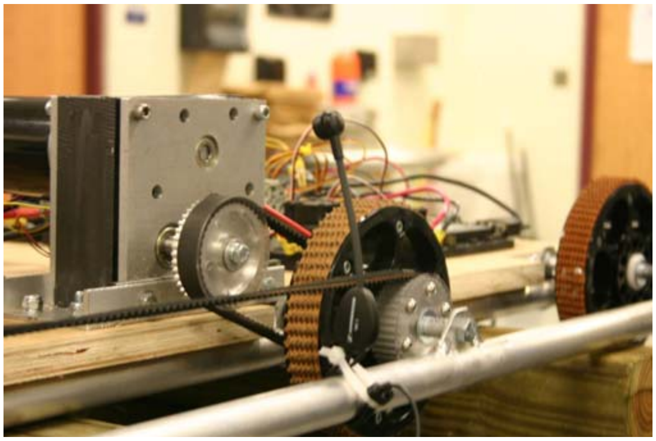
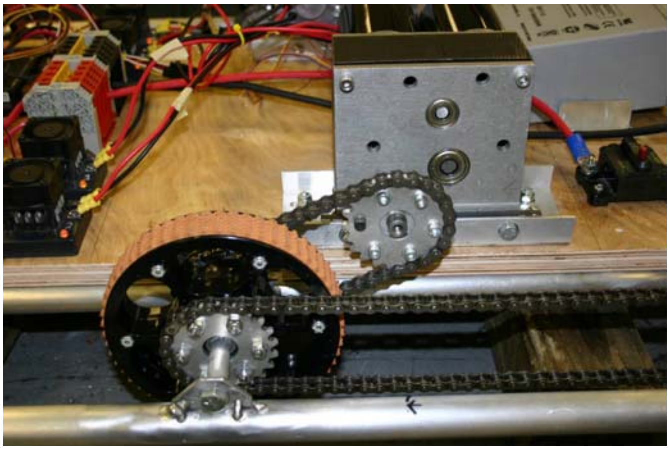
FIRST Robot Drive System Analysis
Belt vs. Chain
Fall 2008
Team 234 - Cyber Blue Robotics





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I. EXECUTIVE SUMMARY

A. Introduction

The FIRST Robotics Competition (FRC) is a program designed to introduce high school students to math, science, engineering and technology and to develop an interest in those fields as career choices. One of the major components of the FRC program is the design, fabrication and competition of a 120 pound remote controlled robot. These robots must be designed for a combination of speed, power, durability and meet a stringent weight requirement.

Cyber Blue, FIRST Team 234, wanted to explore an option for power management and weight reduction in the drive system of replacing the commonly used chain drive and sprockets with drive belts and pulleys. However, there were several questions to be answered about this option before the team would be willing to use it an FRC tournament robot.

To help answer those questions, the team utilized a “Design of Experiments” methodology to create an objective, unbiased test plan to compare the two drive options - #35 chain and 15 mm belt.

B. Conclusions

Based on the results from this testing, the following high level conclusions can be drawn:

1. A belt drive system could save approximately 2 pounds on a six wheel drive.
2. The Belt drive system is approximately 3 – 4% more efficient.
3. The belt drive system was approximately 6% faster to a set distance.
4. The belt drive system traveled about 8% further for a given time of power application.
5. There was no measurable difference in belt or chain stretch when pulled under load.
6. There was no noticeable difference in noise level of belt or chain.
7. Chain is overall simpler to work with from a design / repair perspective.

II. TEST INFORMATION

A. Background

A high percentage of FRC Robots are designed with #25 or #35 chain drive and use 4 or 6 wheels for the final transfer of power from the robot to the driving surface. Chain drive is a known, proven system for transfer of power from the drive motors / transmissions to the drive wheels and between the wheels and is by far the most common design used by FIRST teams. A recent, unofficial, survey of the 2008 Indiana Robotics Invitational robots showed a fairly even split between #25 and #35 drive chain.

There are several potential benefits of making a change from chain drive and to belt drives, but there are also some risks. Some of these benefits and risks are real and some are perceived, based on levels of experience or comfort with a particular design. The purpose of this design / test program was to attempt to identify and quantify the benefits and risks of chain drive compared to belt drive and to develop an objective test program that can provide data to allow teams to make an assessment of the two options for their designs.

Some of the factors considered in developing this design / test program were weight, strength, durability, repair-ability, design complexity and costs. Each of these factors, as well as several others, is detailed in the following pages.

To complete this study, the team also designed and built a new chassis. Some chassis design decisions were made specifically to support this testing, but the chassis is not under test per se.

One goal of the FIRST Robotics program is to expose student team members to new tools, technologies and methodologies. It is important for students to learn test and evaluation processes that can lead them to make unbiased decisions based on technical data. One of these methods, Design of Experiments (DoE), was introduced and used as a part of this project to help the team members understand the basics of this process and how DoE methodology can help create an unbiased, fair evaluation.

B. Conclusions – Overview of Results

A short summary of the major findings is below. Details are included in the Test Results – Method and Data Section, Section II E and Section IV.

<u>WEIGHT</u> – As tested, there was no difference in the chain vs. belt drive system weights. However, the belt drive system provides an opportunity to save approximately 2 pounds on a 6 wheel drive system by weight reduction machining of the drive pulleys. The chain drive components used in this testing have already been weight reduced through the use of aluminum sprockets.

<u>EFFICIENCY</u> – Several measures of system efficiency showed the belt drive to be 3 to 4% more efficient than the chain system. This was based on testing that compared power consumption per RPM and power consumption per distance traveled.

ROLLING EFFICIENCY / SPEED – The belt drive system was approximately 6% faster to a set distance and traveled 8% further for a given power utilization. The belt system was 14% faster in a block time measurement from a 25 foot mark to a 50 foot mark.

LOAD CAPACITY / STRETCH – The completed testing showed no difference in stretch or strength for the loading on FIRST robots, with loading up to 80 pounds per side (160 pounds total load on the belt or chain loop).

