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Agricultural & Biosystems Engineering

Design and Development of a CVT and Front Axle for a Quarter Scale Tractor

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Report
Submitted as part of the course ABEN: Senior Design Project II

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Executive Summary

This project was requested by the Bison Pullers to aid in the development of their tractor for the 2009 international competition. The goal of the project was to design and prototype a CVT and Front Axle to be incorporated into the 2009 Bison Pullers quarter scale tractor. General considerations used across both the design areas include the design meeting all of the rules of the International Quarter Scale (IQS) competition, for each to meet specific weight goals set by the Bison Pullers to place the tractor below the 850lb limit, with further considerations of each discussed in this report.

The most critical goal of the front axle design is the 80lb weight limit, meaning special considerations were to be taken to use aluminum to fabricate components whenever possible. FEA was used to adequately determine whether or not aluminum would be able to support the tractor in extreme loading cases. A series of knuckle designs, knuckle joint considerations, axle joint considerations, and steps taken to implement the Ackerman steering principle are discussed in full detail within the front axle section of the report. When delivered to the Bison Pullers, the front axle must be easily integrated to the tractor's frame, to allow for easy access if the axle needed to be serviced. Beyond the actual axle, complete Pro Engineer models and drawings will be given, to aid in prototyping the components.

The most critical goal of the Continuously Variable Transmission (CVT) design was to be able to effectively transmit the engine's torque and to have a well performing control system. Working with engineers at Polaris in Roseau, MN it was determined that the CVT the Bison Pullers had on hand from a 1995 Sportsman ATV would be sufficient. The CVT is forced by a electric linear actuator. The operator move a lever to control the CVT gear ratio. The control system was designed using a PIC microcontroller. All testing to date, has shown that the completed control system met or exceeded the requirements specified by the Bison Pullers.

I. Introduction

The Bison Pullers design and build a tractor annually for the American Society of Agricultural and Biological Engineers (ASABE) quarter-scale tractor competition. This competition provides an excellent educational experience for students, by allowing them to complete an entire design cycle. This improves their skills as engineers and makes them more attractive to employers. It also provides recognition for Agricultural and Biosystems Engineering Department and the University in general.

The main objective of the Bison Pullers was to place well at the competition. The scoring system can be found in the competition handbook at http://www.asabe.org/students/tractor/asaecomp.html. Another overall objective is that as much of the tractor as possible be manufactured in our Department's shop. Outsourcing parts is expensive and can lead to delays. The final overall objective for the Bison Pullers is that it be as low cost to produce as possible without major sacrifices in performance or reliability, since he Bison Pullers must fundraise all the money for building the tractor.

Figure 1 shows the overall design of the 2009 tractor. The Senior Design team's focus was on the tractor's Continuously Variable Transmission (CVT) and front axle design and prototyping. The remaining portions of the tractor was designed by the Bison Pullers organization. The CVT allows the tractor to have variable speed, but at a much lower weight and higher efficiency than previous years hydrostatic transmission. The main features of the CVT include electronic control, variable speed, and light weight design. The new design of the front axle allows for a lighter, more efficient design over last year's tractor. The highlights of the front axle design include light weight knuckle design, tight turning radius, and pivoting feature to aid in tractor stability.

Figure 1.1. Top Level assembly of the 2009 Tractor

II. Design Considerations

II. 1 General Objectives

The design of the team must comply with all of the rules of the competition; these rules may be found at http://www.asabe.org/students/tractor/asaecomp.html. For all parts of the design weight was a major consideration. The tractor must meet a weight restriction of 850lb. Further constraints were assigned modified through discussions and approval at team meetings with the Bison Pullers organization.

The objective was to design and manufacture a front axle and CVT drive system for the Bison Puller's tractor. The design must comply with the criteria discussed below. One of our main objectives was to make our design as light as possible. The initial goal was 50 pounds for the CVT system, this includes the sheaves, belts, mounting, and control mechanism, and 80 pounds for the complete front axle. Also, the CVT must be able to transmit the torque at any gear ratio and engine speed with minimal belt slip. The belt should not heat excessively. The control of the CVT should be smooth and able to respond quickly. The CVT should be able to go from fully open to fully closed within two seconds.

The senior design team was to supply the following as an end result; a complete Pro-E model of the design, complete drawings for all parts to be manufactured, assistance in manufacture the parts and assemblies, aid in preparing reports for the IQS competition, and any other requirements placed on the team with consent of both the team and the Bison Pullers. The team was required to deliver a completed front axle that can be integrated with the tractor's frame and a CVT, with control system, that is integrated with the tractor's drive train. A copy of the senior design report was also be provided to the Bison Pullers.

II. 2 Front Axle

Much of the design of the front axle is open ended, with only a select few design goals set by the Bison Pullers. These include the front axle being able to adequately support the weight of the tractor with minimum deflection. FEA shall be used to determine the deflection of design concepts. It should have a tight enough steering angle to perform well in the maneuvering course. This angle should be within 10 degrees of last year's tractor (30 Degrees). Special consideration will be given to the steering angle because the tractor will be longer than the 2008 model, hence good steering will be required to score well in the maneuverability part of the competition. The axle should be able to pivot +/- 6 degrees from the horizontal. The axle pivot should also be wear resistant and have low friction. Outside of these particular areas, the Bison Pullers allowed our team free reigns to the overall design of the front axle.

The first design goal and likely most important goal set by the Bison Pullers was the weight limit. While in initial design stages, special consideration to use aluminum wherever possible was established as a desirable design goal by our team. The second goal set by the club was for the axle to adequately support the weight of the tractor, with little to no deflection. This is of equal importance to the first, thus a number of finite element analysis (FEA) cases must be incorporated to accurately reflect high load situations. High strength, light weight bearings and joints must be considered to fulfill both weight and strength constraints. Parts and ideas from the racing community will be utilized as well for their lightweight, high performance construction. The pivoting requirement of the axle will be addressed by a pin mechanism, placed above the differential. The goal is the have the pin ride in a low friction structure, most likely with bass inserts for wear. Power steering accommodations will be implemented as the design progresses, utilizing aluminum brackets to house the cylinder. To attain a steering angle of at least 20°, goals must be set to accurately compare and contrast a variety of axle joints to accommodate large angles at high torques.

Design criteria defined the Bison Pullers:

- Total axle weight must be less than 80 lbs
- Axle must adequately support the weight of the tractor, with little to no deflection
- Should pivot +/- 6 degrees from the horizontal
- The pivot pin area should have low friction and be wear resistant
- Must have accommodations for Power Steering; preferably hydraulic
- Steering angle should be tolerance within 10° of the previous years' tractor
- Must accommodate specified Polaris differential provided by the Bison Pullers

Design criteria defined the Front Axle / CVT Team:

- Special consideration be taken to use aluminum wherever possible
- A number of FEA cases incorporated to accurately reflect high load situations
- High strength, light weight bearings and joints considered to fulfill constraints
- Parts and ideas from the racing community utilized for their lightweight, high performance construction
- Pin mechanism will be placed above the differential; will ride in a low friction structure
- Power steering accommodations implemented in design; utilizing aluminum brackets to house the cylinder
- Accurately compare and contrast a variety of axle joints to attain the minimum 20° turning angle

II. 3 Continuously Variable Transmission

The CVT consists of variable diameter sheaves that can vary the gear ratio from the drive to the driven pulley. The team cooperated with the Bison Pullers to determine the appropriate gear ratios and speed range of the CVT. The CVT sheaves were required to be forced, i.e. controlled by the operator using some type of an actuator; not by rpm. This allows the operator to select any gear ratio, within the allowed range, desired. To accomplish this an electronic control system was necessary. It is very important that this system be reliable and safe. It needed to be able to withstand adverse weather conditions that the tractor may be exposed to, such as cold, heat, and moisture. It also needed to have safeguards incorporated to prevent the operator from mistakenly damaging equipment or causing unintended results.

The CVT system was required to meet all competition rules. The most applicable of which is shield requirements. All rotating components met or exceed ASAE Standard S493, and in addition, they must have peripheral shielding of at least 1/4" aluminum or 1/8" mild steel. These components must also be shielded in order to prevent inadvertent contact by the operator.

Design criteria defined by the Bison Pullers:

- Total compete assembly weight must be less than 50lbs
- The control system must be reliable and durable
- The control system must be responsive, i.e. very little delay between input and output
- The CVT must be able to transmit the maximum torque of the engines with minimal belt slip
- Complete system should be as low cost as possible

Design criteria defined by the Front Axle / CVT Team:

- Special consideration be taken to use aluminum wherever possible
- Mechanical control system should be as compact as possible
- Mechanical control system should fit well into the tractor's design
- The CVT should go from fully open to fully closed in less than 2 seconds

III. Front Axle Design

III. 1 Material Selection

Two possible materials were evaluated for structural integrity and weight characteristics in both Pro Engineer and Algor applications. The two materials discussed are given in tables 3.1 and 3.2 respectively.

Table 3.1. 6061-T6 Aluminum Characteristics

Aluminum 6061-T6 Aluminum	
Modulus of Elasticity	10000 ksi
Shear Modulus	3770 ksi
Yield Strength	40000 psi
Ultimate Tensile Strength	45000 psi
Density	.0975 lb/in^3

Table 3.2. 1040 Hot Rolled Steel Characteristics

1040 Hot Rolled Steel	
Modulus of Elasticity	29000 ksi
Shear Modulus	11600 ksi
Yield Strength	42100 psi
Ultimate Tensile Strength	76100 psi
Density	.2834 lb/in^3

When Finite Element Analysis was performed on the 6061-T6 aluminum, the results were much better than first expected. Due to the severe nature of the loading performed, the analysis results were very acceptable. The decision was made to use 6061-T6 aluminum at this point for its structural integrity at during maximum load situations, as well as its 65% reduction in weight versus using 1040 hot rolled steel. It was decided to use this aluminum to fabricate the axle tubes, frame mount, tie rod, and knuckles. Stock hub assembly, CV axle shaft and differential are made of other various materials. A synopsis of the FEA report is described in the following section, showing the load cases, as well as the results from one of the cases.

III. 2 Finite Element Analysis

Front Axle Load Cases

Front axle loading is composed of two primary loading directions. One being the weight of the front portion of the tractor applying force to each outer hub surface in the y-direction, and the other applying force by the tractive effort of the wheels driving the tractor ahead in the positive z-direction.

Items to be evaluated in this analysis include stress levels in the inner and outer knuckle, the axle tubes, as well as the mount attached to the tractor. Loading cases being developed in this analysis represent maximum load factors that would typically only be seen in extreme conditions. Material selection and thickness as well as component geometry will be determined by this analysis. The desired material to be used for the mount, tubes and knuckles is 6061-T6 Aluminum. Properties can be found on the previous page.

Starting with the loading in the y-direction, the front portion of the tractor weighs 1200 lbs and is equally distributing a force of 600 lbs to each wheel. An estimated acceleration of 2.5 g's was taken into consideration in for power hop situations, causing each end of the axle to receive 1500 lbs of force. Forces are shown in Figure 3.1.

