Design of a Belt-Driven Continuously Variable Transmission

by

John Gregory McCandless

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering

at the

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Author .............................................................

Department of Mechanical Engineering

May 6, 1994

Certified by ..........................................................

Carl Peterson
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by .......... ....

Peter Griffith
Chairman, Undergraduate Thesis Committee
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Abstract

In completing this thesis, I designed and constructed a continuously variable transmission component using an array of gears and pulleys. A continuously variable transmission is a mechanical device capable of converting torque to rotational velocity in a continuous, infinitely variable manner. This is a useful device because it allows for instantaneous optimization of torque-velocity conversion. Presently, continuously variable transmissions exist, but they each have drawbacks (as does this design). This device was conceived and designed on CAD software, and built and tested in prototype proof of concept form.

Thesis Supervisor: Carl Peterson
Title: Professor of Mechanical Engineering
Acknowledgments

Thank you to the MIT UROP program for making it possible for me to turn my ideas into reality.
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Chapter 1

Introduction

Continuously variable transmissions have been sought after for centuries by mechanical engineers. They are optimizable versions of every transmission on every device. Thus they are of supreme importance to mechanical engineers and the industry.

The design that I have proposed offers large ratio changeability, infinite variability between the ratios, elegant simplicity, and the ability to change the ratio while the pulley is at rest. Drawbacks to the design are that the pulley that changes the gear ratio has six discreet pulses for each revolution, and the pulley cannot handle extremely large torques (limited by the design configuration and the need for a belt drive).

This thesis is organized in the following manner:

Chapter one contains the introduction and a description of how the device works.

Chapter two describes the brainstorming session that led to the design, and explains the motivations for the selection of the final design.

Chapter three describes the elements of the design in detail, and explains assembly.

Chapter four analyzes the strengths and weaknesses of the design.

Chapter five suggests modifications and redesign considerations, and suggests where the project could go in the future.
1.1 Motivations for Building a CVT

Continuously variable transmissions (CVTs) generally function by having some sort of pulley or sprocket that changes in diameter. The change in diameter relates to a change in length of the moment arm of the force transmitted through the pulley, as well as a change in length of the circumference that is travelled by the belt during one revolution of the pulley. Thus a pulley that changes diameter continuously can change the ratio of torque and rotational velocity transmitted through the pulley continuously.

Existing continuously variable transmissions are usually limited in their performance. Most CVTs have drawbacks such as limited range of variability, limited power handling capabilities, limited efficiency, and an inability to change ratios at a standstill. It was these limitations that persuaded me to rise to the challenge of designing a better CVT. While the design that I came up with may be better than existing CVTs in some ways, it also has disadvantages to existing designs as well. However, the design experience that I acquired from the exercise is invaluable.

1.2 Description of The CVT Designed

The general goal of the design was to achieve a large diameter change with a mechanically simple design that lied in one plane (See Chapter 2 for alternative designs considered). This goal was achieved via the use of several gears and pulley elements (small pulleys) that make up the larger “pulley” that changes in diameter.

The larger “pulley” consists of two halves, split down its center on the plane in which the belt rides. On each half, a small gear lies in the center, surrounded by three large gears with diameters about five times the small gear. The arrangement is almost like a planetary gear, except that the sun gear is small, and the planet gears are as large as they can be without interfering with each other. All of these gears are mounted on an aluminum plate so that they are free to rotate.

When the sun gear is rotated, all three planet gears rotate in the same direction
as each other. Attached to the outer diameter of each planet gear is a pulley element made to accommodate a $\frac{1}{2}$ inch belt. The pulley elements are attached rigidly to the planet gears, so that they DO NOT rotate on their axis. However, rotating the planet gears (by rotating the sun gear) moves their position.

The pulley elements are aligned with each other, so that when one of them is as close to the sun gear as possible, so are the other two (so that the three describe a small triangle). When the sun gear is rotated, the planet gears all rotate, thus moving all three pulley elements to a position further away from the sun gear. When the pulleys are as far away as possible from the sun gear, they describe a large triangle.