OVERALL –

1. The belt system provides slightly improved efficiency and rolling resistance when compared to a chain drive system. This allows more power capacity for other robot systems.
2. The belt drive system can provide for a lighter drive system, allowing more weight for other robot systems.
3. The belt system requires a more integrated design and manufacturing activity, as the belt length and wheel to wheel center distance is more "fixed" once the belt is procured and the wheels / belts must be assembled concurrently (unlike chain, which can be added later and assembled with a master link).
4. The belt system requires more physical space, as the drive belt / pulley system may be wider than a chain / sprocket system for a given load capacity.
5. For FIRST applications, we found no difference in stretch / load capacity capabilities.

For a team that can work through the design / manufacture issues, the belt drive offers a lower weight option for drive system power transmission.

The following pages provide a detailed analysis of the test plan development, test procedures, analysis techniques and final results and conclusions.

All testing was completed using a 3 second autonomous cycle to remove the human factor influence of the testing.

III. APPROACH

The team following the following steps in creating the test program and completing the testing:

A. Agree Objectives
B. Brainstorm Methods to Meet the Objectives
C. Evaluate Test Methods based on DoE Principles
D. Create Test Plans
E. Complete Testing
F. Review of Data and Results
G. Create Test Report

A. Agreed Objectives

Before design work began, the team discussed the project and agreed on the following high level objectives:

Objective 1 – Complete an unbiased assessment of chain drive and belt drive systems for applicability with robots designed for the FIRST Robotics Competition.

Objective 2 – Expose students to the basics of a systematic approach to testing, using the concepts of Design of Experiments (DoE) methodologies.

Objective 3 – Design and fabricate a new chassis that is adaptable for chain or belt drive evaluation. (This chassis was developed as a potential design for future FRC robots.)

B. Brainstorming

1. Considerations

After an introduction of the design concept objectives and agreement of the objectives, the team brainstormed ideas on each drive system. This brainstorming included benefits and risks of each system, factors to be considered in a system design, types of measurements that would be needed, and general questions that would need to be answered through the evaluation.

1. System Factors to be Evaluated
    a. Size, Weight, Durability, Reliability, Speed, Noise, Aesthetics

2. Design Parameters – To Be The Same Between Systems
    a. Frame and Chassis, Transmission, Front Wheels (undriven), Motors, Power Supply / Input Voltage, Dead Axles

3. Design Parameters – To Change Between Systems
    a. Chain, Sprockets (all sized the same for no speed reductions), Belts, Pulleys (all sized the same for no reductions), Driven Wheels (same design but different parts), Bearings

4. Measurements Required From Testing / Evaluation
    a. Weight – Total System and Unique Components, Input Voltage, Shaft Speed / Robot Speed, Breaking Strength, Yield Strength, Slack / Backlash, Torque Capability, Noise Level

5. Measurements Required From Observation
    a. Assembly Time, Repair-ability, Drive-ability, Design / Manufacturing Integration Impact, Aesthetics

2. Output - Benefits / Risks

EXPECTED BENEFITS / RISKS OF SYSTEMS

CHAIN DRIVE		BELT DRIVE	
BENEFITS	**RISKS**	**BENEFITS**	**RISKS**
Experience	Heavier	Lighter	New Concept
Proven (Robotics)	Louder	Quieter	Buy to Fit
Replaceable	Stretch	Innovative	Spare Pieces
Quick Repairs	Easy to Damage	Cleaner	Less Experience
Flexible Sizing		Proven (Other Apps)	Cost
Available			

3. Brainstorming – Questions

QUESTIONS - CHAIN AND BELT DRIVE

Efficiency	Breaking Strength
Tension Control	Durability
Space Requirements	Interchangeability
Slippage / Backlash	

C. Evaluation Based on Design of Experiments Principles

1. Design of Experiments (DoE) Basics

One of the key considerations in designing an accurate, objective evaluation is the elimination or minimization of variables that could impact the outcome of the test data and to identify variables that may drive an interaction.

To minimize the test variables, the following remained constant for the testing:

Component	Configuration Tested (1 & 2)
Chassis	Cyber Blue Fabrication
Wheel Mountings	Cyber Blue Fabrication, Integral to Chassis
Transmissions – Locked into Single Speed	AndyMark Super Shifter
Drive Motors	CIM, 2 per side
Robot Mounted Controls Components	2008 FRC Control System
Control Board and Input Devices (joy sticks)	2008 FRC Control System
Third Wheel / Axle Assembly (not driven)	AndyMark With RoughTop
Battery *	2008 FRC KOP Battery

* The battery was charged from test to test. The team does not have the ability to maintain an exact voltage input for each test. To address this concern, some of the speed data is evaluated as an efficiency, which factors input voltage to output shaft speed.

The following items changed between the chain and belt tests:

Component	Configuration 1 Chain	Configuration 2 Belt
Transmission Drive	Sprocket	Pulley
Main Drive Wheels	2 Sprockets	2 Pulleys
Rear Drive Wheels	1 Sprocket	1 Pulley
Transmission to Main Wheels	Chain	Belt
Main Wheels to Rear Wheels	Chain	Belt

Other DoE considerations incorporated into the test plan include:

1. Setting clear, agreed, understood objectives.
2. Quantitative measurements whenever possible.
3. Repeat measurements to address uncontrollable variation.
4. Randomized run order / back to back to back testing.
5. Removal of known sources of variation.
6. Non-advocate review of plans, procedures, data and conclusions.

