
| **Destination** | Transition ->Uphill Movement |
| **Containing Region** | Region |
| **Contained Regions** | Region |

**C.1.E.1 Region**

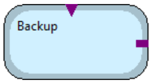



| | |
|---|---|
| **Description** | - |
| **Containing State** | Turn Around 2 |
| **Contained Objects** | Initial, Backup, Spin, Waiting for Reload |
| **Contained Transitions** | Transition, Transition, Transition |

**C.1.E.1.A Initial**

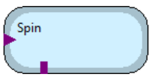
| | |
|---|---|
| **Description** | - |
| **Destination** | Transition ->Backup |
| **Containing Region** | Region |

**C.1.E.1.B Backup**



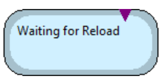

| | |
|---|---|
| **Description** | - |
| **Source** | Initial ->Transition |
| **Destination** | Transition ->Spin |
| **Containing Region** | Region |

#### C.1.E.1.C Spin




| | |
|---|---|
| **Description** | - |
| **Source** | Backup ->Transition |
| **Destination** | Transition ->Waiting for Reload |
| **Containing Region** | Region |

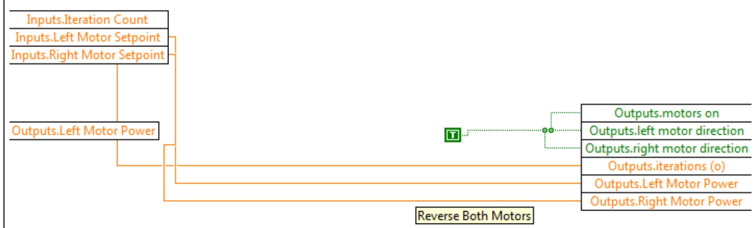
#### C.1.E.1.D Waiting for Reload



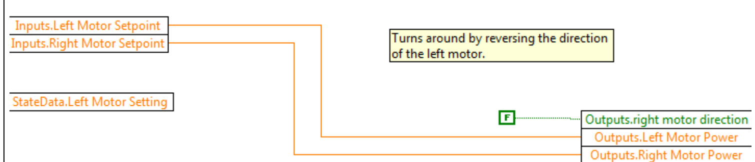

| | |
|---|---|
| **Description** | - |
| **Source** | Spin ->Transition |
| **Destination** | |
| **Containing Region** | Region |

#### C.1.E.1.E Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Initial |
| **Destination** | | | Backup |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | {Responds to all triggers} |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

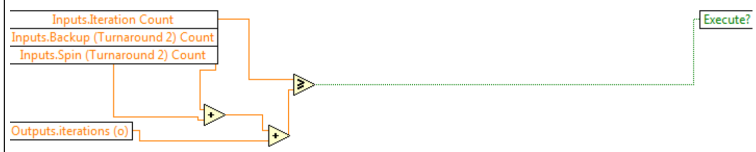
**C.1.E.1.F Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Backup |
| **Destination** | | | Spin |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

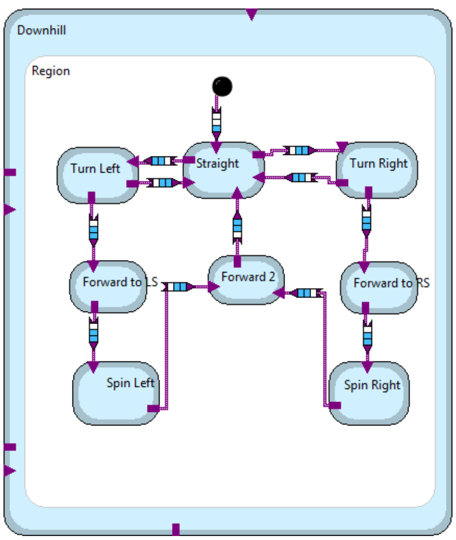
**C.1.E.1.G Transition**

| | | | |
|---|---|---|---|
| Description | | | - |
| Source | | | Spin |
| Destination | | | Waiting for Reload |
| Containing Region | | | Region |
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code | |