Two such mechanisms are constructed, so that each one has a sun gear and three planet gears, with each planet gear having a small pulley solidly affixed to it near the outer diameter. The two halves are put together and aligned so that all six of the pulleys are at the position closest to the sun gear. A single shaft is then placed through the two sun gears, so that they transmit the same position and torque. The plates on which the gears are mounted are affixed to each other via a ring of steel with a diameter slightly greater than that of the sun gears.

When completely assembled, the device has six pulley elements that, upon rotation of the center shaft, move on a circular curve away from the center of the large "pulley." This moves the pulley elements to the "pulley"'s outside diameter, thus creating a hexagonal "pulley" that changes in diameter continuously. (See Figures 1-1 and 1-2.)
Figure 1-1: Conceptual Drawings
Figure 1-2: Isometric Concept Drawing
Chapter 2

Other Designs Considered

This chapter covers the four basic design configurations that were considered for this project, explains why three were eliminated, and explains why the final one was chosen.

The objective for each design is to somehow create a pulley that changes diameter via discreet pulley elements that moved radially outwards. Performance criteria considered included: Can the design be constructed easily in proof of concept form? Does the design offer a large ratio changeability? Does the design lie in one plane? Is the design mechanically simple? Can the design easily be controlled?

2.1 Sliding Cone Concept

The original concept which gave birth to this thesis was a cone-shaped structure that moves horizontally back and forth. The pulley elements ride on the frame of the cone, and they transmit torque perpendicular to the axis of rotation. Eight or ten such pulley elements could make up a “pulley”. (See Figure 2-1)

This concept has many drawbacks. One is that it is mechanically complex. It would require precise construction of the conical frame. There are also many sliding and rotating bearing surfaces. Another is that it does not allow for a great deal of ratio changeability. A third is that it does not lie in one plane. Lastly, the control mechanism requires a back and forth motion of the entire assembly, making
Figure 2-1: Sliding Cone Concept
Figure 2-2: Pushrod Actuated Linear Sliders Concept

applications difficult.

For these reasons, the concept was discarded.

2.2 Pushrod Actuated Linear Sliders Concept

The idea here is that lateral motion on the center bearing (mounted on the center shaft) exerts a force through pushrods to the pulley elements, thus moving them linearly outward. Again, as many as eight or ten of these pulley elements could make up the large "pulley." (See Figure 2-2)

This idea, while being relatively simple, still requires linear sliders and lateral motion to control it (although the control motor does not have to rotate with the device). Also, the more ratio desired, the longer the pushrods must be, and the more lateral space the device consumes. Another drawback is that the compression force
Figure 2-3: Hydraulically Actuated Linear Sliders Concept

in the pushrods and the load on the slider bearings becomes infinitely great at small diameters.

For these reasons, the concept was discarded.

2.3 Hydraulically Actuated Linear Sliders Concept

This concept involves a "pulley" consisting internally of hydraulic pistons that are moved out and in via master cylinders/pistons in the hub of the "pulley." Lateral motion by the master pistons generates linear radial motion in the slave pistons, which are connected to multiple pulley elements. (See Figure 2-3)

This concept is viable, but hydraulics are difficult to make in prototype/proof of
concept form, since many seals are required. Also, the largest ratio possible is the ratio of the throw of the slave pistons to the largest radius, which can’t be more than 1:2). Lastly, this design is also not in one plane.

Again, for these reasons the concept was discarded.

2.4 Cantilevered Pulley Elements on Cams Concept

This was the concept that was chosen. For a review of how it functions, see Chapter 1 and Figures 1-1 and 1-2. This concept was selected because of the feasibility of construction, mechanical simplicity, ease of control, large ratio capability, and the fact that it lies in one plane.

Disadvantages to this configuration are that the pulley elements are cantilevered, there is a limit of six pulley elements due to geometric constraints, the controller motor needs to rotate with the “pulley,” and the ratio is also limited by geometric constraints.
Chapter 3

Assembly and Detailed
Description of the Elements

This chapter will describe the different parts of the present design, and explain how they fit together to make the whole “pulley.”