D. Test Plan Creation

1. Data Required From Testing / Evaluation

The data below was captured during the design, fabrication and testing process:

MEASUREMENTS NEEDED

	OBJECTIVE MEASUREMENTS	MEASUREMENT METHOD
1	Weight	Accurate Scale
2	Input Voltage	Voltage input to each motor - LabView
3	Output Speed	Speed Sensor on Transmission Output
4	Breaking Strength	Weight Incrementally Applied until Breakage
5	Stretch	Weight Applied, Stretch Measured
6	Backlash	Angular Measure of Wheel "Freedom"

	DERIVED DATA	
1	Efficiency	RPM / Volt = Output Speed divided by Input Voltage
2	Stretch	Inches / Pound = Stretch divided by Weight Applied

	SUBJECTIVE MEASUREMENTS	
1	Noise	Sound Recording Software
2	Assembly Time	Controlled Builds or Estimations
3	Repair Time	Opinion
4	Drive-Ability	Opinion
5	Design / Manufacturing Integration	Opinion

4	Uniqueness	Opinion

WEIGHT MEASURES - CHAIN

1	Wheel Assembly - 1 Sprocket	
2	Wheel Assembly - 2 Sprocket	
3	Transmission - 1 Sprocket	
4	Chain - Trans to Wheel	
5	Chain - Wheel to Wheel	
6	Tensioner - A	NOT USED
7	Tensioner - B	NOT USED
8	Total System	

WEIGHT MEASURES – BELT

1	Wheel Assembly – 1 Pulley	
2	Wheel Assembly – 2 Pulley	
3	Transmission – 1 Pulley	
4	Belt – Trans to Wheel	
5	Belt – Wheel to Wheel	
6	Tensioner – A	NOT USED
7	Tensioner – B	NOT USED
8	Total System	

IV. TEST METHODOLOGY AND RESULTS

1. Speed and Efficiency Tests

A. Methodology

To measure the speed and efficiency of the two systems, on-board data was collected. The robot was first built using the belt drive components. The factory installed encoders were used to measure counts (can be calculated into output shaft RPMs) and battery voltage was collected during each test run. This data was captured using LabView software.

To complete the distance and efficiency tests. The robot was taken to a hallway at the school. Starting lines were marked for consistency in the two courses. Testing was completed on a flat section of the hallway and on a ramp section (approximately 4 degree incline).

With a laptop connected via a long tether line, the robot was started and a 3 second autonomous run was completed. During this run, the computer captured encoder counts per computer cycle and battery voltage per computer cycle and cumulative encoder count (total distance). The students measured total distance traveled with a tape measure.

(For the belt drive data, the total cumulative encoder count was not accurately measured. Following the 3 second autonomous mode, the computer only recorded data for one additional second. With the coast time of the robot, this caused the total cumulative count to be less than the actual total distance traveled. This was not identified before the belt and chain systems were changed, so the total encoder count data for the belt drive is not available. For the chain drive tests,

three additional seconds of data was captured. This does not affect the actual total distances traveled, as this distance was measured on the floor, not calculated based on encoder counts. It also does not affect the distance based calculations listed below.)

For the times tests, two observers timed the robot from a full stop to a 50 foot and a 25 foot marker. This data was then averaged for each timer and each run.

B. Conclusions

Based on the testing completed, the following conclusions can be made.

1. The belt drive system is more efficient, providing 2 - 3% higher encoder counts per volt. Counts are equivalent to higher output RPMs of the transmission and the driven wheels.
2. The belt drive system traveled 3 – 4% further during the 100 record block (records 15 – 115).
3. The belt drive system traveled 3 – 6% faster to reach a counter level of 500, indicating a faster acceleration.
4. The belt drive system traveled 8% further in the autonomous test (includes the unpowered rolling distance), indicating a more efficient system.
5. The belt drive was 5% faster to 50 feet, and 14% faster after the initial acceleration period to 25 feet.

2. WEIGHT MEASUREMENTS

A. Methodology

To assure the total system level impact on the weight was determined, three methods of determining weight were used.

1. Each component was weighed and the weight recorded. These weights were taken on a very accurate digital scale.
2. The fully assembled robot was weighed with a fully installed belt drive system and chain drive system. Measurements were taken with and without the battery, with the same battery used.
3. The full set of unique components for one side was weighed, with an equivalent “set” for the belt drive and chain drive weighed.

B. Conclusions

Based on the testing completed, the following conclusions can be made.

1. There was no difference in weight of the systems as tested.
2. There is little opportunity for weight reduction of the chain system, as the drive sprockets are lightweight aluminum and were attached directly to the drive wheels.
3. There is an opportunity for 0.25 pound / pulley weight reduction on the belt drive system. A direct drive, 6 wheel drive system would require a total of 8 pulleys (4 per side),

representing a 2 pound weight saving opportunity by machining the center of the pulley hubs. This was not done on the test pieces to save machining time and to leave the pulleys in their full configuration in case they were needed for other testing or other uses that required a smaller hub diameter.

4. Tensioners were not used for either system, and it is assumed a tensioning system for either one would be similar in design and weight. (A free spinning sprocket was used on one side of the chain drive to minimize some of the chain slack, but it is not included in the weights.)

3. NOISE MEASUREMENTS

A. Methodology

A small headset style microphone was placed in the same location on the robot for each drive system. This location was marked on the robot and measured for repeatability. The robot was then run at full power and a data sample taken using a laptop computer and software.

B. Conclusions

Drive system noise was recorded on a laptop computer with a microphone mounted to the robot. Data was taken on at the same location on the belt and chain drive system.

The test data was viewed real time, but was not saved. The real time analysis showed that there was little measurable difference in noise level between the two systems. We believe this is due to the transmission set-up and that transmission noise was overpowering the belt or chain noise level in both cases.

4. SUBJECTIVE MEASURES

A. Methodology

The subjective parameters have been evaluated based on the input of team members, especially those who were most involved with the design, fabrication and testing of the robot drive system. These subjective measures are summarized in the conclusions section.

B. Conclusions

The primary subjective measure of belt drive compared to chain drive is the ease of design and assembly.

Belt Drive Points (Positive and Negative)

1 The most efficient design method is to identify a pulley size and then design the wheel / axle mounting locations for a standard length belt. This must be done early in the process.