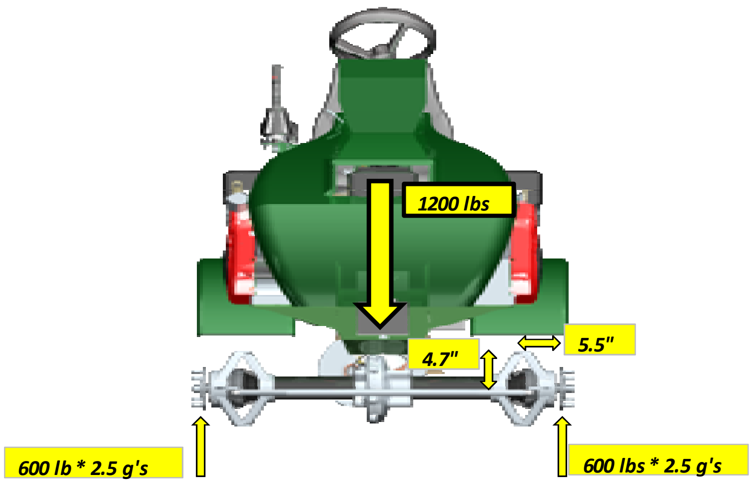


Figure 3. 1. FEA Load Analysis

These 1500 lb loads being placed 5.5"horizonally and 4.7"vertically away from the knuckle joints cause a moment about the centerline of the axle resulting in a force pushing in on the upper joint, and pulling out on the lower joint. Taking horizontal and vertical dimensions of joint placement into consideration, the forces resulting from this moment can easily be found. The value found acting on each of the joints is 1755.32 lbs. The 1500 lb load also causes a direct loading of 750 lbs on each of the pads housing the spherical bearing joints. Forces are shown in Figure 2.

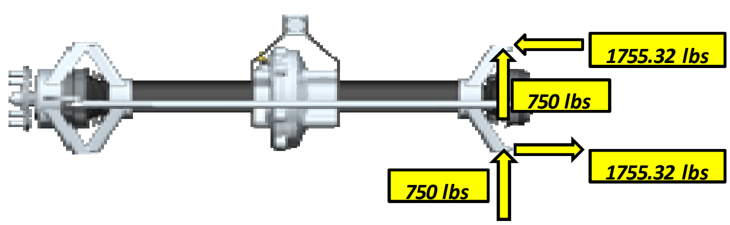


Figure 3.2. Inner Knuckle Load Analysis

The tractive effort of the tires driving the tractor forward also adds loading to the not only the inner knuckle, but the outer knuckle as well. It is approximated by earlier tests that a force of 900 lbs is created by the tires pulling the tractor forward. A safety factor of two is calculated into the total force as well, bringing total force on each hub to 1800 lbs. Force is shown in Figure 3.3.

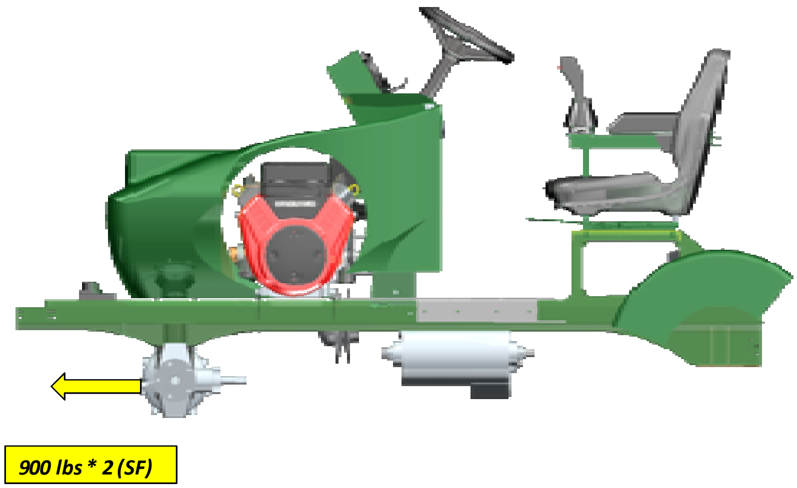


Figure 3.3. Tractive Wheel Force Analysis

This 1800 lb force creates two areas of loading on the knuckle. The first being the loading that is transmitted through the knuckle to each of the joints, meaning 900 lbs of loading is applied to each joint. This loading is applied in the same direction as the initial 1800 lb force.

The second area of loading is focused around the knuckle arm connected to the tie rod of the steering system. The 1800 lb force naturally wants to drive the wheel inward, causing loading on the arm due to the tie rod acting equal and opposite to the force. Knowing x and y distances from the moment, the force on the arm can easily be calculated. The value found is 2275.34 lb. Forces caused by the tractive effort of the tires can be seen in Figure 3.4.

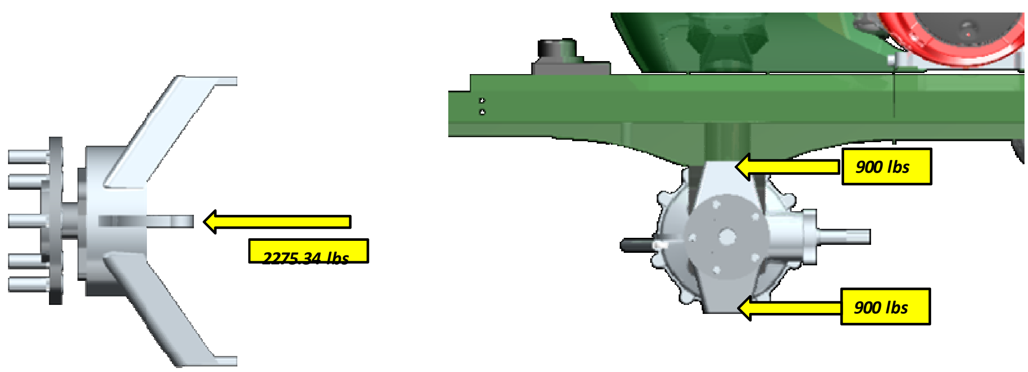
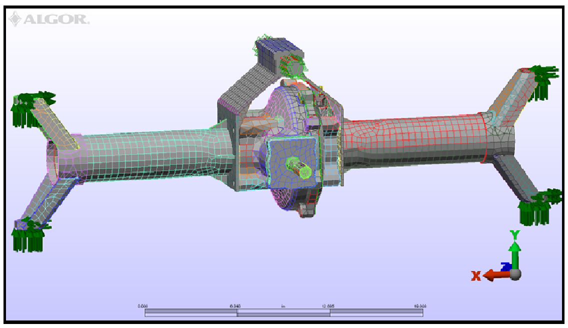


Figure 3.4. Outer Knuckle Load Analysis

Preliminary Test
Tractor Weight Loading/Power Hop Scenario

Using the loadings calculated above, the model can be brought into ALGOR to perform initial load cases. The analysis is setup as follows:

- Top pin fixed in the x, y, and z directions
- 1755.32 lb force applied to inside surface of upper spherical bearing housing
- 1755.32 lb force applied to outside surface of lower spherical bearing housing
- 750 lb force applied to bottom of each (upper and lower) pad housing the spherical bearings
- 900 lb force applied to the front surface of the upper and lower spherical bearing housing
- Element types are set to brick
- Material properties set to 6061-T6 Aluminum



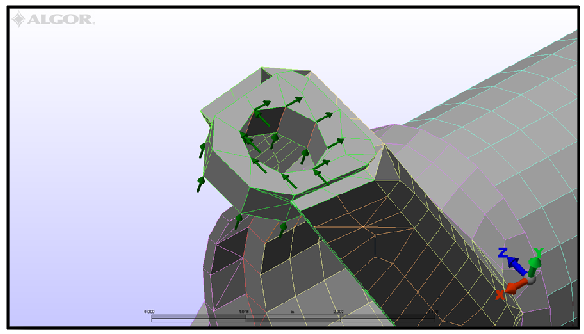


Figure 3.5. Tractor Weight Loading/Power Hop Scenario Analysis Setup

Round 1 Results
Tractor Weight Loading/Power Hop Scenario

The analysis was run, and initial impressions of the results are quite good. The results of the analysis are provided in Table 3.3.

Table 3.3. Tractor Weight Loading/ Power Hop Scenario Results

Strain
• Max Strain = .00584281 in/in
• Max Strain seen on the mount, near differential lock linkage area
• Concentrated regions of strain seen on all four corners of the mount
• Regions of high strain in ≈.004 in/in range seen near the mounting points of each knuckle
Stress
• Max Stress = 43901 lb-f/in²
• Max Stress seen on the mount, near differential lock linkage area
• Concentrated regions of stress seen on all four corners of the mount
• Regions of high stress in ≈ 30730 lb-f/in² range seen near the mounting points of each knuckle
Displacement
• Max Displacement = .237 in
• Max Displacement is seen on the outermost tips of each knuckle
• Least displacement seen is near the mount pivot
• Displacement increases as you travel further away from the center of the axle

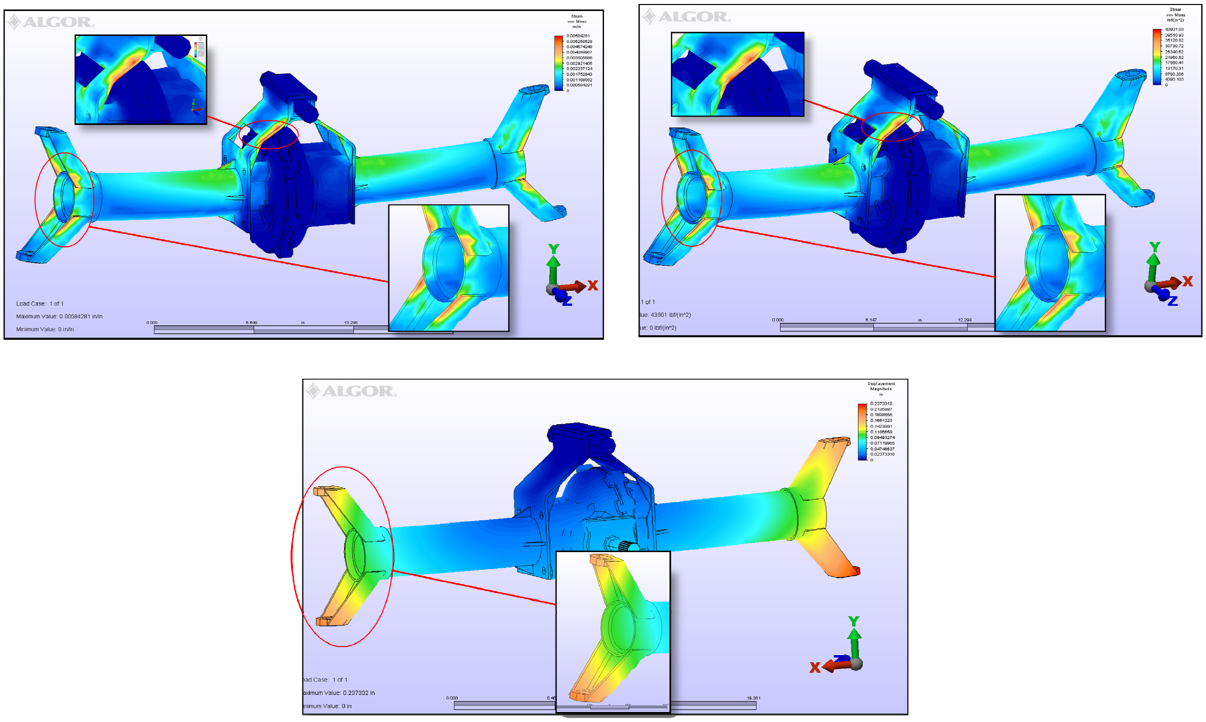


Figure 3.6. FEA Results Images: Axle Strain, Axle Stress, Axle Deflection (From top left, to right, to bottom)

Further iterations of analysis and loading cases can be found in the complete FEA report in Appendix B.

III. 3 Steering Design

Knuckle Considerations

Initial design considerations of the knuckle consisted of a more traditional style knuckle, composed of a knuckle mount off the axle tube housing the steering knuckle. Although this method of design would be acceptable for strength characteristics, the weight of the knuckle would be undesirable. A variety of stock 4-wheeler knuckles were also looked at initially, but the size and weight constraints of the design caused the team to investigate designing a custom knuckle.
It was decided to use a two piece knuckle, with an inner and an outer knuckle fabricated of either 1040 steel plate or 6061-T6 aluminum plate. The design concept allowed for easy fabrication with current outside resources of the Bison Pullers being able to laser cut steel or aluminum, as well as forming of each of them. Through the considerations listed above in material selection, 6061-T6 aluminum was chosen.