3.1 Design of Mechanical Components

In this section, all of the important mechanical elements of the design will be described.

3.1.1 Gears and Pulley Elements

The gear arrangement on each half of the “pulley” is the heart of the design. The gears were selected and modified for geometric constraints and to reduce weight.

The most important aspect of the gears is their diameters, based on geometric constraints. In this case, it is the ratio of the diameter of the sun gear to the planetary gears that matters most. This ratio determines whether or not the gears will interfere with each other. The first step in figuring out this ratio was to determine the minimum number of pulley elements that was satisfactory. The conclusion was that six pulley elements allowed for a reasonable approximation of a circle without sacrificing too much ratio changeability. With six pulley elements, the largest possible ratio of planet
Figure 3.1: The Trade-Off Between Number of Pulley Elements and Ratio of Changeability

gear to sun gear diameter was 5:1. Had the design called for only four discreet pulley elements (two on each half), the ratio of the diameters could have been infinitely great. However, this would lead to a "pulley" that was essentially square, which would give very uneven torque transmission. Eight pulley elements would have made for smoother operation (eight bumps per revolution instead of six), but at the expense of valuable ratio changeability. Six elements was decided on as a compromise between discreet bumps during a revolution and ratio changeability. (See Figure 3.1)

A modification that was made to the planet gears was that they were machined down to reduce weight. The gears only need to travel 180 degrees in order to move the pulley elements from their innermost position to their outermost, so approximately half of each gear was removed. Additional material was removed inside the face of each gear. This is allowable because the gears are being used to transmit position, not velocity. They do not need the material because they are not being loaded heavily. (See Appendix A for machined gear drawing).

Once the planet gears were machined, the pulley elements were rigidly fixed to
them at the proper radius from the center. This was achieved in several steps:

First, small steel pulleys were purchased and machined down to pulley elements. This process consisted of removing the hub from the small pulleys to save space and weight.

Next, a steel shaft was machined to the diameter of the bore for each pulley element. The shafts were long enough to go through the pulley element and the planet gear, and they extended beyond the face of the planet gear for the delrin bushing sleeve described below.

Each shaft was then welded onto each pulley element, with one edge of the shaft flush with the face of the pulley element. This solidly fixed the pulley elements to the shaft.

Holes with diameters of .001" less than the shaft diameter were then reamed in the planet gears at the proper radius from the center.

The pulley element/shaft pieces were then submerged in liquid nitrogen long enough to reach thermal equilibrium with it. This shrank the size of the shafts temporarily. While the shafts were cold, they were press-fit into the planet gears. Once the shafts warmed to room temperature, they were rigidly fixed to the planet gears. (see Figure 3-2)

### 3.1.2 Bushings and Mounting Plates

All of the bushings for this design are made out of delrin, a low-friction plastic that is easy to machine. The bushings all lie in the two plates on either half that make up the outer casing of the “pulley.” The only notable point about the bushings is that for the planetary gears, the outside of the hub was used as a bushing surface instead of using a shaft through the bored hole with a set screw.

This was done for several reasons. One is that this reduces the overall thickness of the “pulley.” Another is that by reducing the distance from the plate to the pulley element (‘L’ in Figure 3-3), the torque on the cantilevered gear and pulley element is minimized. If a shaft were run through the bore of the gear, then the closest that the gear could get to its mounting surface would be the length of the hub, which would
Figure 3-2: Construction of the Planet Gears and Pulley Elements
Figure 3-3: Using the Hub as a Bushing
make for more torque on the bushing surface and increased thickness of the pulley. This is because the material in the hub is necessary because it contains a tap for the set screw. By using the hub itself as a bushing surface, the length of the hub could be machined down without worrying about the set screw tap, and the gear could sit up close to the plate it is mounted on. The hub also has a larger diameter than the drilled bore, and a larger diameter bushing surface means less force on the bushing surface. (See figure 3-3)

In addition, the shafts that the pulley elements are mounted on go through the gear face to the plate that the gears are mounted on. On the end of each shaft is a delrin sleeve. Each shaft with the delrin sleeve fits in a circular milled slot in the face plate concentric with the planatary gear. This shaft serves several purposes. One is that it eases the normal force on the main bushing for each gear by taking some of the reaction force. Another is that it transmits some of the torque from the pulley elements to the plates on which the gears are mounted.