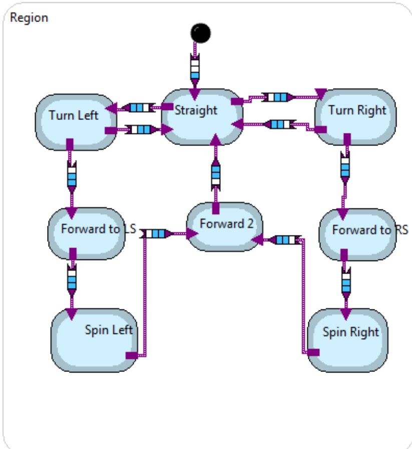

| | | | |
|---|---|---|---|
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

**C.1.F Downhill**




| | |
|---|---|
| **Description** | - |
| **Source** | Turn Around ->Transition, Lead Screw Upright ->Transition, Speed Up Prior To End ->Transition |
| **Destination** | Transition ->Turn Around 2, Transition ->Lead Screw Upright, Transition ->Speed Up Prior To End |
| **Containing Region** | Region |
| **Contained Regions** | Region |

**C.1.F.1 Region**

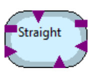



| | |
|---|---|
| **Description** | - |
| **Containing State** | Downhill |
| **Contained Objects** | Straight, Turn Right, Turn Left, Initial, Spin Left, Spin Right, Forward 2, Forward to LS , Forward to RS |
| **Contained Transitions** | Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition, Transition |

#### C.1.F.1.A Initial

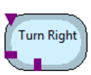
| | |
|---|---|
| **Description** | - |
| **Destination** | Transition ->Straight |
| **Containing Region** | Region |

#### C.1.F.1.B Straight




| | |
|---|---|
| **Description** | - |
| **Source** | Initial ->Transition, Turn Left ->Transition, Turn Right ->Transition, Forward 2 ->Transition |
| **Destination** | Transition ->Turn Left, Transition ->Turn Right |
| **Containing Region** | Region |

#### C.1.F.1.C Turn Right




| | |
|---|---|
| **Description** | - |
| **Source** | Straight ->Transition |
| **Destination** | Transition ->Straight, |
| **Containing Region** | Region |

#### C.1.F.1.D Turn Left


| | |
|---|---|
| **Description** | - |
| **Source** | Straight ->Transition |
| **Destination** | Transition ->Straight, |
| **Containing Region** | Region |

#### C.1.F.1.E Spin Left


| | |
|---|---|
| **Description** | - |
| **Source** | Forward to LS ->Transition |
| **Destination** | Transition ->Forward 2 |
| **Containing Region** | Region |

#### C.1.F.1.F Spin Right


| | |
|---|---|
| **Description** | - |
| **Source** | Forward to RS ->Transition |
| **Destination** | Transition ->Forward 2 |
| **Containing Region** | Region |

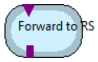
#### C.1.F.1.G Forward 2


| | |
|---|---|
| **Description** | - |
| **Source** | Spin Left ->Transition, Spin Right ->Transition |
| **Destination** | Transition ->Straight |
| **Containing Region** | Region |

#### C.1.F.1.H Forward to LS

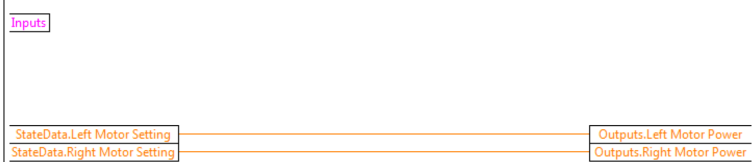

| | |
|---|---|
| **Description** | - |
| **Source** | Turn Left ->Transition |
| **Destination** | Transition ->Spin Left |
| **Containing Region** | Region |

