Integration of a Testbed for Examining the Interaction of Mars Rover Wheels with a Mars Soil Simulant.

by

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING.

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ABSTRACT

Integration and experimental testing was performed on a testbed for examining the interaction of Mars rover wheels with a Mars soil simulant. The testbed included a horizontal carriage that had a encoder to measure the horizontal displacement of the Mars rover wheel. A DC motor was attached to the top of the carriage and controlled the horizontal velocity of the Mars rover wheel. The testbed had a vertical carriage with a 6-axis load cell attached to measure vertical load and the tractive force developed by the Mars rover wheel. There was another motor and a torque sensor attached to the Mars rover wheel that controlled the angular velocity of the wheel and measured the applied torque.

A program was created in order to run tests on the Mars rover wheels testbed using LabVIEW. The program had an interface that allowed the user to input a desired horizontal velocity and slip. The program recorded the distance the wheel traveled, velocity it traveled at, sinkage of the wheel into the soil, tractive force of wheel on soil, vertical load applied to wheel, torque applied to wheel, and the amount of time the system ran for. The user was also able to reset the system after each test to start again.

Thesis Supervisor: Karl Iagnemma
Title: Principal Research Scientist

Acknowledgements

I have been indebted in the preparation of this thesis to my supervisor, Dr. Karl Iagnemma of Massachusetts Institute of Technology, whose patience and generosity, as well as his academic experience, have been invaluable to me. I am extremely grateful to Dr. Karl Iagnemma's Postdoctoral Associate, Carmine Senatore for helping me greatly throughout my research and thesis work and keeping me and my work on track. I would like to thank Elvine Pineda, who contributed by working on the hardware and construction of the testbed.

I would like to thank my parents, Anthony and Grace Okafor, who have been a constant source of emotional, moral, and financial support during my undergraduate years, and this thesis would certainly not have existed without them.

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1. Introduction

1.1 Summary

The mobility of vehicles over soft terrain is a very important factor in a vehicles overall performance. A vehicles design, analysis, and simulation is all modeled after its traction mechanics while traversing over deformable terrain. The study of vehicle interaction with deformable terrain is known as Terramechanics. This engineering discipline originated from the work of Polish engineer and scientist, Mieczyslaw G. Bekker in the beginning of the 1960's.

Terramechanic methods were first derived for large, heavy vehicles. These vehicles were usually over 2000 lbs. Organizations like the Army and NASA have recently began developing small lightweight vehicles. These vehicles usually are less than 100 lbs and 3 ft in length. Since these vehicles are significantly smaller than the vehicles primarily developed using classical Bekker theory, there have been some discrepancies between theoretical data and experimental data.

1.2 Objectives

The main objectives include integrating a testbed enabling the examination of the interaction of Mars rover wheels on a

Mars soil simulant and creating a program to control the testbed. Using this testbed, tests were done in order to calculate the forces exerted on the wheels, torques applied to the wheel, the amount of sinkage of the wheel into the soil, and the amount of slip of the wheel on the soil for a given linear and angular velocity.

2. Testbed Design and Development

2.1 Background

The main motivation for the work originated from the NASA Sprit rover which was part of the Mars Exploration Rover mission in 2009. The Spirt rover became embedded in the loose Mars soil and was unable to be retrieved. This put an abrupt end to NASA's several hundred million dollar mission. Because of this, work has been aimed at improving terramechanics models for small ground vehicles.

2.2 Design

The work done was based around 2 modules: the testbed and the program used to control the testbed. The testbed included many parts. A Mars soil substitute was used that resembled similar properties of actual Mars soil. There were 2 motors used, one for the carriage and one for the wheel. There were 2 linear encoders used, one for the horizontal displacement and one for the vertical displacement of the wheel. There was a 6-axis sensor used to measure the vertical load and the tractive force exerted on the Mars rover wheel. There was also a torque sensor the measured the torque applied to the wheel. All of these parts can been seen below in the model of the testbed in Figure 1.