2. The belt drive system requires assembly of the drive system at once, to capture the belts around pulleys, axles and frame materials. There is less flexibility to move components once the design is set.
3. Belts must be ordered to the specific size required.
4. Belts and pulley systems are slightly wider than chain systems, taking more robot space.
5. Belt systems must be machined for weight reduction.
6. Belt systems are less likely to wear and stretch.

Chain Drive Points (Positive and Negative)

1. Drive components can be installed in steps, with the chain added at the end of the process.
2. The ability to cut and reassemble chain provides for a more flexible system at final assembly and for any needed repairs.
3. A chain system more prone to stretch and wear as the metal components run against each other.
4. More teams have experience with chain systems and are comfortable with them.
5. There is more availability of spare parts at local stores and competition sites.

V – DATA TABLES AND DEFINITION

SUMMARY DATA - ALL TESTS												
	DATA LOCATION	BELT / CHAIN	FLAT / HILL	TEST #	LEFT C/V	RIGHT C/V	DISTANCE	D/V	REC to 500	TOTAL DISTANCE	ENCODER COUNT	COUNTS / FOOT
1	CCF	CHAIN	FLAT	1	4.44	4.48	4866	449.69	22.62	552	7362	160.04
2	CCF	CHAIN	FLAT	2	4.43	4.50	4886	452.14	22.31	554	7397	160.22
	CCF	CHAIN	FLAT	AVE	4.44	4.49	4876	450.91	22.46	553	7380	160.13
3	CCH	CHAIN	HILL	1	4.23	4.28	4546	430.16	22.00	448	6178	165.48
4	CCH	CHAIN	HILL	2	4.24	4.30	4566	432.18	21.67	452	6261	166.22
	CCH	CHAIN	HILL	AVE	4.24	4.29	4556	431.17	21.83	450	6220	165.85
5	BCF	BELT	FLAT	1	4.57	4.62	5079	464.76	21.05	603	n/a	
6	BCF	BELT	FLAT	2	4.54	4.60	5033	462.72	21.18	595	n/a	
	BCF	BELT	FLAT	AVE	4.55	4.61	5056	463.74	21.11	599		
7	BCH	BELT	HILL	1	4.31	4.39	4697	441.27	21.68	487	n/a	
8	BCH	BELT	HILL	2	4.34	4.40	4707	442.01	20.83	488	n/a	
	BCH	BELT	HILL	AVE	4.33	4.39	4702	441.64	21.25	488		
	TIME TESTS		to 50	to 25	BLOCK 25							
	CHAIN	AVG	4.55	2.38	2.18							
	CHAIN	FPS	10.99	10.53	11.49							
	BELT	AVG	4.33	2.43	1.90							
	BELT	FPS	11.56	10.31	13.16							
	BELT / CHAIN COMPARE		FLAT / HILL	TEST #	LEFT C/V	RIGHT C/V	DISTANCE	D/V	REC to 500	TOTAL DISTANCE	FPS - 0 to 50	FPS - 25' BLOCK
		CHAIN	FLAT		4.44	4.49	4876.00	450.91	22.46	553.00	10.99	11.49
		BELT	FLAT		4.55	4.61	5056.00	463.74	21.11	599.00	11.56	13.16
		CHAIN / BELT			0.97	0.97	0.96	0.97	1.06	0.92	0.95	0.87
		BELT / CHAIN			1.03	1.03	1.04	1.03	0.94	1.08	1.05	1.14
		CHAIN	HILL		4.24	4.29	4556.00	431.17	21.83	450.00		
		BELT	HILL		4.33	4.39	4702.00	441.64	21.25	487.50		
		CHAIN / BELT			0.98	0.98	0.97	0.98	1.03	0.92		
		BELT / CHAIN			1.02	1.02	1.03	1.02	0.97	1.08		

The LabView data was saved and opened in Excel for analysis and calculations. Additional measured data was added to the data file. The following calculations were made on two sets of data from each of 4 different robot runs (2 each flat and hill for belt and chain drive).

1. COLUMN A - Record Number
2. COLUMN B - Left Side Count – Encoder Counts per computer cycle (raw data)
3. COLUMN C – Right Side Count – Encoder Counts per computer cycle (raw data)
4. COLUMN D – Voltage x 100 (Battery)
5. COLUMN E - Total Count – Total distance traveled (cumulative encoder count).
6. COLUMN F - Left Counts per Volt – Left Side Count, divided by Voltage (calculated value).
    a. This is a measure of efficiency, as it equated to shaft rpm (output) per volt applied (input).
7. COLUMN G - Right Side Counts per Volt - Right Side Count divided by Voltage (calculated value).
    a. This is a measure of efficiency, as it equated to shaft rpm (output) per volt applied (input).

The primary data was analyzed for records 15 – 115 for each data set. This allowed time for the robot to begin accelerating and before the autonomous program reduced power. The selection of records 15 – 115 was a subjective decision based on a review of the raw data and was consistent for each data set.

(Due to the size of the data files, the raw data is not included in this report.)

SECTION 1 – Drive Data

1. LEFT C/V (Counts / Volt), Average, for records 15 – 115
2. RIGHT C/V (Counts / Volt), Average, for records 15 – 115
3. Distance, Total Encoder Counts, for records 15 – 115
4. D/V (Distance / Volt), Cumulative Distance / Average Volt for cumulative records 15 – 115
5. Records to 500, Number of Records Observed Before the Cumulative Cycle Counter was at 500. (This was extrapolated based on the count just below and above 500 where necessary.) This is a measure of acceleration.
6. Total Distance – Measured value, in Inches
7. Encoder Count – Total Encoder count at stop (only for chain drive)

SECTION 2 – Timed Tests

1. To 50, Average time, in seconds, to the 50 foot marker
2. To 25, Average time, in seconds, to the 25 foot marker
3. BLOCK 25, Block Time, from the 25 foot to the 50 foot marker (calculated from the 50 and 25 foot times)

4. FPS – Speed, Calculated in Feet Per Second, based on the timed measurements.

SECTION 3 – Comparison

This section takes the data from Section 1 and Section 2 and compares the averages of the chain and belt drive data.