#### C.1.F.1.I Forward to RS



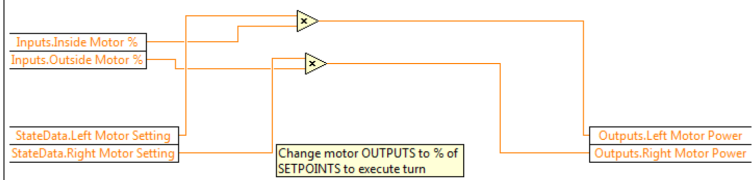
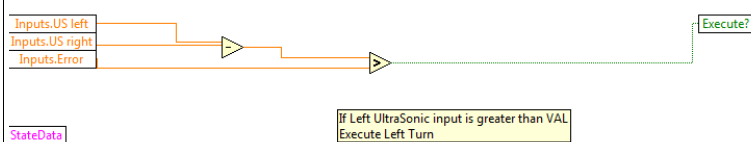

| | |
|---|---|
| **Description** | - |
| **Source** | Turn Right ->Transition |
| **Destination** | Transition ->Spin Right |
| **Containing Region** | Region |

#### C.1.F.1.J Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Initial |
| **Destination** | | | Straight |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | {Responds to all triggers} |
| | **Action** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

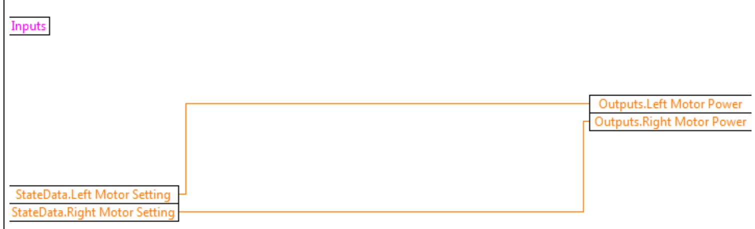
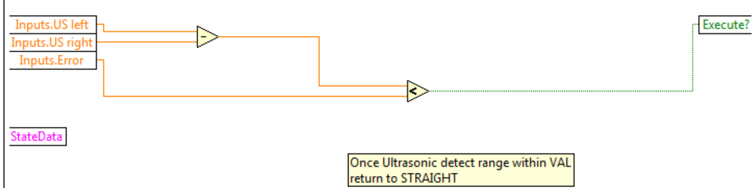
#### C.1.F.1.K Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Straight |
| **Destination** | | | Turn Left |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

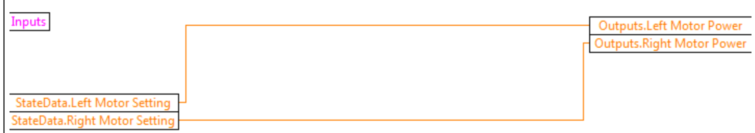
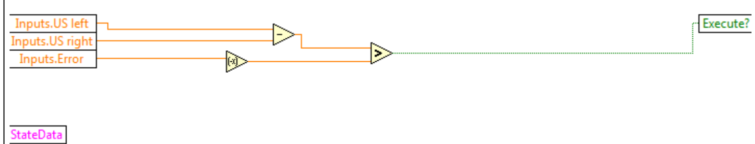
**C.1.F.1.L Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Turn Left |
| **Destination** | | | Straight |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

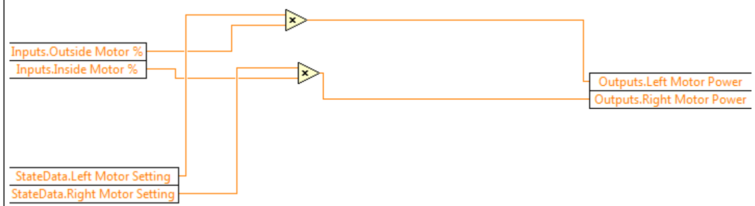
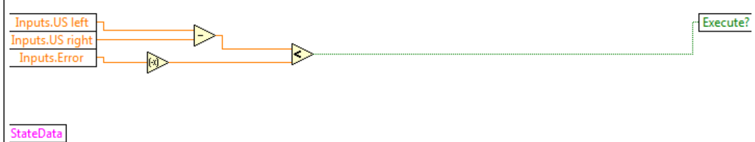
### C.1.F.1.M Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | [Turn Right] |
| **Destination** | | | [Straight] |
| **Containing Region** | | | [Region] |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