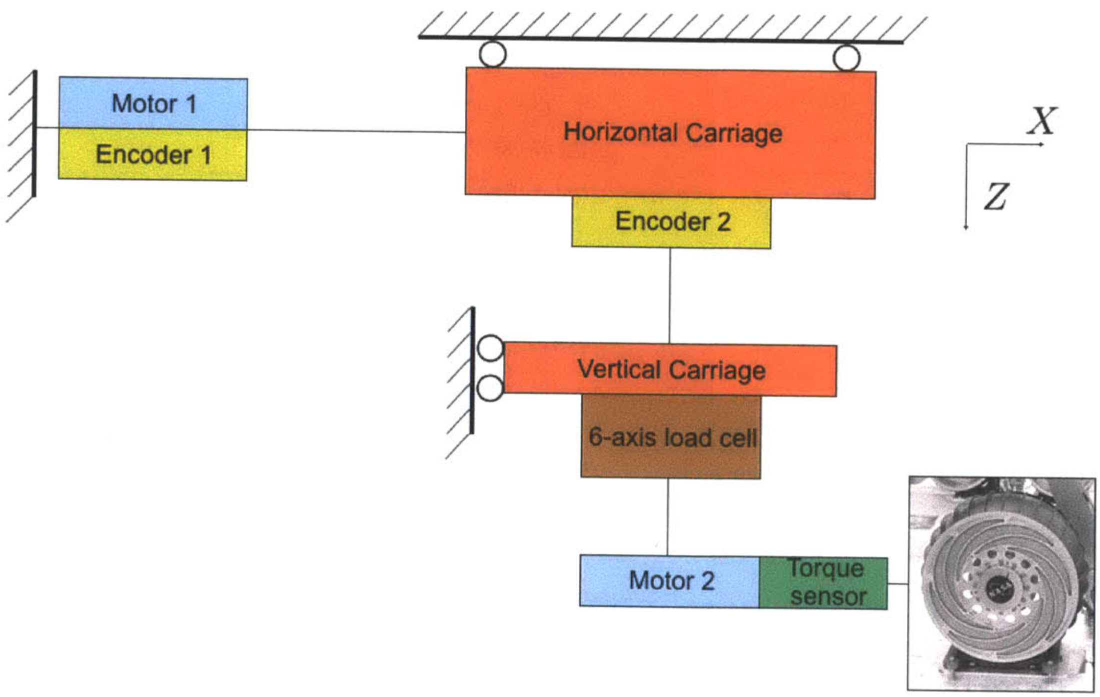


Figure 1: Model of Testbed Parts.

For the program to control the testbed, LabVIEW was used. All of the sensors were integrated into a LabVIEW Virtual Instrument (VI) file. The program took the desired linear horizontal velocity of the carriage, the desired slip of the wheel on the soil, and the desired file name and target folder as inputs. It would then display the linear velocity, 6-axis forces and torques, and the motor torques. All of these implementations can be seen below in the model of the LabVIEW program in Figure 2.

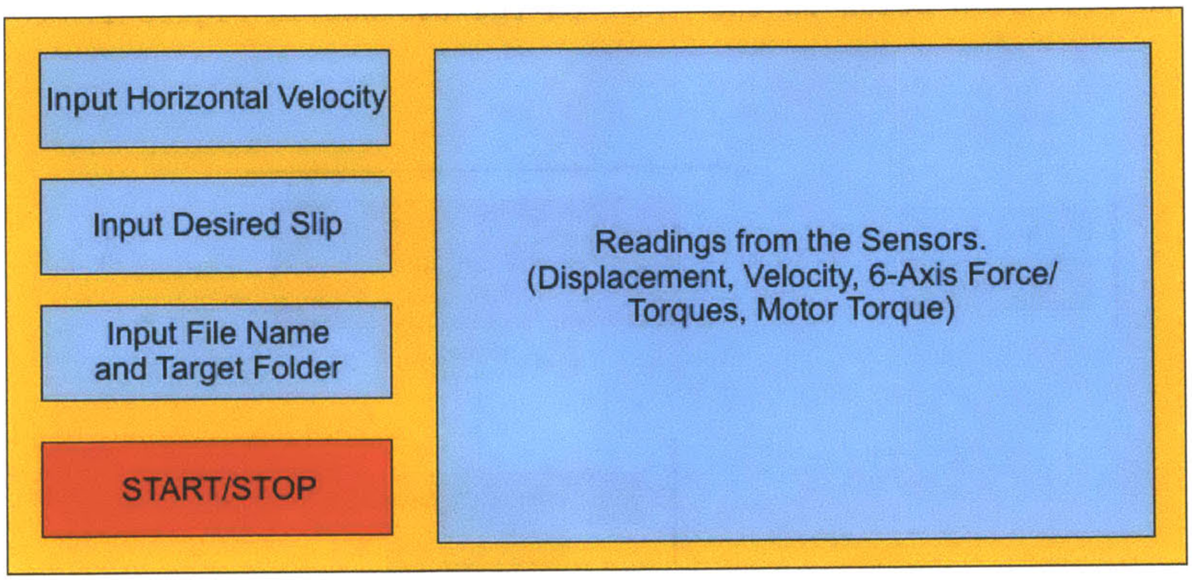


Figure 2: Model of LabVIEW Program.