See Appendix B and C for machine drawings of a mounting plate and bushings.

### 3.1.3 Ring Connecting the Two Halves of the “Pulley”

The ring that connects the two halves of the pulley is a stainless steel thick-walled tube section with six evenly-spaced drilled and tapped holes. The six holes are for three bolts from each half of the “pulley.” The ring that connects the two halves needs to be inside the diameter of the smallest radius of the “pulley,” so that it doesn’t interfere with the travel of the pulley elements or the belt. This caused spacial constraints, since the diameter of the ring takes away from the ratio of changeability of the device.

Also, the ring needs to connect to the face plates of each half of the “pulley” without interfering with the gears. Because of this constraint, the six bolts that thread into the ring need to fit between the planetary gears, three on each side. The bolts also need to be surrounded by spacers so that the bolts compress the spacers and not the bushing surfaces. (See Figure 3-4)

See Figure 3-5 for assembly of all of the mechanical elements, and Appendix D for a scaled cross-section of the “pulley” showing the gears, bushings, plates, spacers,
The Connecting Ring Cannot Interfere with Any of the Gears. It Connects the Plates that the Gears are Mounted On.

Figure 3-4: Spacial Constraints of the Connecting Ring
and connecting ring arrangement.

3.2 Electrical Components

This section will explain all of the electrical elements in the current design setup. It should be noted that the electrical components were added to complete the proof-of-concept model, but in actual use the arrangement would be quite different. This will be discussed in more detail in Chapter 5.

3.2.1 Motor

The motor that is currently on the device is a 12 volt DC worm gear motor from the power window mechanism of a Cadillac. This motor was chosen because of availability and performance characteristics. Specifically, it is a high-torque, low-speed, non-back drivable motor that I had access to.

The motor is temporarily attached to the pulley via several "tie-wraps" that wrap around the motor and through holes in the face plate on one side of the device. A gear is press-fitted onto the motor shaft, and that gear meshes with another gear that is attached to the control shaft of the device via a roll pin. Thus, a voltage across the motor results in turning the control shaft on which the sun gears (one for each half of the "pulley") are mounted, which rotates all six of the planet gears, which moves the pulley elements inward or outward radially following a circular arc.

3.2.2 Batteries and Switch

A switch which supplies forward and reverse voltage is mounted on the plate, and is wired in parallel with the 8 'AA' batteries and the motor. The eight 'AA' bateries supply 12 volts to the motor, and they are mounted on the same plate surface that the motor is mounted on via tie wraps.
Figure 3-6: Electrical System for Prototype

3.2.3 Controller

The controller consists of a digitally proportional Futaba servo motor connected to 4 ‘AA’ batteries and a remote control reciever. These components are also mounted to the same plate as the motor and batteries via tie wraps. The servo arm is linked to the switch that controls the motor.

This entire arrangement enables the ‘pulley’ to rotate and change diameter simultaneously by sending a remote control radio signal to the device. There are better ways of achieving this, and they will be discussed in Chapter 5. This arrangement was constructed to complete the proof-of-concept prototype only. (See Figure 3-6)
Chapter 4

Analysis

The purpose of this chapter is to analyze the performance strengths and weaknesses the CVT.

4.1 Performance Analysis

4.1.1 Ratio Changeability

Ratio changeability is probably the most important characteristic of any CVT. The term describes what range of gearing ratios the device can produce. For a regular gear, this ratio is fixed. For an automobile, the ratio is quantized at five different ratios corresponding to the five gears (in a “five-speed”). An automobile usually goes from a ratio of around 2.5:1 in first gear to around 1:1 in “overdrive.”