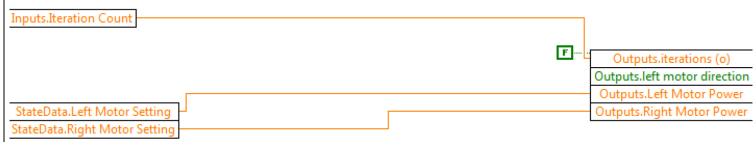
**C.1.F.1.N Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Straight |
| **Destination** | | | Turn Right |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

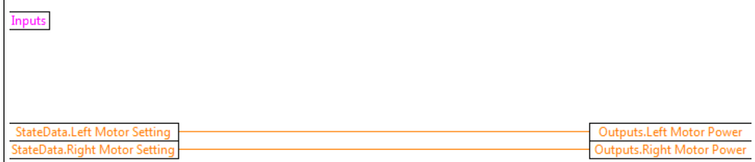
**C.1.F.1.O Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Spin Left |
| **Destination** | | | Forward 2 |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

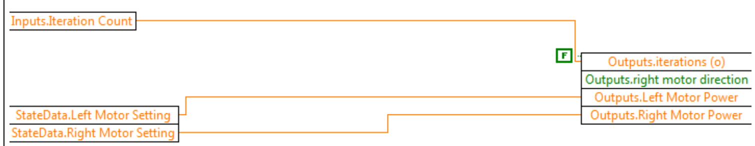
**C.1.F.1.P Transition**

| | | | |
|---|---|---|---|
| Description | | | - |
| Source | | | Forward 2 |
| Destination | | | Straight |
| Containing Region | | | Region |
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code | |

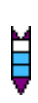
| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

#### C.1.F.1.Q Transition

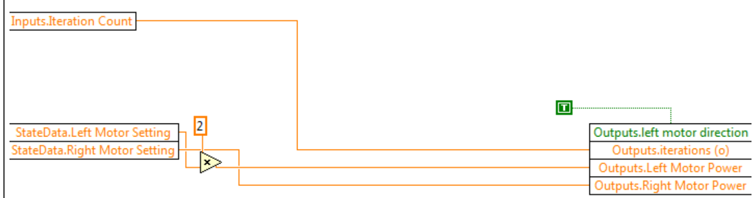
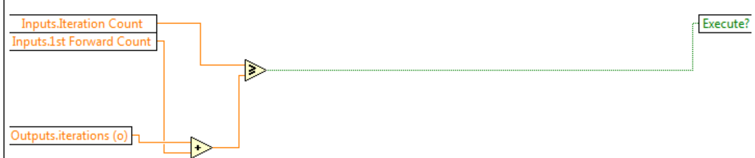
| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Spin Right |
| **Destination** | | | Forward 2 |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

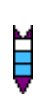
**C.1.F.1.R Transition**



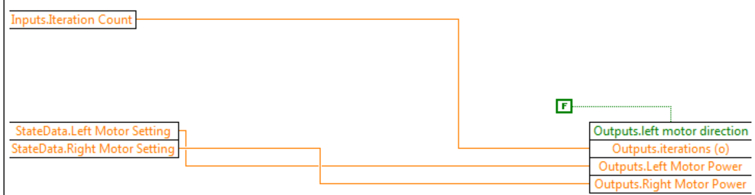
| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Forward to LS |
| **Destination** | | | Spin Left |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | | |
|---|---|---|---|---|
| | | | |  |
| | | | Disable | FALSE |
| | | | AutoPreAllocate | FALSE |
| | | Guard | Code |  |
| | | | Disable | FALSE |
| | | | AutoPreAllocate | FALSE |