The inner knuckle is composed of two formed channels, which are welded to a larger diameter tube which is able to slide over the axle. On the top of each channel a 3/8” piece of flat aluminum with a 1” bore is welded to each to provide not only structural support for the knuckle but also to house the 1” spherical bearing as well. The purpose, and design considerations of the bearing selection are provided under the knuckle joint bearing considerations heading.

The outer knuckle half contains two larger formed channels to mate to the 5” cylindrical hub assembly mount. The hub assembly mount has a four bolt pattern to mate to the hub assembly. This allows the hub to be easily attached by four bolts, similar to how it is assembled in a car. The top of each channel has a 3/8” piece of flat aluminum welded to it as well, just like the inner knuckle, but only has a ½” bore to accommodate the bolt to join the knuckles together. This type of knuckle design allows for easy modification to attain adequate camber angles to account for the total deflection of the axle. Hole positioning of the outer knuckle will be paramount in achieving the 1-2° of camber desired.

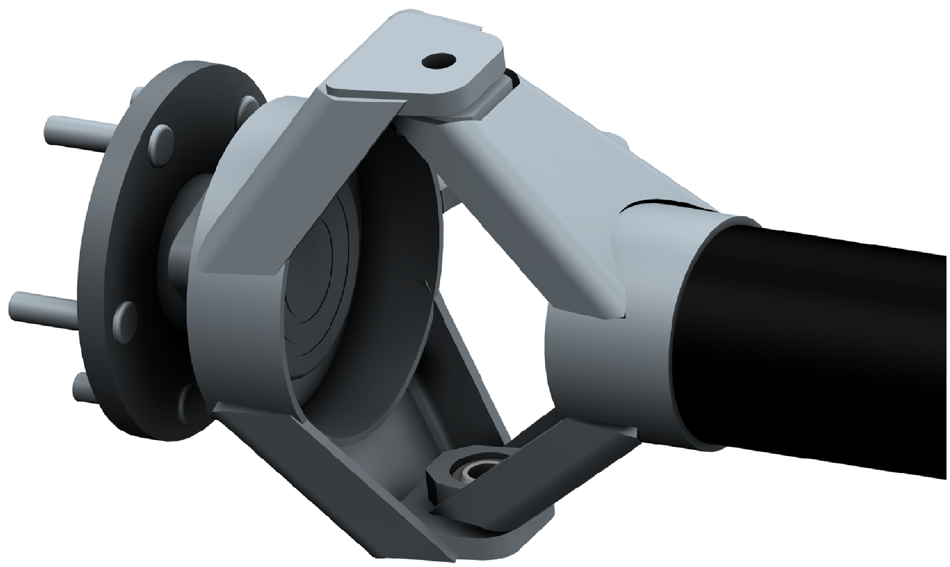


Figure 3.7. Front Axle Knuckle Assembly

This two piece knuckle design poses many benefits to the overall tractor performance and cost. Table 4 explains some of these benefits.

Table 3.4. Benefits of a Two Piece Knuckle

Two-Piece Knuckle Design Benefits	
Benefit	**How Benefit will Aid in Tractor Performance**
Lighter than traditional knuckle design	Will help achieve 80lb front axle weight goal
Allows for 55° of steering angle	Will aid in maneuverability course at competition
Customizable knuckle height	Very tight space limitations due to wheel-knuckle interface
Fabricated in house to decrease expense	Off the shelf aluminum steering knuckles are rare and expensive
Ability to fabricate out of aluminum	

Knuckle Joint Bearing Considerations

Initially, a spherical roller bearing as shown in figure 3.8, was considered to join the inner and outer knuckle together to allow rotation at both the top and bottom joints, as well as account for misalignment properties introduced by the camber of the outer knuckle. Spherical roller bearings contain two rows of rollers with a concave outer ring raceway. This raceway allows the bearing to be self-aligning and insensitive to as much as 2-3° of misalignment. Although these properties are very beneficial in our application, these bearings are able to handle much higher speeds than what we will be presenting them with and no added benefit would offset the added cost of the bearing.

Figure 3.8. Spherical Roller Bearing (Source: SKF)

The second bearing selection option was the plain spherical bearing as shown in figure 3.9, which poses many of the same benefits of the spherical roller bearing including the concave outer ring allowing for self-alignment and high misalignment properties. The only item absent from this bearing versus the spherical roller is the rollers themselves. Due to the very low speed and frequency these bearings will be spinning, it was decided that this type of bearing would be the best choice for our application. Axial and radial load characteristics of the plain spherical bearing meet and exceed the specifications needed for the front axle.

Figure 3.9. Plain Spherical Bearing (Source: SKF)

Axle Joint Considerations

Double-cardan universal joints were first considered to serve as the articulation mechanism for the driven axle shaft from the differential. This joint needs to lie in-between the two halves of the knuckle, in line with the pivot of the knuckles themselves. The double-cardan joint was thought to be a good first option due to the second u-joint phased in relation to the first to cancel the changing angular velocity typically seen in traditional universal joints, as well as the enhanced articulation angle. A minimum steering angle of 20° (total articulation of 40°) was set by the Bison Pullers to allow the tractor to maneuver adequately during the maneuverability portion of the competition as well as for general everyday use. While a double-cardan universal joint would be adequate to achieve this, the space occupied by the joint would be large, causing the knuckles to be larger and heavier than they need to be. Thus, it was decided that other viable options be explored.

The next option considered was a constant velocity or CV joint. These joints are able to transmit power and absorb large torque impulses at large angles more effectively than universal joints. These joints are typically seen on front wheel drive cars for this reason. A CV joint is a ball and socket style joint with slots incorporated into the ball to house 5-6 steel balls. These balls serve as the drive mechanism for the joint, and also allow for the 45-48° of articulation typically output by a CV joint. A CV joint, along with its internal layout is pictured in figure 3.10.

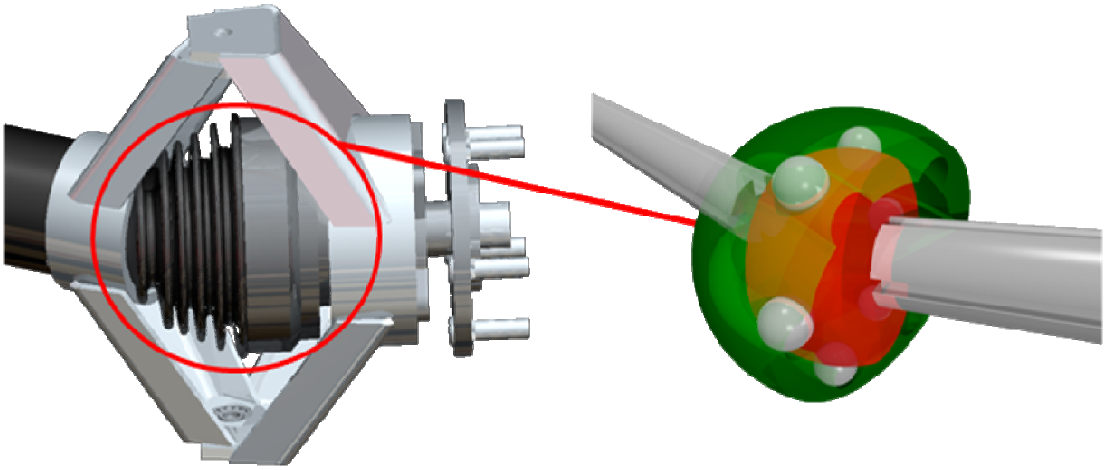


Figure 3.10. CV Joint

CV joints are typically more compact than using a double-cardan u-joint. This creates a weight reduction in the knuckle material needed, as well as the weight of the joint itself. A CV joint from a 1995 Mitsubishi Eclipse was chosen for its small and lightweight design, allowing the joint to easily rest in-between the two knuckle halves. Each joint only weighs 5lbs, helping the front axle reach its 80lb goal at completion. The Eclipse was not just chosen for its CV design, but for its simple hub assembly that pairs with it as well. On the stock Eclipse, the light 8lb hub assembly is bolted onto the knuckle for easy replacement. This allows us to have a matched set of splines found both on the shaft and the drive hub. Machining of splines can be a very expensive process at a machine shop, making the choice a very cost effective and viable option.

Ackerman Steering

Ackerman steering defines the geometry that enables the correct turning angles of each wheel when negotiating around a turn. This theory was incorporated into the front axle to aid in overall maneuverability of the tractor during tight turning situations. The Ackerman steering principal suggests that angled steering arms permit toe out on turns, allowing the outside tire to turn at a greater radius during turns. The main goal of the principal is to have the centerline angles of the front tires meet on the axis of the rear axle as shown in figure 3.11. This phenomenon prevents scrubbing of the inside tire while turning thus limiting tire wear, and producing a smaller turning radius for the tractor. This will aid the tractor in two ways, both for general maneuverability, as well as for the actual maneuverability portion of the competition. This portion of the competition makes the tractor navi-

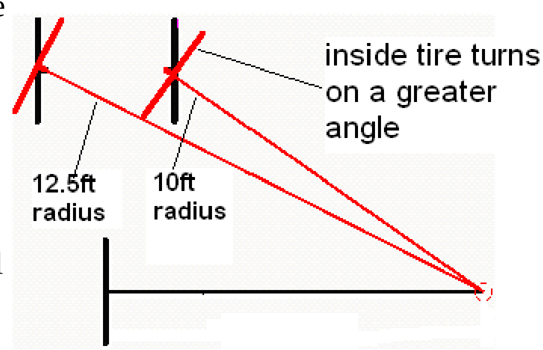


Figure 3.11 Ackerman Steering Principal

gate around a series of cones, judging the overall maneuverability of the tractor. Many points may be taken off for cone impact violations.

To aid in the modeling of this principal, a Pro Engineer sketch was made. Geometries such as wheelbase, front axle width, angles of steering arms, as well as a variety of lengths from the knuckle pivot were taken from the current model of the front axle and incorporated into the sketch. Angles and lengths of the steering arms were adjusted to find optimal steering geometries to achieve Ackerman steering. Shown in figure 3.12, the length of the hydraulic cylinder was modified to represent the extension and retraction of the cylinder, which acted on the steering linkages. The axis protruding from the centerline of each wheel was then used to judge if they intersected with the rear axle axis. Different lengths and angles were input into the model until desired results were achieved.