The ratio of changeability of this prototype covers approximately this range of 2.5:1 to 1:1, meaning that it can change its speed by a factor of 2.5 when connected to a constant velocity belt source. This number is determined by adding the total distance that the belt travels in one revolution when the “pulley” is in the “out” position, and dividing that by the total distance that the belt travels in one revolution in the “in” position (See Figure 4.1).
4.1.2 Power-Handling Capabilities

Another important aspect of CVTs is how much power they can handle. In this case, the limiting factor may be the fact that it needs to be driven by a belt. The proof of concept accepts a \( \frac{1}{2} \) inch belt, which is usually rated at about \( \frac{1}{2} \) to 1 horsepower. However, a bigger version could be made that could possibly handle more power.

The other limiting factor in power-handling capabilities is weak links in the design. While an analysis of the actual power that the device can handle is difficult, the weak links can be pointed out.

The weakest link in this design is the route that the force takes through the "pulley" when being loaded by a belt. The belt supplies radial force and tangential force from the belt driving force and the belt tension. In this design, the pulley is slightly cantilevered (described in section 3.1.2), and force is taken by a combination of the planet gear mount and the motor mount, depending on the position.

When the belt is in the "out" position, most of the radial force is taken by the
planet gear mount. Most of the tangential force is taken by the worm gear, which in turn is taken by the motor mount.

When the pulley is in the "middle" position, most of the radial force is taken by the motor mount, and most of the tangential force is taken by the planet gear mount.

When the pulley is in the "in" position, most of the radial force is taken by the planet gear mount, and most of the tangential force is taken by the motor mount.

However, regardless of whether the force is transmitted through the planet gear mount or the motor mount, it always ends up instantaneously on one of the aluminum plate sides. Depending on which side it goes through, the force may be transmitted through the connecting ring in the center to the side where the load is (the side that is bolted to the tire, motor, etc). This ring has a relatively small diameter, and all of the strength comes from the shear strength in the three bolts used to connect it to the plates. (See Figure 4-2)

Using a lower-bound limit analysis, the force that would cause the bolts to shear would be:

$$\text{Force}_{\text{failure}} = \tau_{\text{yield}} \times \text{Area}_{\text{bolts}}$$  \hspace{1cm} (4.1)

where $\tau_{\text{yield}} = \frac{\sigma_{\text{yield}}}{2}$

For steel, $\tau_{\text{yield}}$ is 30 kpsi, and the cross-sectional area of the bolts in the proof of concept form is

$$\text{Area}_{\text{bolts}} = 3 \times \pi \times r^2_{\text{bolt}}$$  \hspace{1cm} (4.2)

where $r_{\text{bolt}}$ is .125 inches, and $\text{Area}_{\text{bolts}} = .147in^2$.

Therefore, the amount of force that it would take to shear the bolts is:

$$\text{Force}_{\text{failure}} = 30\text{kpsi} \times .1473in^2$$  \hspace{1cm} (4.3)

This means that the bolts will sustain approximately 4417 lbs.

Given that the bolts are at a radius of 1 inch (.083 feet) away from the center of the pulley, the amount of stall torque that the pulley prototype can handle is:
Figure 4-2: Location of the Reaction Forces
\[ Torque_{\text{failure}} = Force_{\text{failure}} \times R \] (4.4)

Using the appropriate values and units, \( Torque_{\text{failure}} = 4400\, \text{lbs} \times .083\, \text{ft} \) which equals 365 lb-ft.

This number could be improved via the use of harder bolts, increased cross-sectional area of the bolts, or increased distance \( R \) from the center (although the second two suggestions would take away from degree of ratio changeability).

Another alternative is to change the design dramatically by putting only the pulleys between the plates, and mounting all of the gears on the outside of the plates. This would allow for more cross-sectional area of the ring connecting the two halves, since there would be no worry about interference with the gears. This option will be further explained in Chapter 5.