**C.1.F.1.S Transition**

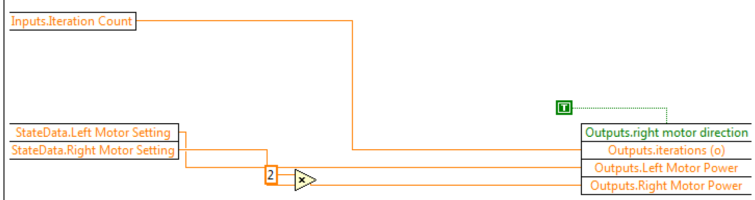


| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Turn Left |
| **Destination** | | | Forward to LS |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

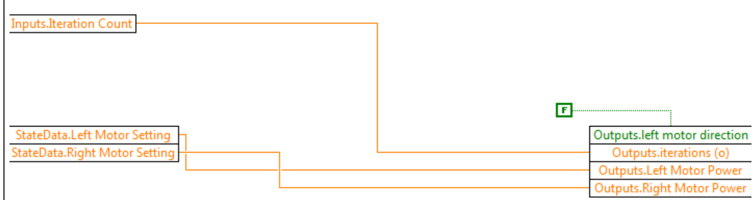
**C.1.F.1.T Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | [Forward to RS]() |
| **Destination** | | | [Spin Right]() |
| **Containing Region** | | | [Region]() |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

#### C.1.F.1.U Transition

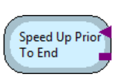
| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Turn Right |
| **Destination** | | | Forward to RS |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |   |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |   |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

### C.1.G Lead Screw Upright

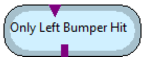

| | |
|---|---|
| **Description** | - |
| **Source** | Downhill ->Transition |
| **Destination** | Transition ->Downhill |
| **Containing Region** | Region |

### C.1.H Speed Up Prior To End



| | |
|---|---|
| **Description** | - |
| **Source** | Downhill ->Transition |
| **Destination** | Transition ->Downhill |
| **Containing Region** | Region |

### C.1.I Only Left Bumper Hit



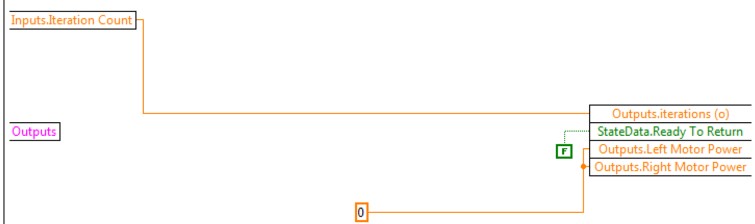
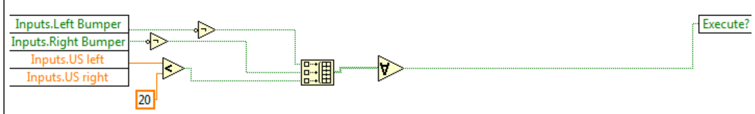

| | |
|---|---|
| **Description** | - |
| **Source** | Uphill Movement ->Transition |
| **Destination** | Transition ->Unload |
| **Containing Region** | Region |

### C.1.J Only Right Bumper Hit

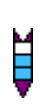

| | |
|---|---|
| **Description** | - |
| **Source** | Uphill Movement ->Transition |
| **Destination** | Transition ->Unload |
| **Containing Region** | Region |

### C.1.K Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Uphill Movement |
| **Destination** | | | Unload |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** | Ultrasonics must be reading less than 10 while both buttons are depressed to ensure we are at the offload position. |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

#### C.1.L Transition

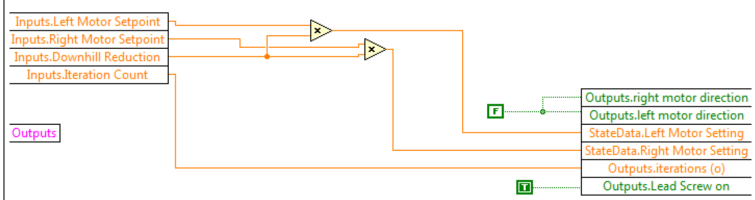
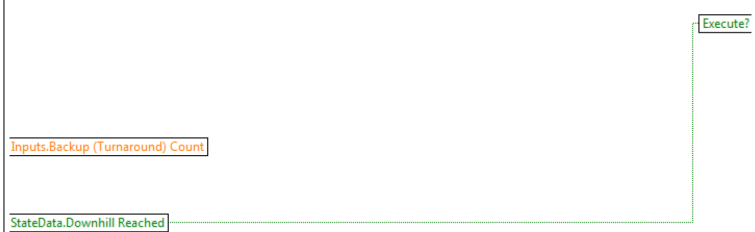


| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Unload |
| **Destination** | | | Turn Around |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |   |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |   |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