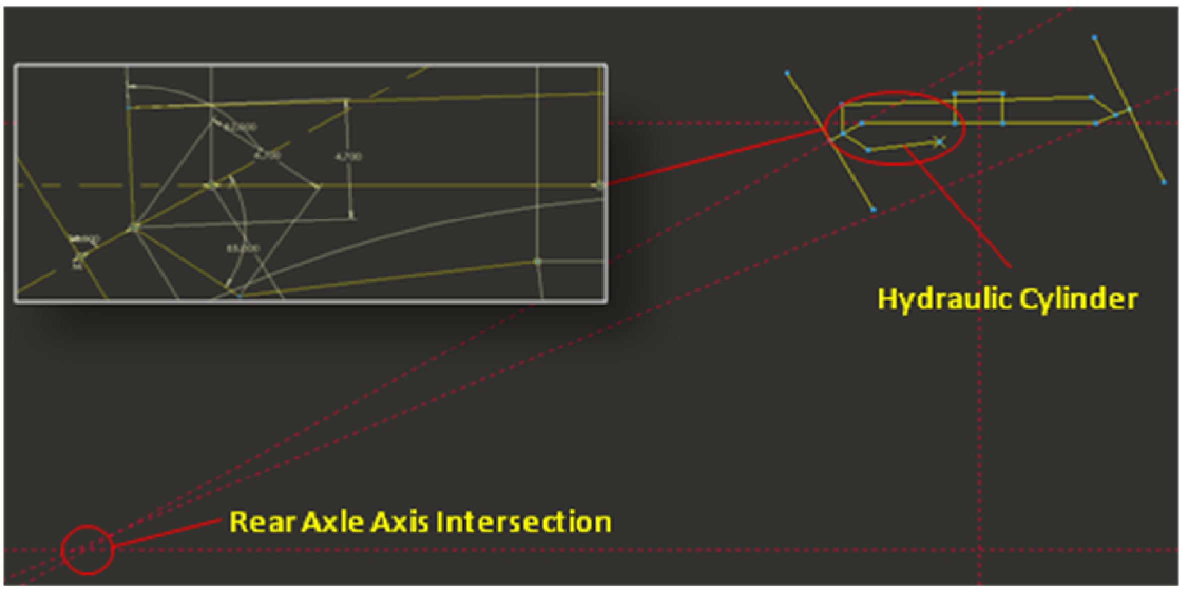


Figure 3.12. Ackerman Steering Model

Using the model, a steering arm length of 4.7”@62° from the centerline of the wheel was found to be suitable for optimum steering performance. On the left side of the axle will be an additional steering arm for the hydraulic cylinder to act on. The optimal length for this arm was found to be 4.7”@65° from the centerline of the left front wheel. These values were input back into the Pro Engineer and Algor models to undergo further analysis such as FEA to find suitable material thicknesses.

III. 4 Safety

Safety was considered a major factor in the design of the front axle. Three likely failure modes were considered for evaluation: failure/deflection of the inner knuckle weld joint, failure/deflection of the axle mount, and failure/deflection of the tie rod, tie rod arms, or hydraulic steering cylinder mount on each of the outer knuckles. Each of these failures have the possibility of causing serious damage to both the tractor and/or harm to the operator. Each of these situations can be avoided with proper welding installation of each of the components, but considerations of possible failure modes are necessary.

The front axle utilizes a long reach of the inner knuckle to bring the centerline rotation of the knuckles in line with the constant velocity joint. Although favorable for correct geometry, severe stress concentrations may be developed not only in the inner knuckle area, but also at the front axle mount as well if proper welding considerations are not taken. These two failure modes are of concern due to the tractor possibly reacting violently under a high speed situation. Safety measures have been taken to ensure that operator safety is maintained in this type of situation. These safety concerns were addressed by the addition of safety chains to adequately support and maintain the integrity and placement of the axle in a catastrophic failure. These chains will ensure the axle stays with the tractor to prevent a rollover situation.

The tractive force of the wheels along with the added force of the hydraulic cylinder will place extreme amounts of stress on both of the tie rod mounts and hydraulic steering cylinder mount found on the outer knuckle. Representative simulations of most load cases were evaluated in the finite element analysis report, but a variety of unforeseen circumstances may still exist. If a failure were to occur on either of the tie rod mounts, the wheels would begin to rotate forward and the tractor would decelerate. The operator would merely have to shut off the tractor or depress the clutch to avoid any further damage to the tractor structure. If performed in a quick manner, no further damage beyond the mount broken would be suffered. This actions would also prevent any bodily harm to the operator or bystanders.

III. 5 Front Axle Discussion

Through finite element analysis, 6061-T6 aluminum was found to be acceptable for it's structural integrity during maximum load situations, as well as its 65% reduction in weight versus using 1040 hot rolled steel. All FEA load cases fell below the yield strength of 6061 aluminum, even in extreme loading conditions, much of which the front axle will not see in typical roading scenarios. This type of Aluminum was used to fabricate the axle tubes, frame mount, tie rod, and knuckles. The stock hub assembly, CV axle shaft, differential, and pivot pin are made of other various materials.

A custom designed, two piece knuckle with an inner and an outer knuckle was fabricated of 6061-T6 aluminum plate. The design concept allowed for easy fabrication with current outside resources of the Bison Pullers having the ability to laser cut and form aluminum. Spherical bearings were chosen over spherical roller bearings due to the nature of axle loading. Axial and radial load characteristics of the plain spherical bearing meet and exceed the specifications needed for the front axle.

Constant velocity (CV) joints were chosen over a double-cardan u-joint configuration due to weight and space criteria. The more compact design of the CV joint allows for a reduction in size of the knuckles, thus promoting a lighter axle. Ackerman steering principal was considered when designing the tie rod arm and steering mount angles. Optimal steering geometries were determined using a Pro Engineer sketch.

Following the main objective above, as well as the other objectives set forth by the Bison Pullers organization, the front axle design meets all of the original design criteria. The total axle weight met the 80lb weight limit, weighing a total of about 75lb. The axle, per FEA results, is able to adequately support the weight of the tractor, with little to no deflection. No further comments can be made about the rigidity of the front axle at this time, due to the axle not yet being completed to the point of being placed on the tractor. However, from the FEA results conducted and the severity of the loading induced, I have no concerns about the structural integrity of the axle. The pivot pin design allows for the +/- 6 degrees of rotation required for proper tractor maneuverability. Accommodations for hydraulic power steering were implemented into the design, with the addition of a power steering mount to the front of the differential and a mounting arm to the outer knuckle. Adequate steering angle within 10° of the previous years' tractor was achieved by the combination of knuckle design and CV joint capacity.

IV. Continuously Variable Transmission Design

IV. 1 Control System Design

It was determined by the Bison Pullers that the CVT should be forced. Meaning that the operator is able to set the gear ratio of the CVT at independent engine speed. Normally a CVT such as one on a ATV or snowmobile varies its gear ratio automatically based on engine rpm. This was determined, by the team in cooperation with the Bison Pullers, to not be desirable operating method because tractor operators would not be familiar with its operation. Two main of methods to accomplish this were are: proportional hydraulic control and an electronic linear actuator. The linear actuator method was selected for three main reasons: weight, price, and usability.

A hydraulic system was first considered. It would be able to easily produce a significant amount of force. Based on the estimation of 500 pounds of force being the maximum amount required to close the CVT with a reasonable safety factor, and a system operating pressure of at least 1000psi, a cylinder with a piston end cross-sectional area of only 0.5 inches would be required. This estimation was based on information obtained from Bison Pullers members who have experience with CVTs on snowmobiles. This would initially make this choice seem very favorable. However, controlling the fluid flow is a very significant challenge. Either a proportional or servo valve would be required. Based on the experience of team members and our advisor this would prove to be very expensive, likely more than $500. Also, though the tractor will have a hydraulic power steering system, it would be difficult to take pressure off this system. When the steering wheel is not being turned, the fluid flow is dumped over the open center valve at very low pressure. In order to take pressure to control the CVT from this system a control valve would need to be used to shut off flow through the power steering orbital and push the pressure up to system relief. This would be an inefficient use of power and could cause loss of steering control. It was therefore determined that a separate pump would need to be added for the CVT control system. The system would require a pump, lines, a control valve, reservoir, and a cylinder. This system was deemed likely to be prohibitively heavy and expensive.

The second and chosen idea was to use an electronic linear actuator to move the CVT. A linear actuator is essentially a screw that is slowly turned by an electric motor. A collar is threaded onto the screw and is held stationary; as the screw turns it is forced to move linearly. A cutaway of the linear actuator that has been chosen is shown in figure 4.1. There are numerous advantages to

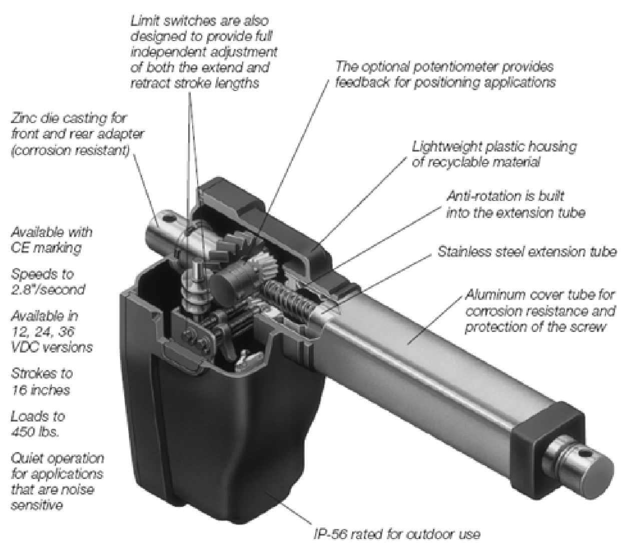


Figure 4.1. Cut away of an Electrak E150 actuator (Source: Danaher)

such a system: it can draw power off the tractor's battery, its speed is relatively easily controlled by a PWM (Pulse Width Modulation) unit, it is fairly light (between 5 and 15lbs), and often includes a feedback potentiometer, which will be useful in the control system design.

IV. 2 CVT Mounting Locations

Different concepts for the location and mounting of the CVT and its control system were investigated. It was decided early on that the best way to mount the CVT itself was to mount the primary, or drive pulley, directly to the shaft coming out of the gear box that connects the three engines together, and mount the secondary or driven pulley, directly below it and attached to the clutch. This mounting scheme keeps the tractor as short as possible and fits well within the frame.

It was decided by the Bison Pullers to incorporate a clutch between the secondary and the transmission. This allows the CVT to remain at a set gear ratio while the tractor is stopped and then reengaged. This could be beneficial in the pulls. There was also a concern about the tractor ability to drive slow enough for the maneuverability course. The transmission designed by the Bison Pullers sets the minimum speed at 3.3 mph and its max at 13mph. 3.3mph could be too fast for the course. Allowing the CVT to slip to reduce this speed would cause high belt slip and damage the belt. By using the clutch, the operator could ride the clutch to reduce speed. The wet clutch is designed to absorb some slip it will not be damaged by it.

Determining a method for mounting the control system challenging. The two primary challenges were limited space and high rigidity requirements. Figure 4.2 shows the chosen design. The actuator must force on the right side of the primary. This location is difficult to get to. It is very important that the entire mechanical control system be very ridged. Flex in the system would reduce the operator's

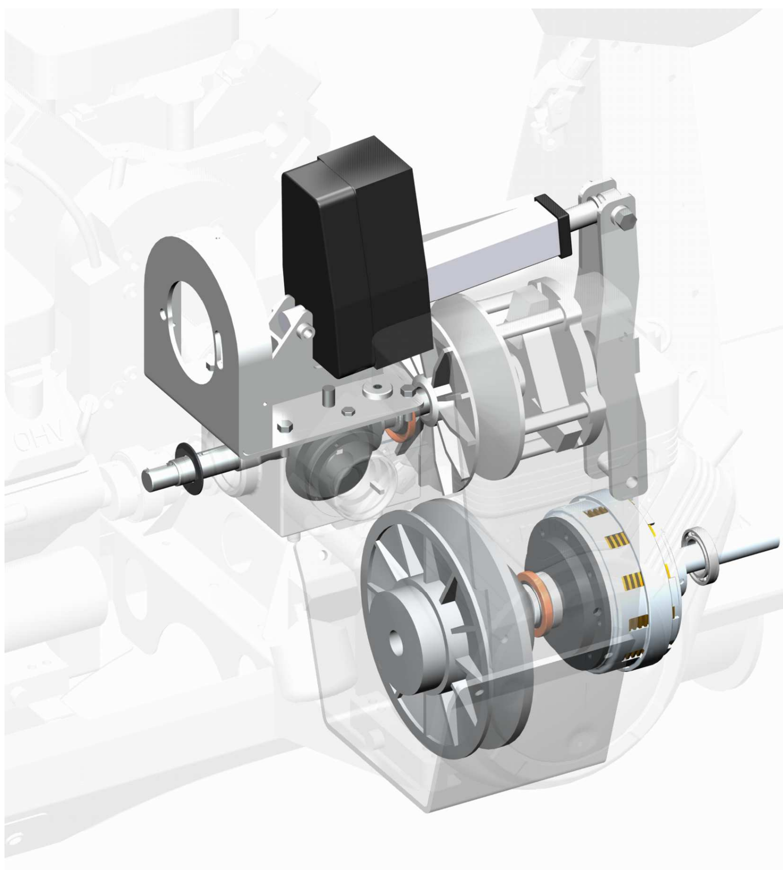


Figure 4.2.. CVT Assembly

ability to accurately control the position of the CVT. It could also lead to vibration, which could damage the belt.