2.3 Development

The frame of the testbed were assembled using 80/20 Aluminum Framing, and the walls of the bed used to hold the Mars soil simulant were assembled using 0.5 inch thick Lexan sheets. The Mars rover wheel was attached to a metal platform that was attached to retractible bars allowing for it to move vertically.

These bars were attached to another platform that was attached to another set of bars allowing for horizontal movement. An image of the testbed can be seen below in Figure 3.

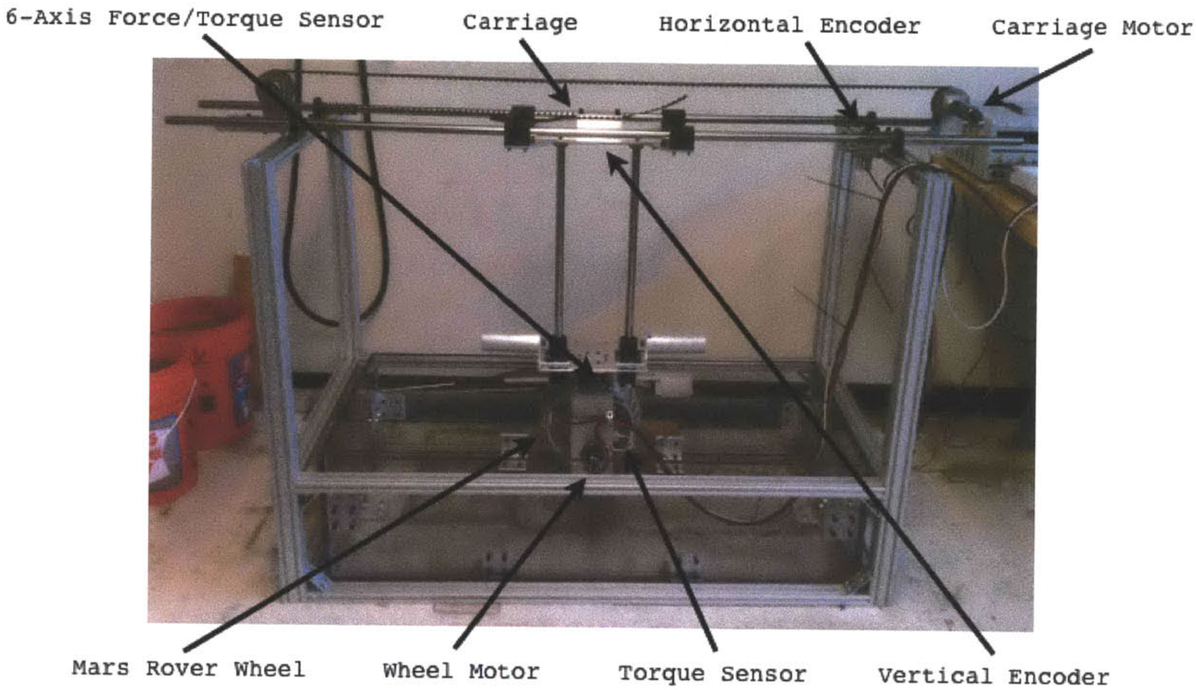


Figure 3: Image of Testbed.

3. LabVIEW Integration

3.1 Integrated Parts

As stated before the integrated parts I worked on were 2 linear encoders, 2 motors, a 6-axis sensor, and a torque sensor. Each of these parts were attached to the testbed and hooked up to a connector block and a main power supply unit in order to be controlled in LabVIEW. A picture of the connector block and power supply used can be seen below in Figures 4 and 5 respectively.