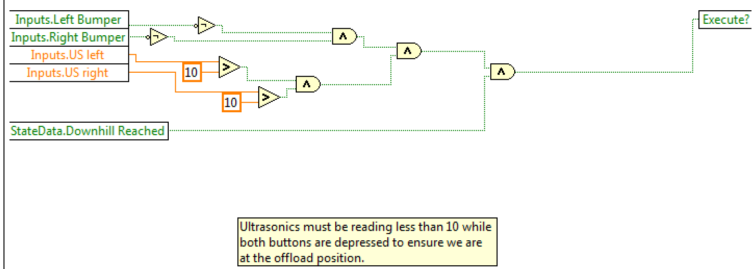
#### C.1.M Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Turn Around |
| **Destination** | | | Downhill |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

**C.1.N Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Downhill |
| **Destination** | | | Turn Around 2 |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Guard** | **Code** | |

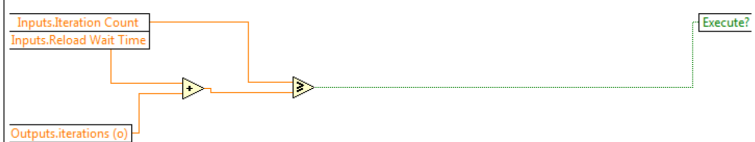
| | | | |
|---|---|---|---|
| | | |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

#### C.1.O Transition

| | | |
|---|---|---|
| **Description** | | - |
| **Source** | | [Initial] |
| **Destination** | | [Uphill Movement] |
| **Containing Region** | | [Region] |
| **Transition Code** | **Description** | |
| | **Trigger List** | {Responds to all triggers} |

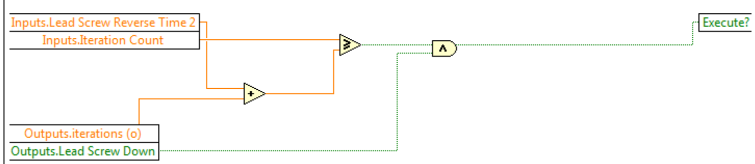
#### C.1.P Transition

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | [Turn Around 2] |
| **Destination** | | | [Uphill Movement] |
| **Containing Region** | | | [Region] |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

<table>
<tr><td></td><td></td><td></td><td>
</td></tr>
<tr><td></td><td></td><td>Disable</td><td>FALSE</td></tr>
<tr><td></td><td></td><td>AutoPreAllocate</td><td>FALSE</td></tr>
<tr><td></td><td>Guard</td><td>Code</td><td>
</td></tr>
<tr><td></td><td></td><td>Disable</td><td>FALSE</td></tr>
<tr><td></td><td></td><td>AutoPreAllocate</td><td>FALSE</td></tr>
</table>

### C.1.Q Transition

<table>
<tr><td colspan="3">Description</td><td>-</td></tr>
<tr><td colspan="3">Source</td><td>Downhill</td></tr>
<tr><td colspan="3">Destination</td><td>Lead Screw Upright</td></tr>
<tr><td colspan="3">Containing Region</td><td>Region</td></tr>
<tr><td rowspan="3">Transition Code</td><td colspan="2">Description</td><td></td></tr>
<tr><td colspan="2">Trigger List</td><td>NULL</td></tr>
<tr><td>Action</td><td>Code</td><td></td></tr>
</table>