For the row labeled CHAIN / BELT, this is a ratio of the average chain data over the average belt data. For the row labeled BELT / CHAIN, this is a ratio of the average belt data over the average chain data. The FLAT data and HILL data are separated and analyzed.

Except for the row labeled “REC to 500”, a number greater than 1 indicates a higher performance level for that parameter between the chain and belt drive.

VI. FINAL SUMMARY

The students and mentors on Cyber Blue learned a great deal of knowledge and gained valuable experience with this design and test evaluation. The team believes that the belt drive system knowledge will be valuable in the future and will most likely be a part of future team robots.

The team would like to thank Gates Corporation, especially Shannon Lynch, for their support of test hardware and technical expertise on synchronous belts, and Rolls-Royce employees Jack Reismiller (Master Black Belt) and Nikki McMullen (Black Belt) for their assistance in the early planning stages of this testing program.

The team would also like to thank the veteran FIRST mentors who provided a review of the drafts of this test report before it was published to the wider community.

VII. CHASSIS DESIGN

A new chassis was designed to allow an easy switch from a chain drive to a belt drive. By utilizing the same chassis for both drives, the potential effects of chassis and other component differences was eliminated. The negative of this approach is that side by side comparisons are not possible with just one chassis system.

The new chassis is designed with 1" diameter aluminum tube. The chassis is a basic rectangular shape, approximately 28" x 38" to match the 2008 FRC size restrictions. The chassis is a welded construction.

The chassis incorporates mount provisions for 6 wheels, and either a belt or chain drive. There is an area for mounting transmissions, motors, a battery, basic control components and any identified onboard measurement devices.

Since the team has limited experience with belt drive systems, an expert from Gates Corporation agreed to provide information and support during the design phase. Gates provided the test pieces for the drive to reduce the cost impact to the team for the evaluation.

The chassis had no influence on the outcome of the testing, and the testing could have been completed on many standard chassis designs.

A picture of the test chassis, set up for chain drive, is below.

Design, Fabrication and Assembly of the Test Chassis

Once the design parameters were agreed, the design team created a basic tube chassis that met the following criteria:

1. Clearance for 6" drive wheels
2. Clearance for wheels with 2 drive sprockets or 2 drive pulleys mounted
3. Ability to mount Two AndyMark SuperShifter Transmissions, each with 2 CIM motors
4. Ability to adjust (slide fore and aft) the location of the transmissions to provide necessary tension on belts or chains
5. Driven Center Wheel to Rear Wheel fixed location to meet a standard belt dimension
6. Ability to mount tensioners (if required)
7. Space for mounting control components and battery

Additionally, since the team was developing a new chassis design as a potential for future FRC robots, the design and fabrication process was documented so that it could be repeated during the regular season. Lessons Learned were captured to allow for continuous improvement.

Photographs of the chassis fabrication and build are included in the Pictures Section.