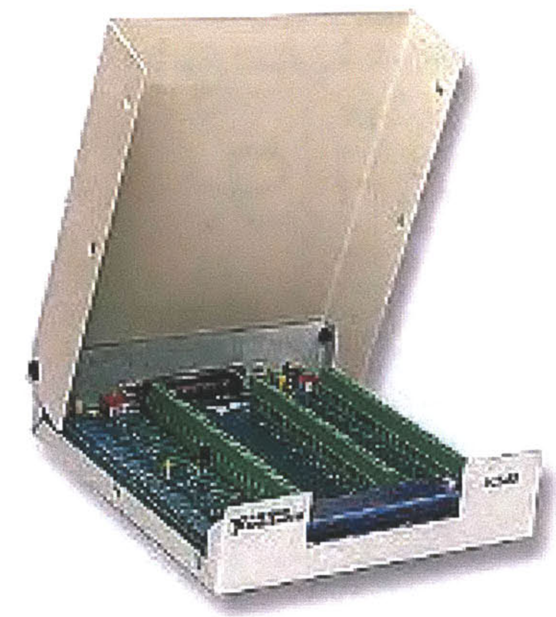
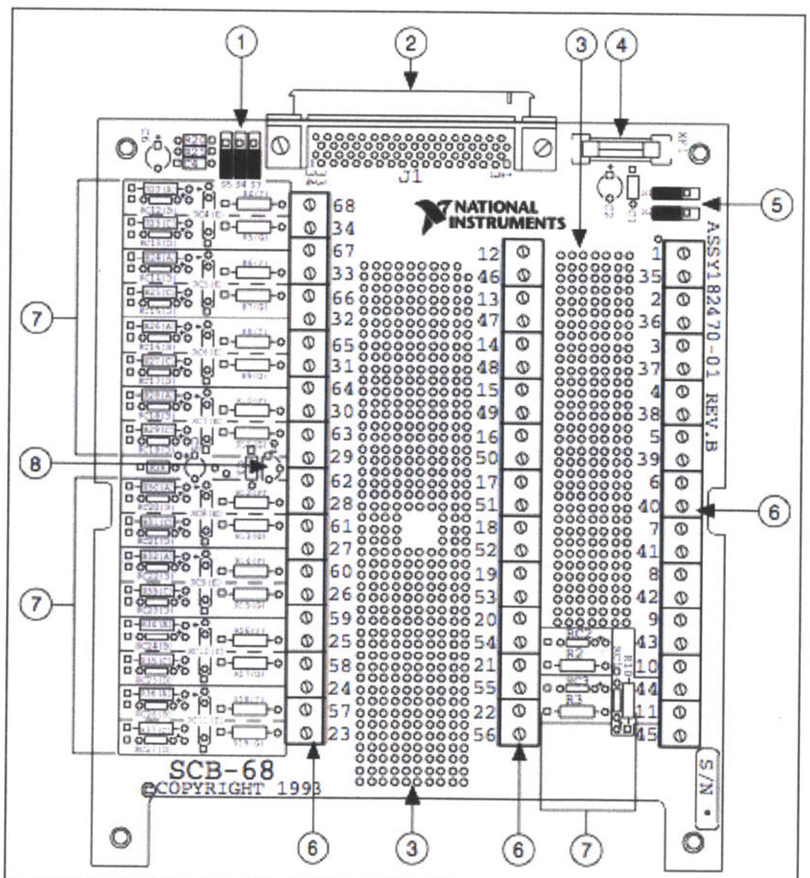


Figure 4: SCB-68 Connector Block.

Figure 5: Mastech DC Power Supply HY3005D-3.

The SCB-68 connector block has multiple ports for different types of connections. It has ports for input/output connections, signaling connections, and also temperature connections. All of the motors and sensors used were connected to the SCB-68 connector block by using the screw terminals. A schematic of the different connections and ports that make up the SCB-68 connector block can be seen below in Figure 6.



1	Switches S3, S4, and S5	5	Switches S1 and S2
2	68-Pin I/O Connector	6	Screw Terminals
3	Breadboard Area	7	Signal Conditioning Areas
4	Fuse (800 mA, 250 V, 5 · 20 mm)	8	Temperature Sensor

Figure 6: Schematic of SCB-68 Connector Block.

3.2 Motors

The motors used were Maxon DC motors. Each of the Maxon DC motors were connected to a 4-Q-DC servoamplifier ADS for motor control. These servoamplifiers were then connected the SCB-68 connector block and the DC power supply. A picture of the Maxon DC motor and the 4-Q-DC servoamplifier ADS can be seen below in Figure 7.

Figure 7: Maxon DC Motor and 4-Q-DC Servoamplifier ADS.

The Maxon DC motor's outputs inputs were connected to the various inputs from the servoamplifer. Some of the inputs and outputs of the serveroamplifer were in turn connected to the different ports of the SCB-68 connector board. A schematic of the different inputs and outputs of the servoamplifier can be seen below in Figure 8.