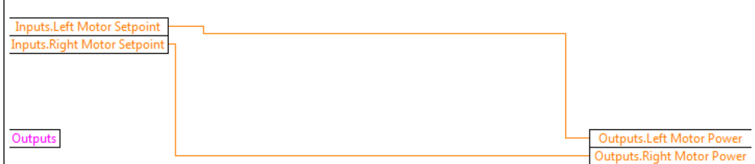
| | | | | |
|---|---|---|---|---|
| | | | |  |
| | | | Disable | FALSE |
| | | | AutoPreAllocate | FALSE |
| | | Guard | Code |  |
| | | | Disable | FALSE |
| | | | AutoPreAllocate | FALSE |

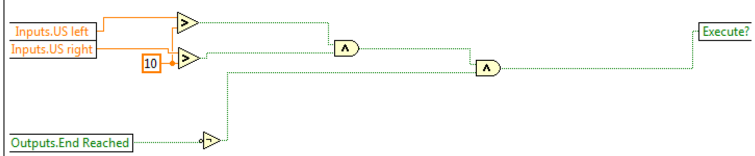
**C.1.R Transition**

| | | | |
|---|---|---|---|
| Description | | | - |
| Source | | | Lead Screw Upright |
| Destination | | | Downhill |
| Containing Region | | | Region |
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code | |

| | | | |
|---|---|---|---|
| | | |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

**C.1.S Transition**

| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Downhill |
| **Destination** | | | Speed Up Prior To End |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** |  |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** | |

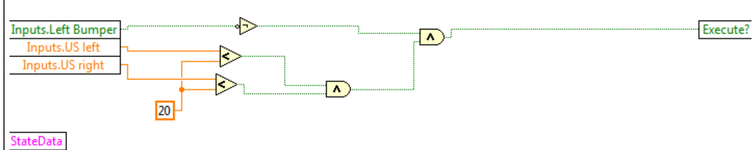
| | | | |
|---|---|---|---|
| | | |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

**C.1.T Transition**

| | | | |
|---|---|---|---|
| Description | | | - |
| Source | | | Speed Up Prior To End |
| Destination | | | Downhill |
| Containing Region | | | Region |
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

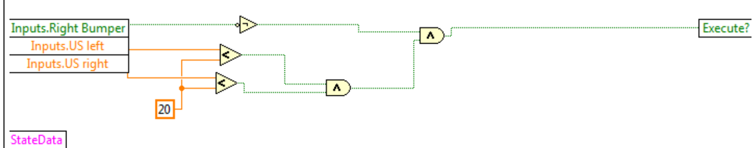
**C.1.U Transition**

| | |
|---|---|
| Description | - |

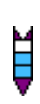
| | | | |
|---|---|---|---|
| **Source** | | | Uphill Movement |
| **Destination** | | | Only Left Bumper Hit |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** |   |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |
| | **Guard** | **Code** |   |
| | | **Disable** | FALSE |
| | | **AutoPreAllocate** | FALSE |

#### C.1.V Transition

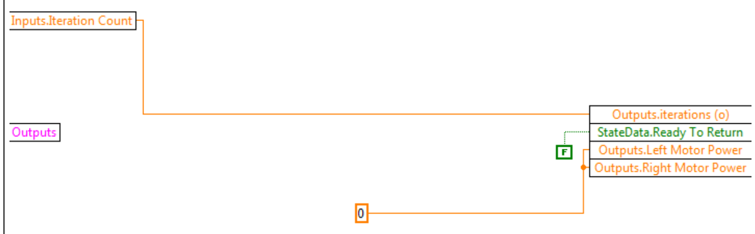
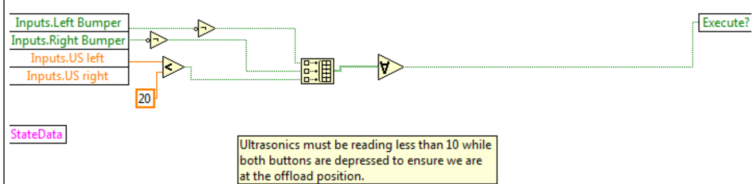
| | |
|---|---|
| **Description** | - |
| **Source** | Uphill Movement |
| **Destination** | Only Right Bumper Hit |
| **Containing Region** | Region |

| | | | |
|---|---|---|---|
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