The first concept investigated was using a short actuator and mounting directly to the primary. The optimum length for the actuator in such a position was 5 or 6 inches. None this size were available. No manufacturer of such a actuator could be found. A longer actuator would stick into the steering column and require that the frame be lengthened. It would be mounted to the steering column, requiring significant reinforcement of the column, which would add weight. For these reasons the concept was discarded.

The second concept was to use a lever arm with a 2 to 1 mechanical advantage, mount the actuator to the bottom of the arm and place it underneath the deck plate and above the transmission. The top of the lever would be mounted to the gear case. This idea was rejected due to a redesign of the transmission, which reduced the space between it and the deck plate; the actuator would no longer fit.

The chosen design, which is shown in figure 4.2, built on this concept, but placed the actuator on top. The left side of the actuator will mount to the top of the gear box. This location was solid and is readily available. The bottom of the pivot arm mounts to the underside of the deck plate. The pivot arm connects to the primary with a clutch throw-out bearing.
FEA has been performed on the pivot arm. It was conducted with the pivots having pinned boundary conditions (fixed displacement in all directions and free rotation), and a force of 200lbs applied to the surface that contacts the throw-out bearing. This loading is based on forces determined by Austin Houkom, an engineer at Polaris Industries in Roseau, Mn. A detailed report can be found in the appendix C. The minimum factor of safety determined was 15.12, using 6061-T6 aluminum. This was deemed acceptable. It would be possible to reduce the safety factor; however the stress concentrations were at weld joints. Due do the Bison Pullers previous experience with welding aluminum, we may not be able to achieve as high quality of weld as is modeled by the FEA.

IV. 3 Actuator Selection

A variety of actuators were considered for use in the system. First, the desirable characteristics of the actuator were laid out. It would need to have enough force to control the CVT at any rpm and torque on the engine’s lug curve. Austin Houkom, an engineer at Polaris (Roseau, MN) was contacted for aid in determining the required force. Given the peak torque output of the engines at 72ft-lbs (according to Briggs and Stratton) and top speed of 3600rpm he was able to determine that the CVT would require a maximum force of 175 lbs. This is not allowing for any factor of safety or degradation in actuator performance due to age. It was decided that the actuator should be able to produce at least 250lbs of force on the CVT.

The actuator also needs to be quick enough to make the CVT feel responsive for the operator, but not so quick that it would move faster than the control system can respond. This high speed could result in oscillations and poor performance. Very high speed could also cause excessive belt tension or even cause the belt to become stuck in the secondary. Based on discussion with the Bison Pullers it was determined that the actuator should be able to move the CVT primary from one extreme to the other in less than about 2 seconds. The chosen CVT primary has a displacement from maximum gear reduction to maximum overdrive of about 0.95 inches, from maximum overdrive to full open is about 1.15 inches. This was measured by hand and does not include the additional opening of the primary to disengage from the belt, as this will not be required in the design due to the use of a clutch. Given the 2 to 1 lever arm, this means that the actuator must move at least .95 inches per second.

There were a few other factors that were considered in choosing an actuator. It would need to be powered by 12volts, as this is what is available on the tractor. It should also be as light as possible to allow for the goal of 50lbs for the complete CVT assemble to be met. Low cost is also desirable, as the Bison Pullers budget is limited. Having potentiometer feedback would also be desirable. It would be possible to design a custom feedback system, however this would likely not be as reliable as a manufacturer installed system.

Initially an internet search was conducted for linear actuators. However, nothing meeting the above criteria was found. Most were actuators requiring 110VACor were too expensive. Duff-Norton's actuators, however seemed to be reasonable. They were contacted referred us to their local distributer, Motion Industries in Fargo. After discussing the requirements with them, Thomson actuators by Danaher were recommended. Their application engineers were contacted and options were discussed. The actuators suggested were the Electrak E150, Electrak 2, or PPA 12 VDC (Danaher, Washington, D.C.).

The Electrak E150 was chosen for its light weight and reasonable speed. It was the lightest of the recommended actuators, weighing 5.2lbs, compared to the Electrak 2 at 10lbs, and the PPA 12VDC at about 15lbs. The E150 also had the lowest amount of force that would meet our requirements, 225 pounds. Only about 125pounds will be required, however Motion Industries was not able to locate an actuator in this force range that was 12VDC and had an acceptable speed. The E150 speed is 1.4inches per second at no load and 1.25 inches per second at 80lbs of load. The specific model ordered was the E150 DF12-10W52-04LPMHN. It also includes potentiometer feedback.

IV. 4 CVT Shielding

CVT shielding was designed according to Quarter Scale Competition Rules which can be found in Section 15 of the Rules. They require that all rotating components have no-contact shielding, and that belts and chains must have peripheral shielding of at least 1/8 inch thick mild steel or 1/4 inch aluminum. Aluminum shielding was chosen due to its light weight relative to the steel, and because the Bison Pullers have a sponsor that will laser cut 1/4 inch aluminum at no charge.

The CVT shielding was designed for minimum weight, ease if service, and manufacturability. The shielding was designed in three parts, as shown in figure 4.3. The lower part attaches by four bolts to the bottom of the frame and is easily removable for servicing the belts. The upper left side shield is attached to the operators station and the frame. It is designed with notches cut into it for the pivot arm and the actuator to fit into. This does make it harder to remove, but is necessary in order to provide adequate shielding of the CVT belt. A CVT belt is very thick and heavy. Therefore failure could be a very catastrophic event if it was not shielded properly. Extending this shield and creating the notches ensures that the belt would be contained should it fail. The third piece of the shield is shown in figure 4.4. It is designed to be the primary access point for service. It bolts to the other shield, steering column, and the deck plate. It can be removed with only four bolts.

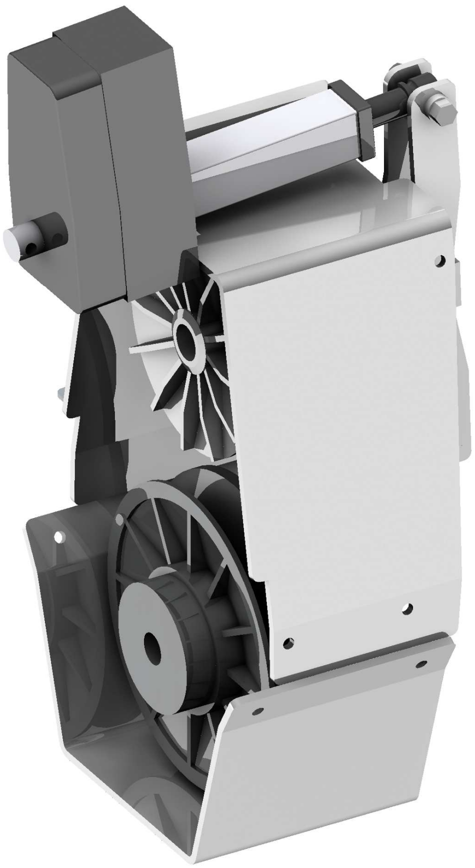


Figure 4.3. CVT Assembly with shields.

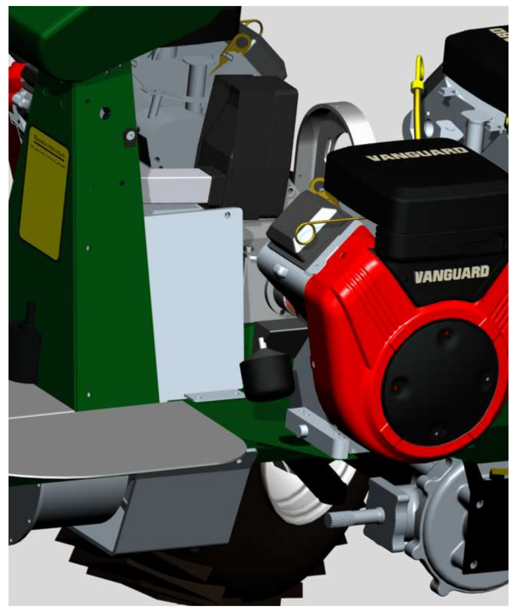


Figure 4.4. CVT with shielding

Another critical advantage of this shielding is that by being bolted to the frame, deck plate, and steering column, it provides additional structural support to the column. The strength of the steering column has been a concern because the operator will likely pull himself up onto the tractor by pulling on the steering wheel supported by it. This makes rigidity important so that the operator feels comfortable and confident on ingress and egress.

IV. 5 Electrical Control System

An electrical control system needed to control the position of the actuator. A microcontroller would be required. Three controllers were investigated based on the input of Dr. Bon and Bison Pullers members: the Basic Stamp 2(BS2) and SX chip from parallax, and a PIC microcontroller from microchip. The Basic Stamp 2 was initially selected because of its ease of programming, the design team's experience with it and its ability to effectively control the system. Code for any of these controllers needed to be written by the team.

Figure 4.5 Standard Servo (source: Tower Hobbies)

Discussions with the Bison Pullers about the control system for the CVT led to the decision to include electronic throttle and choke control as part of the system. This would eliminate the mess of cable linkages that would be required to connect the three engines throttles and chokes together mechanically, and it would not add much complexity to the program for the microcontroller. It was decided to actuate the throttle and choke with a standard servo. The servo chosen for control of the engine throttle controls is shown in figure 4.5. Standard servos are controlled by sending a high pulse of 1ms to 2ms duration every 15 to 25ms. A 1ms pulse corresponds to about a 12 o'clock position of the horn. A 2ms pulse corresponds to about 6 o'clcok position. This allows for precise control and provides the high torque required for the throttle.

The choke position is controlled by a three position switch: position 1 is open, 3 is closed, and 2 is half way. The throttle position is controlled by a potentiometer mounted on a foot pedal. The CVT is also controlled by a potentiometer, but it is mounted on a lever. This layout was chosen because from the Bison Puller's experience it is much easier for the operator to accurately control, especially in the event of power hop. Accurate control of the CVT is necessary during the pull, to be able to put the maximum amount of power to the ground without excessive wheel slip. However through the whole pull the throttle will just be wide open. Because of this experience, it was decided that the CVT control needed to be on the lever.

The overall scheme for the CVT control is to have the operator move a lever and the actuator follow the motion. The control lever is attached to a potentiometer, which provides an input position to the microcontroller. The actuator also has a potentiometer embedded in it, which allows the microcontroller to know its position. It then compares the two and moves the actuator as required. A wiring schematic and code for the microcontroller can be found in the appendix. The decision was made that the position of the potentiometers would be determined by using the RC circuit shown in figure 4.6. The wire at right is connected to a pin on the Basic Stamp. The pin is initially set to high for about 10ms, allowing the capacitor to charge. The pin is then changed to an input and a timer started, allowing the capacitor to begin to decay across the potentiome-

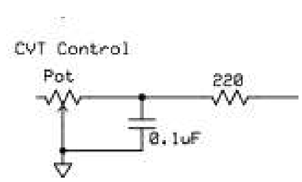


Figure 4.6. RC circuit for reading the Pot

ter. Once the capacitor decays below the lower threshold voltage of the Stamp (~1.4V), the time is stored in a variable. This occurs very rapidly, usually in less than 0.25ms. The time is directly proportional to the resistance of the potentiometer. A more conventional method would be to use an analog to digital converter, however, they are fairly expensive at $5.00 to $10.00 a piece compared to about $0.25 for the capacitor an current limiting resistor used above. An ADC would be more precise, however that would likely not be needed.