VIII – PICTURES

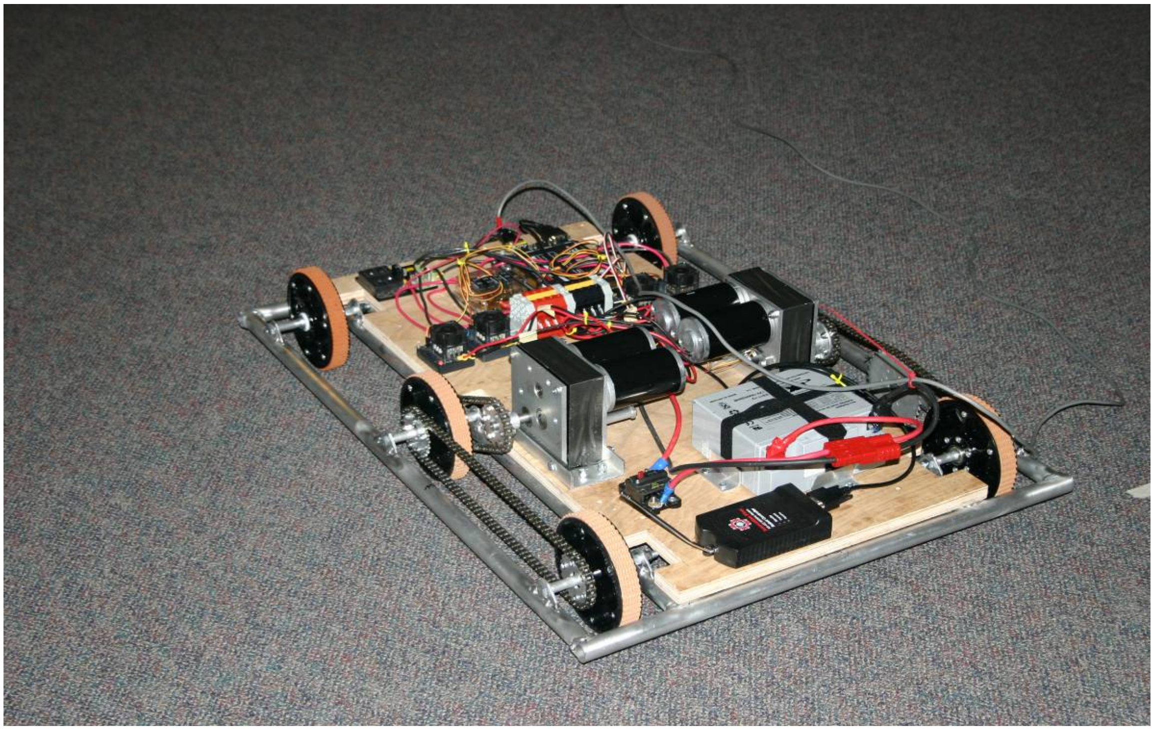

Photo 1 – Chassis with Chain Drive Set-Up

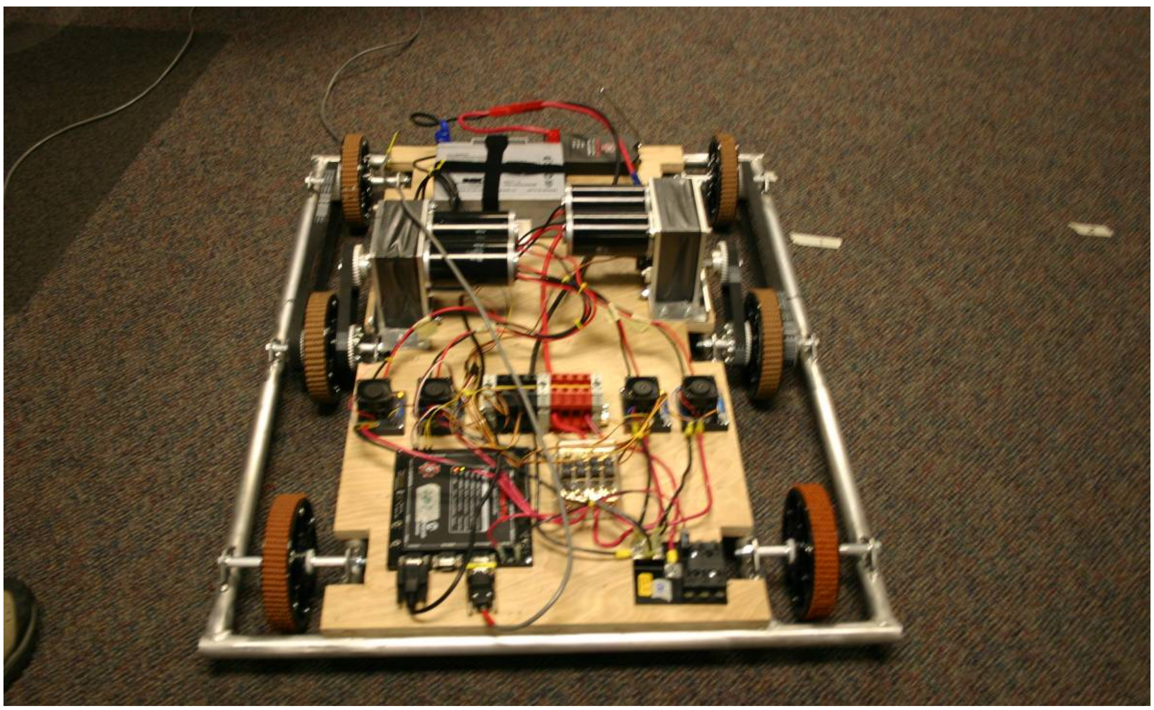

Photo 2 - Chassis with Belt Drive Set-Up

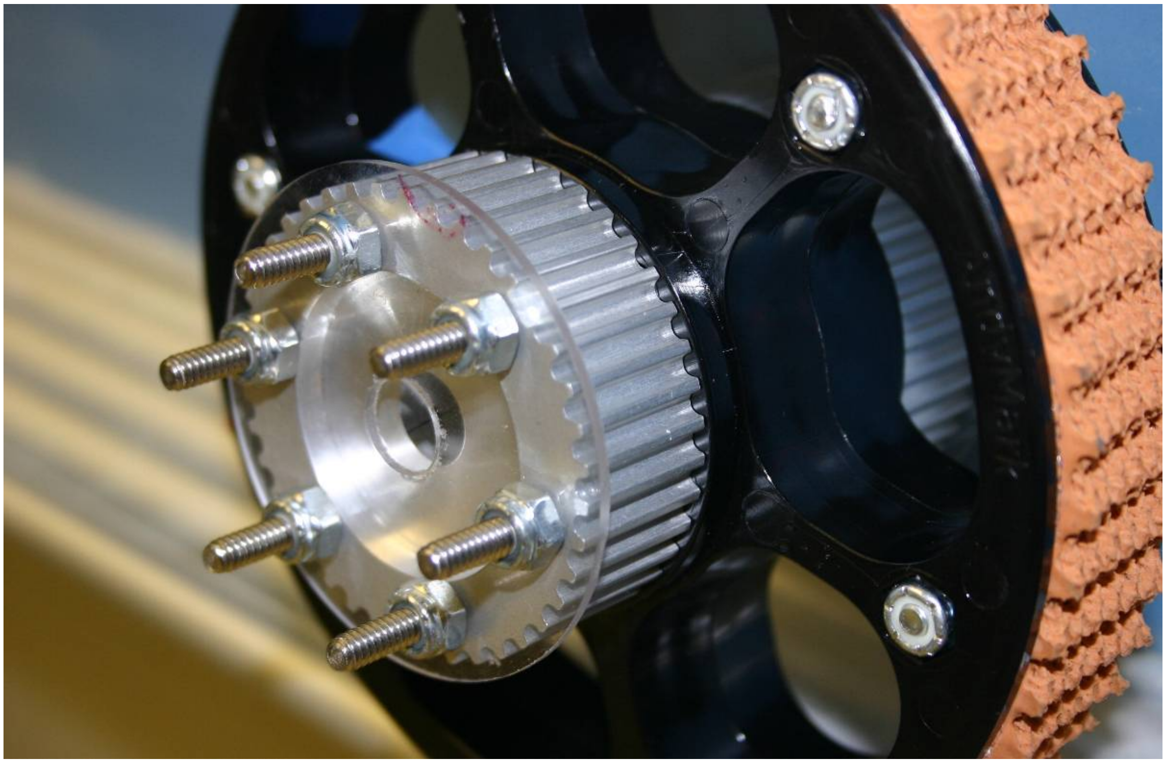