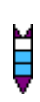
### C.1.W Transition



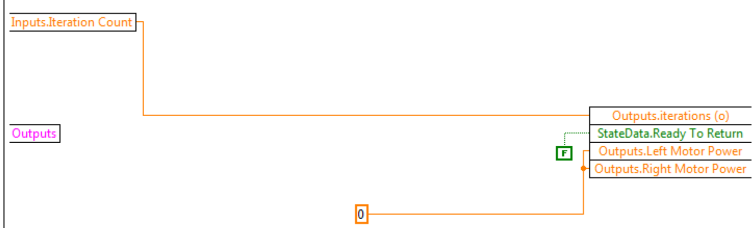
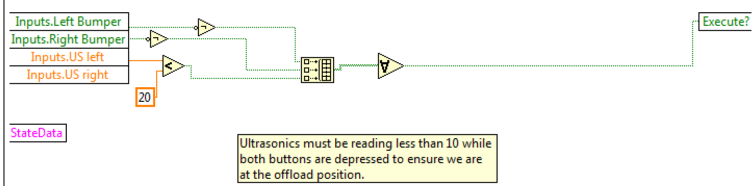
| | | | |
|---|---|---|---|
| Description | | | - |
| Source | | | Only Left Bumper Hit |
| Destination | | | Unload |
| Containing Region | | | Region |
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code | |

| | | | |
|---|---|---|---|
| | | |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

**C.1.X Transition**



| | | | |
|---|---|---|---|
| **Description** | | | - |
| **Source** | | | Only Right Bumper Hit |
| **Destination** | | | Unload |
| **Containing Region** | | | Region |
| **Transition Code** | **Description** | | |
| | **Trigger List** | | NULL |
| | **Action** | **Code** | |

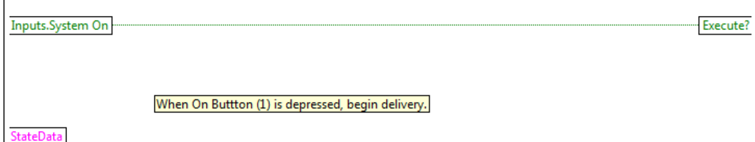
| | | | |
|---|---|---|---|
| | | |   |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code |   |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

**D Transition**

| | | |
|---|---|---|
| Description | | - |
| Source | | Initial |
| Destination | | off |
| Containing Region | | Main Diagram |
| Transition Code | Description | |
| | Trigger List | {Responds to all triggers} |

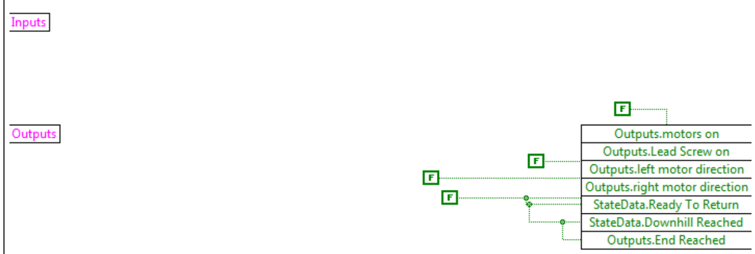
**E Transition**

| | |
|---|---|
| Description | - |

| | | | |
|---|---|---|---|
| Source | | | off |
| Destination | | | on |
| Containing Region | | | Main Diagram |
| Transition Code | Description | | |
| | Trigger List | | NULL |
| | Action | Code | |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code |   |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |

**F Transition**

| | | |
|---|---|---|
| Description | | - |
| Source | | on |
| Destination | | off |
| Containing Region | | Main Diagram |
| Transition Code | Description | |
| | | |

| | | | |
|---|---|---|---|
| | Trigger List | | NULL |
| | Action | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |
| | Guard | Code |  |
| | | Disable | FALSE |
| | | AutoPreAllocate | FALSE |