### 4.2 Other Performance Criteria

Other strengths to this design, unlike conventional CVTs, is that it allows for a change in ratio at a standstill. This would be useful for applications where a particular ratio is desired before startup, such as the case of the automobile, where a driver always wants to be in "first gear" at initial acceleration from zero velocity.

Also, being driven by an electric motor means that an electronic controller can be used easily, with the addition of a rotational position sensor.

In addition, the device lies in one plane, so that if width is a design constraint, such as in the case of a bicycle, this design may be desireable.

Other weaknesses are that there are six discreet bumps in every revolution, the pulley elements are cantilevered, and the controller motor needs to rotate with the device.
Chapter 5

Suggested Modifications and Redesign

This chapter suggests modifications and redesign considerations, and also suggest ideas on where the project may go in the future.

5.1 Additions to Present Design

5.1.1 Electrical

The electrical system on the existing design was used as a temporary measure in order to complete the proof of concept. This section details what would have been done given more time.

First, instead of mounting batteries on the pulley so that they rotate with it, electric brushes would be installed so that power could be supplied from a stationary source, such as a car or motorcycle battery. (See Figure 5-1)

In addition, a worm gear motor with more appropriate performance is needed. A motor with less torque, size, and power consumption would be selected and mounted securely to the plate.

Also, a control system would be designed for various applications such as constant torque output, constant velocity output, or controlled torque and velocity output.
characteristics. A rotational displacement sensor would be placed on one of the planet gears to serve as an input to the control system. The output of this sensor would also need to be transmitted through electrical brushes to the stationary controller.

5.1.2 Mechanical

For the existing design, two major mechanical aspects could be modified. The first is the addition of a rotational spring on the control shaft to counteract the torque provided by the belt tension. Less torque would be needed to move the pulleys in and out, and therefore a smaller motor could be used.

The second modification would be to shape the pulley elements so that at each point in their path, the curve of their surface would match the curve of the circle that the six elements describe. This would require nautilus-shaped pulley elements that contact the belt with more surface area, and do not make the belt bend as much. (See Figure 5-2)
5.2 Redesign

The two major difficulties with this design are that (1) the torque is transmitted through three bolts, and (2) the pulleys are cantilevered. One solution to both of these problems is to put the planet and sun gears on the outside of the aluminum plate, and put only the pulley elements between them. The shafts which go through the pulley elements could extend all the way to the other half of the “pulley” without interfering with the gears, because the gears would be on the other side of the plate. This would allow the use of pulley elements that are not cantilevered.

Without the gears there, the constraints for the connecting ring bolts would also be eliminated, so bigger bolts or more bolts could be used, or the ring could be attached via welding. (See Figure 5-3)

A redesign would also have to include a weight optimization procedure. The current prototype is far too heavy, and weight can be trimmed by thinning the plates, thinning the planet and sun gears, decreasing the size of the motor, and using better
Figure 5-3: Potential Redesign

materials for the application.

5.3 Where To Go from Here

Continuing with the project would be an excellent design opportunity for anyone. One recommendation would be to include a bench setup that better illustrates the velocity and torque characteristics of the prototype. Perhaps a setup could be constructed that consisted of a hand crank and a lever that changes the ratio of the “pulley.” The “pulley” could be bolted to a bicycle wheel or something similar that changes speed and torque via the CVT.

Note that a constant force idler much like the small gear on the rotational spring-loaded lever arm of a ten-speed bike transmission is needed here. This is because as the “pulley” diameter changes, the length that the belt travels changes as well. A constant-force idler would “take up the slack.”

The next step would be to design some sort of simple control system for the device,
described above.

The device could then be installed in a vehicle, perhaps a bicycle or electric bike, where it could be tested for performance and utility. This is a good light-duty test arena. It is useful, it has the potential for a complex control system design that incurs speed, torque, and power consumption optimization, and regenerative braking could be built into the control system for use in an electric vehicle.
Appendix A

Machine Drawing of Gears
Appendix B

Machine Drawing of Mounting Plate
Appendix C

Machine Drawings of Bushings

Tolerances: +/- .003"
Appendix D

To-Scale Front and Cross-Section Drawing