Photo 3 – Wheel with Belt Pulley Attached

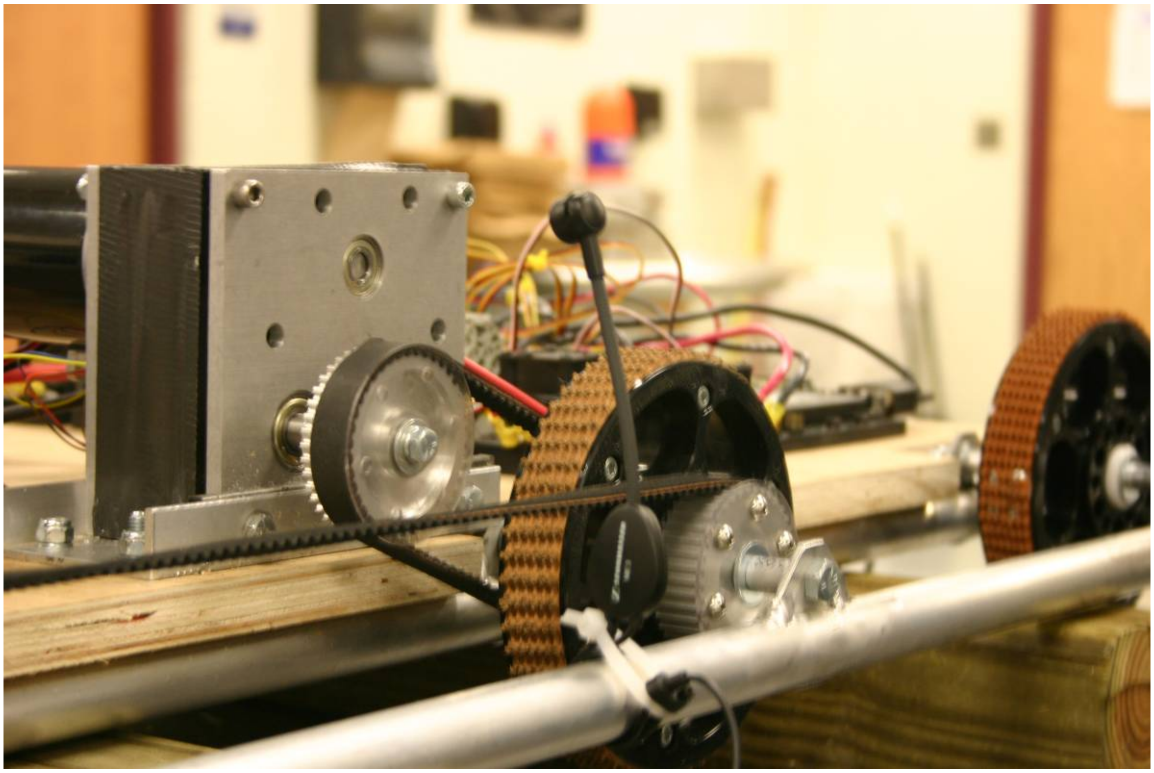

Photo 4 – Belt Drive Set-Up (With Microphone)

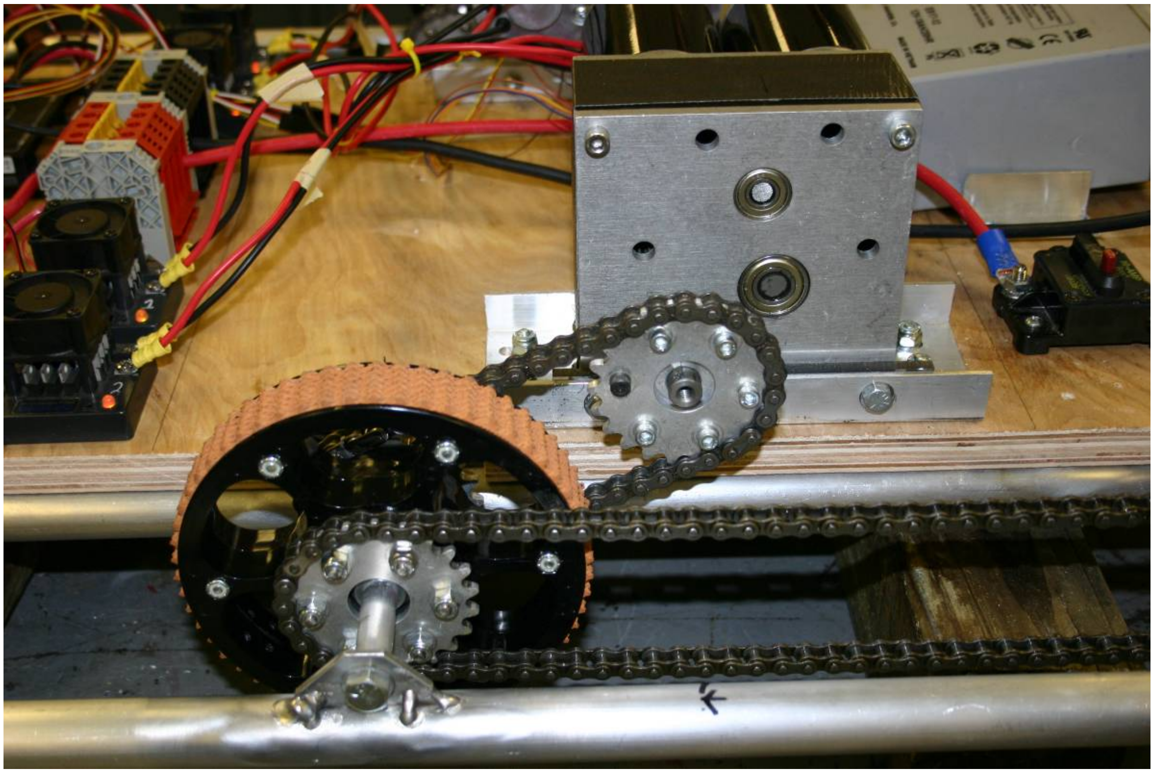

Photo 5 – Chain Drive Set-Up

Photo 6 – Drive Test Underway (Student Alongside with Laptop)