The linear actuator is controlled by an HB-25 PWM (Pulse Width Modulation) and H-Bridge unit from Parallax, which is shown in figure 4.7. This allows the speed of the actuator to be varied from zero to maximum and its direction changed. The HB-25 is designed for 12volts at up to 25 amps, so it exceeds the power demands of the actuator. It is controlled by sending it a pulse from 1.0 to 2.0ms: 1.0ms is full reverse, 1.5ms is stop, and 2.0ms is full forward. It needs to receive the pulse at least once per second.


Figure 4.7. HB-25 PWM Unit (www.parallax.com)

The Basic Stamp is commanded to send pulses by the pulsout command. It is of the format “PULSOUT *Pin*, *Duration*”, where duration is in 2µs increments. The section of the code shown in figure 4.8 takes the decay times from the potentiometers and converts them to a pulse to send to the HB-25. This code is not yet calibrated as the engine test stand has not yet been setup. The proportional constant “k” will need to be determined

```
'CVT control master IF statement
IF engine_on=1 THEN                          'only send control to CVT if engines are on
  IF tCVTlever>tCVTpos THEN                  'if actuator needes to retract
    pulse_c=tCVTlever-tCVTpos
    pulse_c=pulse_c*k                        'for proportional control
    pulse_c=pulse_c+750
    IF pulse_c<760 THEN                      'for deadband to prevent oscillation
     pulse_c=750
    ELSEIF pulse_c>990 THEN                  'set max speed limit
     pulse_c=990
    ENDIF
  ELSE                                       'if actuator needs to extend
    pulse_c=tCVTpos-tCVTlever
    pulse_c=pulse_c*k                        'for proportional control
    IF pulse_c> 750 THEN                     'Prevent a negitive from possibly occuring
      pulse_c = 750                          'in the next statement
    ENDIF
    pulse_c=750-pulse_c
    IF pulse_c>740 THEN                       'for deadband
      pulse_c=750
    ELSEIF pulse_c<510 THEN                   'Set max speed limit
      pulse_c=510
    ENDIF                                     'The pulse to send has been determined
  ENDIF
ELSE
  pulse_c=750                                 'If the engines are off stop the actuator
ENDIF
DEBUG "pulse_c = ", DEC pulse_c, CR           'Display pulse on laptop if connected
PULSOUT HB25, pulse_c                         'Send pulse to HB-25
```
Figure 4.8. Basic Stamp Code for CVT control

to allow for the quickest possible response of the system without it overshooting the set point. Another if statement will also be added to set the minimum and maximum positions of the actuator.

The control program has been tested using an actuator provided by Nic Hodnifield. It is fully functional, but would need to be calibrated once the system is installed on the tractor. A cycle speed of 20 to 30ms was achieved.

The first if statement is the implementation of a safety system. If the operator would attempt to close the CVT sheaves with the engines off, the belt would be pinched between the sheaves and damaged or destroyed. It is therefore necessary to design the control system so that this would not be possible. The controller needs to know if the engines are running. This in implemented using a hall effect sensor on a gear in the gear box. An if statement sets the bit engine_on to 1 if the incoming pulses are fast enough or 0 if not. The HB-25 will be ordered to stop if engine_off is zero.

The system was initially designed using a BS2 microcontroller, however based on information from taking the course ECE 363 Embedded Systems Design, it was decided to redesign using a PIC microcontroller. One of the main reasons for this was that the Tractor's gauge cluster utilizes two PIC microcontrollers. There was sufficient room in the gauge cluster for another PIC and supporting hardware but not enough room for a Basic Stamp 2. Having the microcontroller in the gauge cluster simplifies the wiring for the tractor and places all electronics in one central location.

The PIC also performs better and is more versatile. As previously discussed it was difficult to measure the position of the potentiometer using the BS2. During testing it was found that the method shown in Figure 3 worked fairly well, but did not have a very high resolution. Also, when the potentiometers are at very high resistance it takes much longer to read them than when their resistance is low. This lead to problems in maintaining a fairly constant loop time. The servos require a loop time of between about 20ms and 15ms, otherwise they have the tendency to chatter, which greatly reduces their lifetime.

The PIC solves this problem because it has an onboard 10-bit analog to digital converter. This converter is also very quick, measuring the potentiometer voltages in less than 20µs. The converter has a resolution of 5mV, or 0.26 degrees, assuming a typical 270 degree maximum rotation for the potentiometer. This is much better resolution that was possible with the BS2. A new cirrcut schematic for the PIC is shown in Appendix A.

The only major drawback of the PIC is that it programs in C. A language which most Ag. Engineers are unfamiliar with. This will make it difficult for them to reprogram, if necessary. This was discussed with the Bison Pullers and deemed not to be a major issue as it should never need to be reprogrammed, and there are electrical engineers on the team that have in-depth experience with C. Also the PIC does not have some of the convenient built in subroutines like the BS2, such as *pulsout, pulsing, pause,* or the ever convenient *debug* command.

IV. 6 PIC Programming

Programming for the PIC was approached in a bottom-up method, in which subroutines are developed to accomplish specific task, they are tested, and then they are all put together in the main program.

The first major subroutine developed was to send the pulse to the servo for the engine controller. The subroutine should send out a pulse between 1 and 2ms based on an input value. The initial routine used a simple *for* loop to wait for a period of time. The input values for 1ms and 2ms were about 280 and 380 respectively. In testing this with a potentiometer it was found that the step size was a bit to large, leading to problems in calibration and servo chatter. It was decided that higher resolution was required.

Investigation into the resolution issue showed that the problem was that and *int* variable (16-bit) was used in the *for* loop. Since the Algorithmic Logic Unit (ALU) in the PIC is only 8-bit, 16-bit numbers take more clock cycles to work with than 8-bit numbers. So it was decided to re-write the code to use only 8-bit variables (*char*) in the loops. Testing showed that a value of about 900 would be required for a 1ms delay. This would need to be expressed as four 8-bit numbers (8-bit unsigned numbers go from 0 to 255). The 16-bit variable passed to the subroutine was converted into this form using a for loop. The complete code for this subroutine is shown in figure 4.9. When tested this code controlled the servo accurately and without chatter.

The next subroutine developed was to determine if the engines are running. The input for this is a proximity sensor that reads off of a gear in the gear box which connects the engines together. Through discussions with the Bison Pullers it was determined that the engines should be considered shut off if there speed is less than about 1500rpm. The low idle setting for them is 1700rpm. Given that the gear has 21 teeth this results in an input square wave with a frequency of 525Hz. If the input frequency on RC2 is less than that the subroutine sets a flag to 0, otherwise the flag is set to one.

The subroutine is shown in figure 4.10. It begins by determining if the wave is high or low. It then determines how long the input stays high or low. If the pulse exceeds 380 counts it sets the flag to 0, otherwise it is set to 1. 380 counts was determined experimentally to correspond to an input frequency of 525 Hz. The subroutine will time out if the incoming signal does not change in less than 380 counts. This prevents the program from getting stuck waiting for engine pulses. The subroutine takes between 4 and 2ms to execute for engine speeds of between 0 and 3600rpm. This is important so that the servos for choke and throttle will continue to function properly without the engines running, but the linear actuator will not. The main program simply has an if statement that send the normal pulse to the PWM unit if flag is one, else it commands the unit to stop the actuator.

The subroutine for sending the pulse to the HB-25 PWM unit is the same as to the engine servo accept on a different pin. The code for determining the pulse is the same as what was written for the BS2, accept translated into C. The complete code for the PIC can be found appendix B.

```
// Subroutine for pulse to throttle
void Pulse_Thrt(unsigned int C){
    //variable declaration
    int w;
    unsigned char t[4];
    char i;
    // convert C (0 to 1000) int four 8-bit variables i[0] to i[3]
    for (i=0; i<4; i++){
        if (C>255){
            t[i]=255;
            C=C-255;}
        else {
            t[i]=C;
            C=0;}
    }

    //send pulse
    RC0=0;                      //drive RC0 low
    for (w=0; w<330; w++);      //wait 1ms
    while (t[0]) t[0]--;        //wait 0 to 1ms
    while (t[1]) t[1]--;
    while (t[2]) t[2]--;
    while (t[3]) t[3]--;
    RC0=1;                      //drive RC0 high
}
```

Figure 4.9. PIC code for engine throttle control.

```
//Subroutine to check if engines are on
//flag = 1 if on, 0 if off
char Eng_chk (void)
{
//variable declaration
unsigned int time=0;
char flag;
//determine if sqare wave is high or low
if (RC2){
    while (RC2 & time<380){        //count while high
        time++;}                   //break out if > 1ms and set engines off
    if (time==380) flag=0;
    else{                          //count time low if high did not time out
        time=0;
        while (!RC2 & time<380){
            time++;}               //break out if > 1ms and set engines off
        if(time==380) flag=0;
        else flag=1;               //if both times less than 1ms, engines are on
    }
}
else{                              //same as above but starting with low pulse
    while (!RC2 & time<380){
        time++;}
    if (time==380) flag=0;
    else{
        time=0;
        while (RC2 & time<380){
            time++;}
        if(time==380) flag=0;
        else flag=1;
    }
}
return flag;                       //return the flag to the main program
}
```

Figure 4.10. PIC code to check if engines are on

The PIC is mounted on a custom Print Circuit Board (PCB) designed by electrical engineering members of the Bison Pullers. This board is mounted in the gauge cluster. It was designed by them according to the wiring diagram found in the appendix.

IV. 7 Safety

Safety was a paramount consideration in the design of the CVT system. Three likely failure modes were closely considered: failure of the belt, failure/deflection of control linkage, and failure of the electronic control system. These failures had the potential of causing serious damage to the tractor and/or harm to the operator. These situations should be avoided by proper installation and maintenance, but a consideration of them is necessary.

The CVT uses a fairly heavy belt that rotates at high speed. A failure of this belt could be caused by deterioration, excessive slip, or misalignment. Due to its high momentum belt fragments could be hazardous to the operator and bystanders if uncontained. Therefore, a shielding system was designed in compliance with competition rules. This system is adequate to contain the belt should a failure occur. The shield also exceeds manufacturer shielding which is either fairly thin plastic or thin sheet metal. Peripheral shielding is 1/4 inch aluminum.

The control system for the CVT could fail or deflect if welds are not of sufficient quality or due to deterioration. The concern was that this could damage other components or cause the tractor to behave in an unexpected way. This was addressed by designing the system in such a way that a failure of the system would result in the tractor stopping. If the control system fails the force of the spring inside the primary would cause it to open fully, stopping the tractor. The design of the shield prevents the linear actuator from contacting the primary. In the event of a failure of one of the pins on the pivot arm, it would be contained by the shielding and by the steering column.   If the control system only deflects it would cause the tractor to simply not be able to achieve top speed. This could be corrected by recalibrating the system if the deflection was minor.

The electrical control system could possibly fail due to developing short, water infiltration, or poor connections. During manufacturing all connections are inspected and tested for not only operation, but also quality. This should greatly reduce the chance of an electrical failure. The instrumentation cluster where the PIC is housed is sealed to prevent water infiltration. There are two possible modes of electrical failure that could be hazardous: actuator closing or unexpected actuator response. If the actuator closes without input, it has an internal limit switch that will shut it off when it reaches fully closed. This prevent the actuator from stalling or its force overstressing the mechanical linkage The tractor would accelerate to maximum speed, but no damage would occur. The operator would merely have to either shut off the tractor or depress the clutch. The operator's response would be the same if the system behaved unexpectedly. Again, no further damage would occur.

The design of the CVT system has taken into account these unlikely, but possible failures, and has addressed them in a manner that makes the operator and by standers as safe as possible and assures minimal further damage to the tractor.

IV. 8 CVT Design Summary

The CVT is forced by a Electrak E150 linear actuator manufactured by Danaher. It was decided to use a linear actuator instead of an alternate method such as a hydraulic cylinder due to its comparatively low cost and light weight. The specific actuator was chosen with the aid of applications engineers at Danaher and Motion Industries in Fargo. The actuator connects to the CVT by a lever arm with a 2:1 mechanical advantage. This was done due to the force requirements of the CVT as stated by engineers at Polaris. This design also allows the actuator and mounts to be placed in a convenient and compact location.

The electronic original control system was designed using a Basic Stamp 2 microcontroller from Parallax. This control system was tested and functioned properly, but not with the highest performance levels. Also, the Basic Stamp is fairly high cost, and due to its size, would be difficult to fit into the instrument cluster. It was therefore decided to switch to a small, low cost, and better performing PIC microcontroller.

The program for the PIC was strongly based on the program for the BS2, but translated into C. The PIC program has been tested with the selected linear actuator and performs very well. The system is complete and awaiting the completion of the Bison Puller's transmission for installation on the tractor. This delay is because the CVT pivot arm mounts to the top of the transmission. Once the system is installed it will need to be calibrated, which should be a very quick process.

The design of the CVT meets all of the original objectives. It is able to open and close in about 1.5 seconds. This speed was accomplished by selecting an appropriate actuator and pivot arm. The CVT met the initial weight objective of less than 50 pounds. The complete assembly weight was about 40 pounds, which was primarily due to the use of aluminum and selecting a light weight actuator. The CVT has been designed to be very safe and reliable. The shielding of the CVT and electron fail-safes greatly reduces the chance of injury or component damage in the event of an unlikely failure. The forced CVT allows the operator to have the benefit of variable speed without the heavy weight or inefficiency of a hydrostatic transmission. The electronic control system allows the operator to easily and accurately control the CVT.

V. Conclusion

It was the objective of this project to develop a light weight, durable, and maneuverable front axle, and a responsive, reliable, and low cost forced CVT transmission for the Bison Pullers quarter scale tractor team. These components make the Bison Pullers tractor more competitive by: freeing up weight to allow for an additional engine, improving maneuverability, and allowing for variable speed to improve pulling performance. The CVT met or exceed all established criteria that has been tested; it was 10 pounds below the weight limit, used a low cost actuator system, and had an responsive control system. The front axle also met and exceeded all established criteria. The total weight was 5 pounds below the required limit, adequately supported the weight of the tractor, and was within 10° of the steering angle of last years tractor.

VI. References

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VII. Acknowledgements

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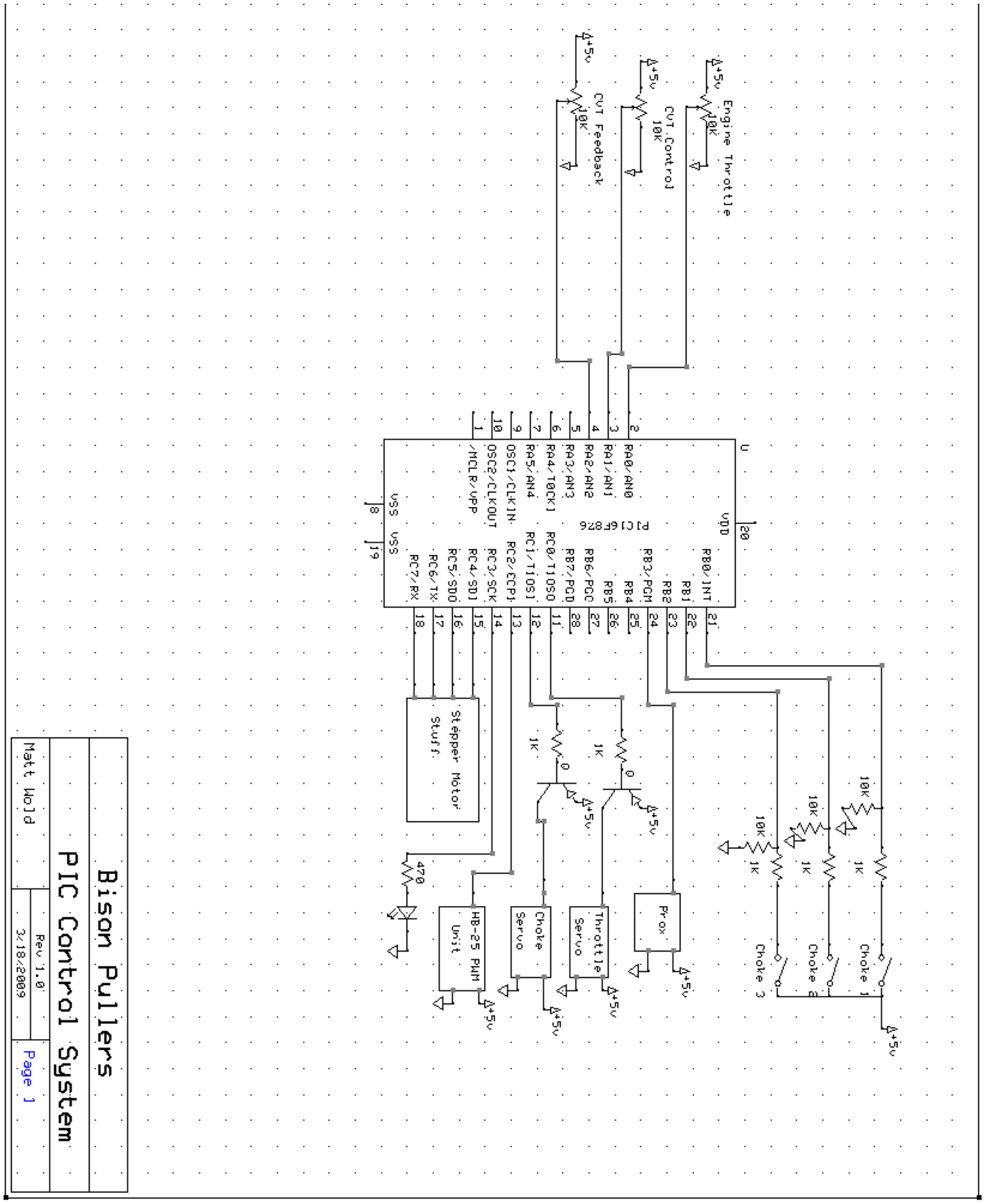
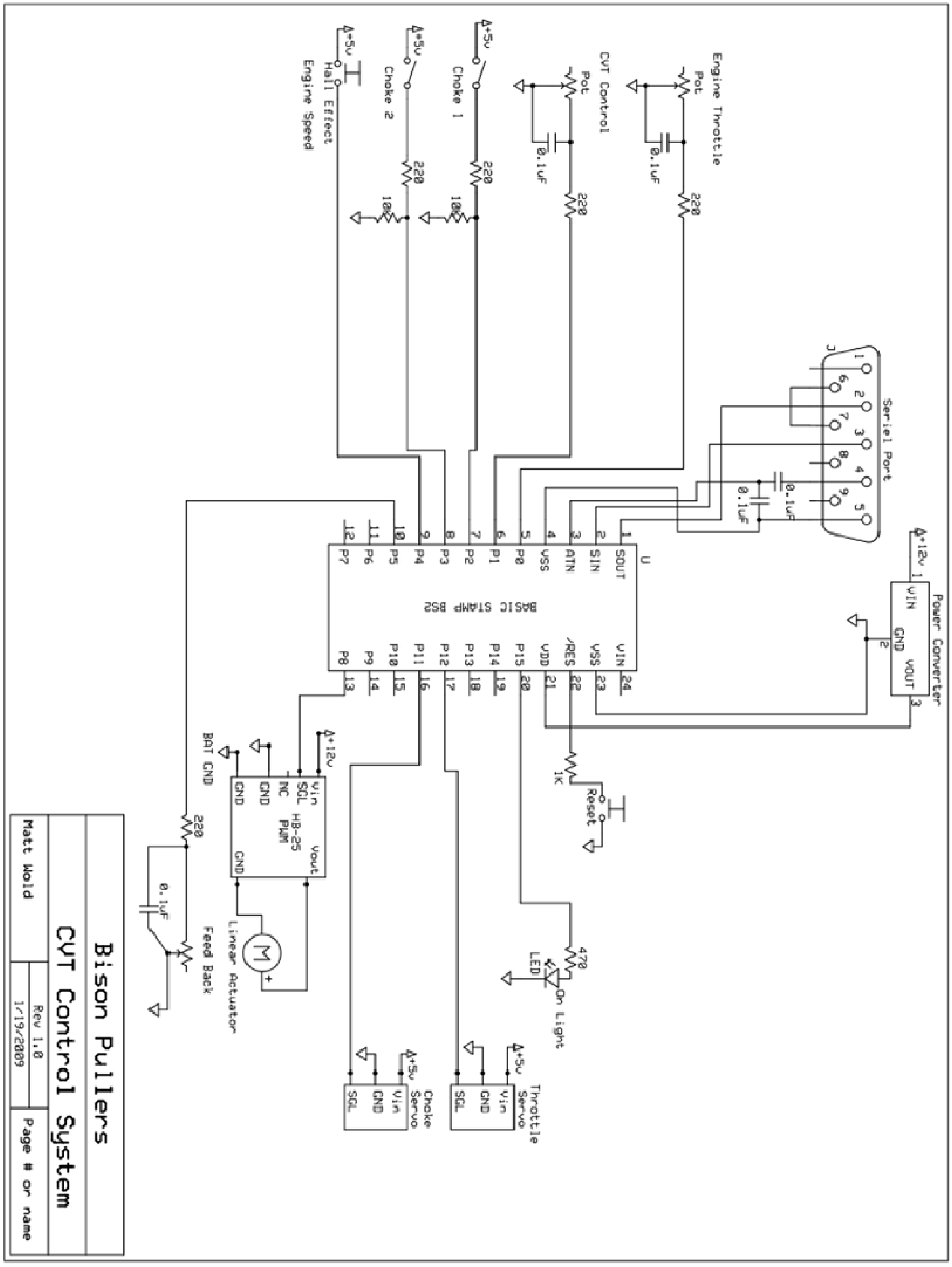
Appendix A
Wiring Diagrams



Wiring diagram for PIC. The diagram does not show PIC supporting hardware (Power supply, crystal, etc.) because it is considered standard. Designed for a 20MHz clock.