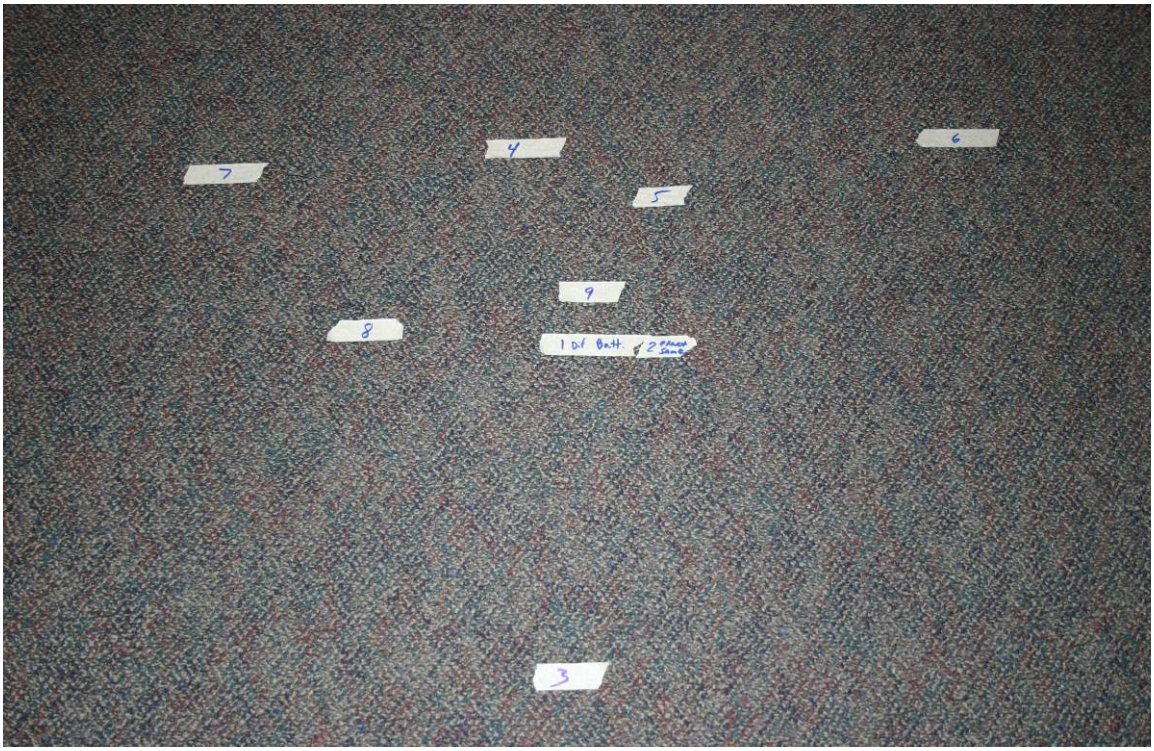

Photo 7 – Tape Marks on Floor For Distance Tests

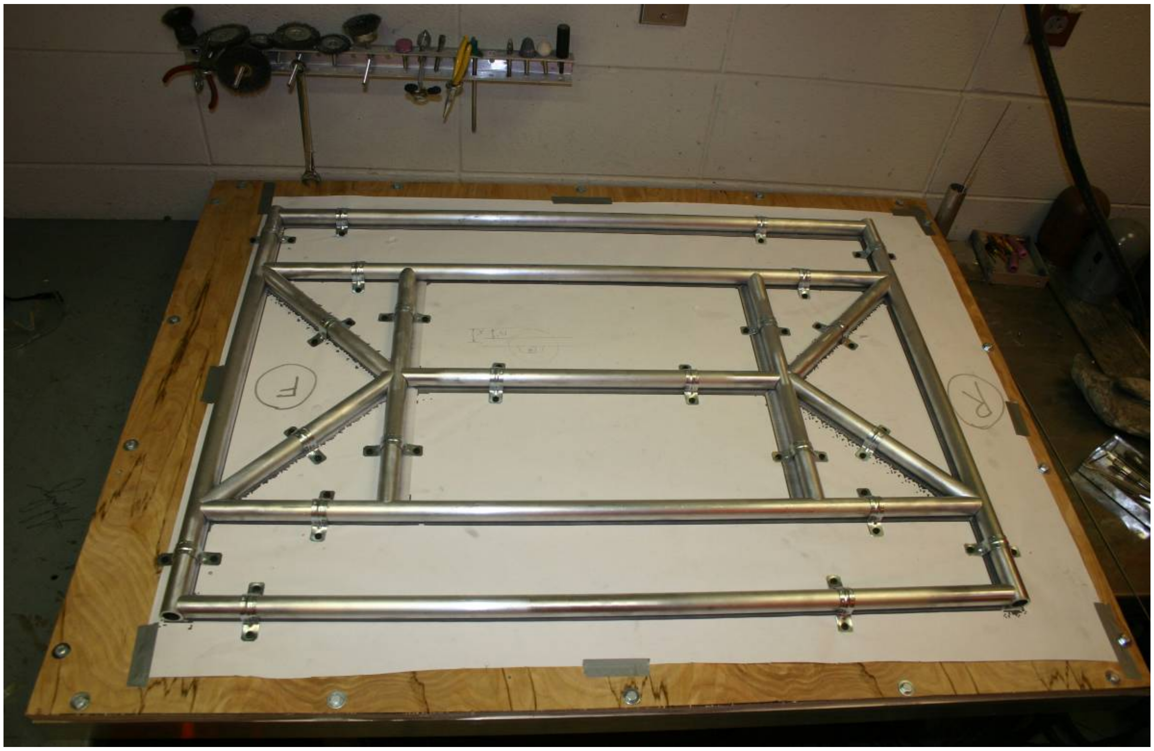

Photo 8 – Test Chassis On Template Board Before Welding