Wiring diagram for the Basic Stamp 2 module. This does show supporting hardware, because cooperating electrical engineers were unfamiliar with the system. The Basic Stamp 2 has an on board 20MHz crystal

Appendix B - Control Code

```
'BP2009 Control Master.bs2

' {$STAMP BS2}
' {$PBASIC 2.5}

' Pin Declarations
CVTlever    PIN  1     'control lever pot
CVTpos      PIN  5     'actuator position pot
Thrtl_p     PIN  0     'Throttle control lever pot
Thrtl_s     PIN  12    'Throttle control servo
Choke1      PIN  2     'Lead one for choke switch
Choke2      PIN  3     'Lead two for choke switch
Choke_s     PIN  11    'Choke servo connection
LED         PIN  15    'LED for debug
Engine_h    PIN  4     'Engine hall effect sensor
HB25        PIN  8     'PWM unit for linear actuator

'Variable Declarations
pulse_c               VAR  Word              'pulse to HB-25
tCVTlever             VAR  Word              'time for control lever pot
tCVTpos               VAR  Word              'time for actuator pot
k                     VAR  Nib               'proportional constant
tThrtl                VAR  Word              'time for throttle lever pot
pulse_t               VAR  Word              'pulse to throttle servo
engine_p              VAR  Word              'pulse from engine hall effect
engine_on             VAR  Bit               '1 if engines on else 0
choke_p               VAR  Word              'pulse_c to Choke servo
choke_by              VAR  Byte              'Bypass for Choke if statment
safety_by             VAR  Byte              'Bypass engine on check


'Main Program
Main:

DEBUG "Program initalizing", CR              'Display words on Computer if connected
choke_by = 0                                 'initialize variables
engine_on = 0
engine_p = 10000
INPUT 2                                      'Set Choke1 and 2 to inputs
INPUT 3
k=10                                         'Constant for proportional control of CVT
HIGH Thrtl_p                                 'Set all pots high to charge them
HIGH CVTlever
HIGH CVTpos

'Initialize Comm with PWM

DO  UNTIL HB25 = 1                           ' Wait For HB-25 Power Up
LOW HB25                                     ' Make I/O Pin Output/Low
PAUSE 5                                      ' Wait For HB-25 To Initialize
PULSOUT HB25, 150                            ' Stop Motor 1
INPUT   HB25
LOOP

DEBUG "Program initialized", CR
PAUSE 10

'Main Loop
DO
  DEBUG CLS
  IF engine_on=0 OR safety_by>100 THEN         'Bypass reading engine speed if it has
    safety_by=0                                'been read in the last 100 loops - saves time
    PULSIN Engine_h, 1,engine_p                'Read input from engine running hall effect
    IF  engine_p < 7000 AND engine_p>1 THEN                 'Set engine on flag to 1 or 0
       engine_on=1                             'Based on 6 holes on pulley and 2:1 gear reduction
      ELSE
```

```
        engine_on=0
    ENDIF
ENDIF

DEBUG "Engine_p = ", DEC engine_p,CR

TOGGLE LED                                  'Debug to see how fast it loops

RCTIME CVTlever, 1, tCVTlever               'READ pots
RCTIME CVTpos, 1, tCVTpos
RCTIME Thrtl_p, 1, tThrtl
HIGH CVTlever                               'Set all posts to high to charge them
HIGH CVTpos
HIGH Thrtl_p
DEBUG "tThrtl = ", DEC tThrtl, CR

IF IN2=1 THEN                               'Choke master if statement
    PULSOUT Choke_s, 740
    choke_by=0
ELSEIF IN3=1 THEN
    PULSOUT Choke_s, 500
    choke_by=0
ELSEIF choke_by > 35  THEN                  'Use choke bypass to skip the pulse after a while
    PAUSE 1                                 'saves time and wear on servo
ELSE
    PULSOUT Choke_s, 250
    choke_by=choke_by+1                     'increment choke bypass
ENDIF


pulse_t=tThrtl/11                           'control for engine throttle
pulse_t=pulse_t+500
PULSOUT Thrtl_s, pulse_t                    'send control to throttle
DEBUG "pulse_t = ", DEC pulse_t, CR

'CVT control master IF statement
IF engine_on=1 THEN   ``                       'only send control to CVT if engines are on
  IF tCVTlever>tCVTpos THEN                    'if actuator needes to retract
    pulse_c=tCVTlever-tCVTpos
    pulse_c=pulse_c*k                          'for proportional control
    pulse_c=pulse_c+750
    IF pulse_c<760 THEN                        'for deadband to prevent oscillation
     pulse_c=750
    ELSEIF pulse_c>990 THEN                    'set max speed limit
     pulse_c=990
    ENDIF
  ELSE                                         'if actuator needs to extend
    pulse_c=tCVTpos-tCVTlever
    pulse_c=pulse_c*k                          'for proportional control
    IF pulse_c> 750 THEN
      pulse_c = 750
    ENDIF
    pulse_c=750-pulse_c
    IF pulse_c>740 THEN                         'for deadband
      pulse_c=750
    ELSEIF pulse_c<510 THEN                     'Set max speed limit
      pulse_c=510
    ENDIF
  else
    pulse_c=750
  ENDIF
Endif
DEBUG "pulse_c = ", DEC pulse_c, CR             'Display pulse on laptop if connected
PULSOUT HB25, pulse_c                           'Send pulse to HB-25
PAUSE 1                                         'Pause to improve loop speed for servo
```

PIC Code

```
//*****************************
// Matt Wold
// Bison Pullers
// March 31, 2009
// code for Tractor controler
// Controls CVT, throttles, and chokes
//*****************************

// Subroutine Declarations
#include    <pic.h>
#include        "FUNCTION.h"
#include        "Lcd_20x4.h"


// Subroutines
#include        "function.c"
#include        "bootloader.c"
#include        "lcd_20x4.c"

#asm
   org   0x0000
   clrf  3
   movwf 0
   movlw 0x0A
   goto  start
   #endasm

//for Calibration purpose only
/*void LCD_Out(unsigned int DATA)
{
    char D[5];
    char i;
    for (i=0; i<5; i++){
        D[i] = DATA % 10;
        DATA = DATA / 10;
    }
    lcd_write(ascii(D[4]));
    lcd_write(ascii(D[3]));
    lcd_write(ascii(D[2]));
    lcd_write(ascii(D[1]));
    lcd_write(ascii(D[0]));
}
*/

void a2d_init(void)
{   ADCON0 = 0x81;
    TRISA  = 0x0F;
    ADCON1 = 0x80;
}
//Subroutine declarations
void Wait(unsigned int X);
void Pulse_Choke(unsigned int A);
void Pulse_Thrt(unsigned int C);
unsigned int A2D_Read(unsigned char c);
void Pulse_HB25(unsigned int D);
void HB25_int(void);
char Eng_chk (void);

// Main Routine

// servo cable black to GND
// servo cable red to +5V
// servo cable white to RC1 for choke
// servo cable white to RC0 for throttle
// servo cable white to RC2 for CVT
void main(void)
{
    // variable declaration
    unsigned int turn;
    unsigned int eng_pot, CVT_pulse;
    unsigned int CVT_in;
```

```
     unsigned int CVT_fb;
     unsigned char eng_on;
    TRISA = 0xff;                    //format ports
    TRISB = 0xff;
    TRISC = 0;
    ADCON1 = 6;
    RC0=1;
    RC1=1;
     a2d_init();                     //initialize A2D converter
//   lcd_init();
//   lcd_move(0,0);
     HB25_int();                     //initialize comm with HB-25

     while(1){                       //main loop

     //Choke Control
     if(RB0) turn= 450;
     else if (RB1) turn=375;
     else turn=250;
     Pulse_Choke(turn);              //send pulse to choke servo


     //Throttle Control
     eng_pot = A2D_Read(0);          //read throttle control pot
     eng_pot = eng_pot/10;           //calibration
     eng_pot = eng_pot + 250;
     Pulse_Thrt(eng_pot);            //send pulse to throttle servo

     eng_on = Eng_chk();             //check if engines are running
     eng_on = 1;
     CVT_in = A2D_Read(0);           //read the CVT control pot
     CVT_fb = A2D_Read(2);           //read the feedback pot on the actuator
     CVT_fb = CVT_fb*4;              //part of calibration

     if(eng_on){                     //if engines are off stop the actuator from moving
         if(CVT_in>CVT_fb){          //propotional control skeem with speed limits and deadband
             CVT_pulse=CVT_in-CVT_fb;
             CVT_pulse=CVT_pulse*4;
             CVT_pulse=CVT_pulse+425;
             if(CVT_pulse<440) CVT_pulse=425;
             else if (CVT_pulse>850) CVT_pulse=850;
         }
         else{
             CVT_pulse=CVT_fb-CVT_in;
             CVT_pulse=CVT_pulse*4;
             if(CVT_pulse>425) CVT_pulse=425;
             CVT_pulse=425-CVT_pulse;
             if(CVT_pulse>410) CVT_pulse = 425;
             else if (CVT_pulse<100) CVT_pulse=100;
         }
     }
     else CVT_pulse=425;

     Pulse_HB25(CVT_pulse);          //send pulse to HB-25

/*   lcd_move(0,0);                  //used for caibration to display what values
     LCD_Out(CVT_in);                //that the PIC is seeing
     lcd_move(1,0);
     LCD_Out(CVT_fb);
     lcd_move(2,0);
     LCD_Out(CVT_pulse);
     RC3=!RC3;
*/
     Wait(5);                        //wait for 5ms to maintain 20ms loop timing
    }
}

//wait routine in ms
void Wait(unsigned int X) {
     unsigned int Y, Z;
     for (Z=0; Z<=X; Z++) {
```

```
    for (Y=0; Y<=500; Y++) {};
    }
}
// Generate a pulse for engine choke
void Pulse_Choke(unsigned int A){
    unsigned int B;
    RC1=0;                          //drop low to send high pulse due to connection
    for (B=0; B<A; B++){            //to pnp transistor
    }
    RC1=1;
}

// Subroutine for pulse to throttle
void Pulse_Thrt(unsigned int C){
    //variable declaration
    int w;
    unsigned char t[4];
    char i;
    // convert C (0 to 1000) int four 8-bit variables i[0] to i[3]
    for (i=0; i<4; i++){
        if (C>255){
            t[i]=255;
            C=C-255;}
        else {
            t[i]=C;
            C=0;}
    }

    //send pulse
    RC0=0;                  //drive RC0 low
    for (w=0; w<330; w++);  //wait 1ms
    while (t[0]) t[0]--;    //wait 0 to 1ms
    while (t[1]) t[1]--;
    while (t[2]) t[2]--;
    while (t[3]) t[3]--;
    RC0=1;                  //drive RC0 high
}

// Subroutine for pulse to HB-25
// Very similar to throttle subroutine
void Pulse_HB25(unsigned int D){
    //variable declaration
    int w;
    unsigned char t[4];
    char i;
    // convert C (0 to 1000) int four 8-bit variables i[0] to i[3]
    for (i=0; i<4; i++){
        if (D>255){
            t[i]=255;
            D=D-255;}
        else {
            t[i]=D;
            D=0;}
    }

    //send pulse
    RC2=1;                  //drive RC0 low
    for (w=0; w<330; w++);  //wait 1ms
    while (t[0]) t[0]--;    //wait 0 to 1ms
    while (t[1]) t[1]--;
    while (t[2]) t[2]--;
    while (t[3]) t[3]--;
    RC2=0;                  //drive RC0 high
}

//A2D read routine
unsigned int A2D_Read(unsigned char c)
{
unsigned int result;
unsigned char i;
c = c & 7;
```

Z:\ECE376\CVT PIC\CVT Code1.c

```
ADCON0 = (c << 3) + 0x81; // set Channel Select (CS2:CS1:CS0)
for (i=0; i<14; i++); // wait 14us (approx)
ADGO = 1; // start the A/D conversion
while(ADGO); // wait until complete (approx 19us)
result = (ADRESH << 8) + ADRESL; // read in the A/D result
return(result);
}

//Initialize comm with HB-25
void HB25_int(void)
{
    TRISC=0b11111011;
    while(!RC2);
    TRISC-0xff;
    Wait(5);
    Pulse_HB25(500);
    Wait(20);
}

//Subroutine to check if engines are on
//flag = 1 if on, 0 if off
char Eng_chk (void)
{
//variable declaration
unsigned int time=0;
char flag;
//determine if sqare wave is high or low
if (RB3){
    while (RB3 & time<380){     //count while high
        time++;}                //break out if > 1ms and set engines off
    if (time==380) flag=0;
    else{                       //count time low if high did not time out
        time=0;
        while (!RB3 & time<380){
            time++;}            //break out if > 1ms and set engines off
        if(time==380) flag=0;
        else flag=1;            //if both times less than 1ms, engines are on
    }
}
else{                           //same as above but starting with low pulse
    while (!RB3 & time<380){
        time++;}
    if (time==380) flag=0;
    else{
        time=0;
        while (RB3 & time<380){
            time++;}
        if(time==380) flag=0;
        else flag=1;
    }
}
return flag;                    //return the flag to the main program
}
```