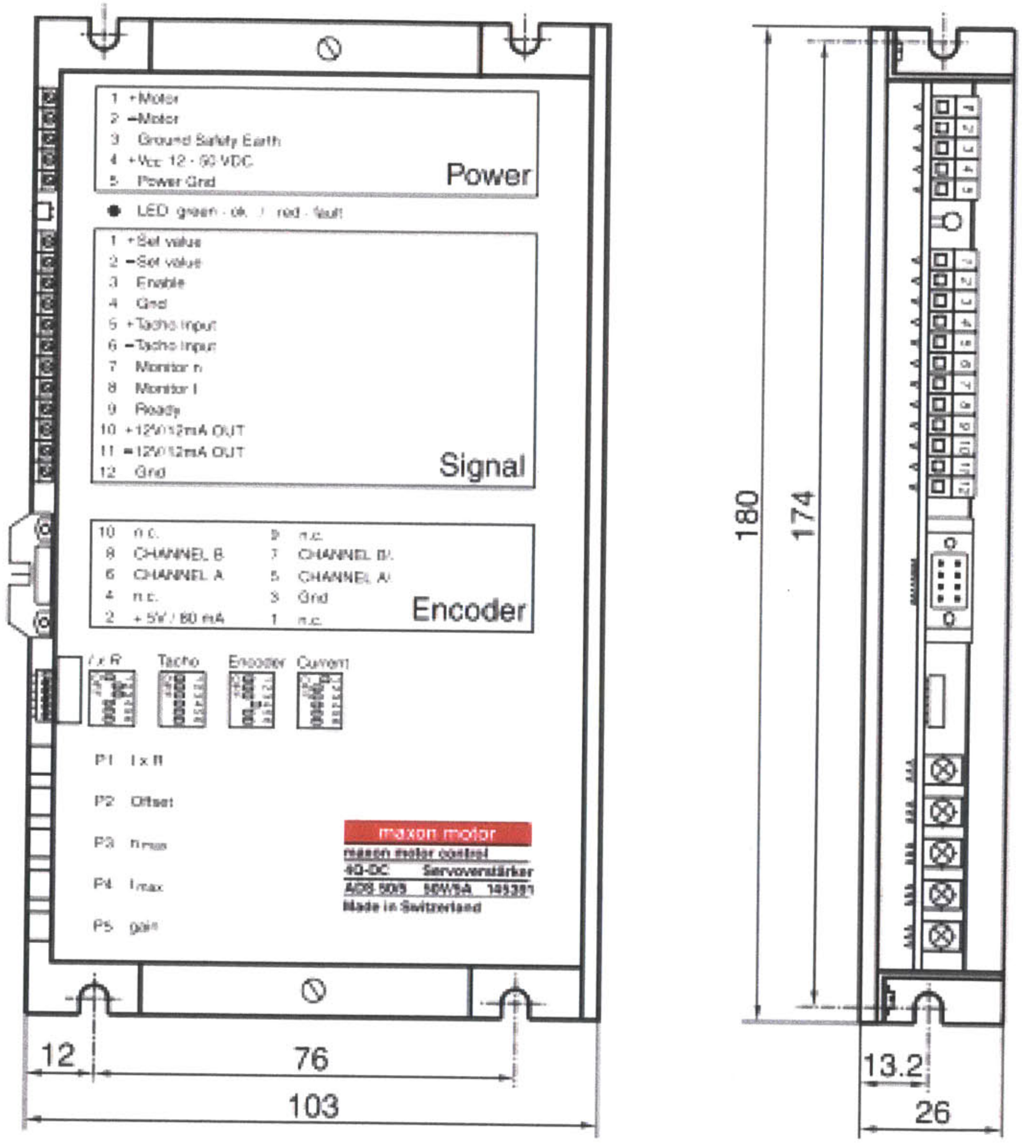


Figure 8: Schematic of the 4-Q-DC Servoamplifier ADS.

3.3 Linear Encoders

The linear encoders used were Kubler draw wire linear encoders type A50. These encoders were connected to the SCB-68 connector block and the DC power supply. A picture of the draw wire linear encoders can be seen below in Figure 9.

Figure 9: Kubler Draw Wire Linear Encoder Type A50.

The draw wire encoders were made up of 4 different wires. Each of these wires served as 4 different types of connections connecting to both the SCB-68 block connector and the DC power supply. A chart of the draw wire encoders wire connections can be seen below in Figure 10.

Pin	Cable colour	0 ... 10 V	4 ... 20 mA	1 kOhm
1	brown	V+	V+	V+
2	white	Signal	n. c.	Slider
3	blue	GND	Signal	GND
4	black	GND Sig.	n. c.	n. c.

Figure 10: Chart of Kubler Draw Wire Encoder Wire Connections.

3.4 6-Axis Sensor

The 6-axis sensor used was an ATI Industrial Automation 6-axis force/torque sensor. The 6-axis force/torque sensor came with its own force/torque data acquisition software from ATI Industrial Automation. Because of this, the 6-axis force/torque sensor was connected straight into the computer used for LabVIEW integration. A picture of the 6-axis force/torque sensor can be seen below in Figure 11.

Figure 11: ATI Industrial Automation 6-Axis Force/Torque Sensor.

The 6-axis force/torque sensor measures the forces applied to the sensor in the x,y, and z directions. It also measures the torques applied to the sensor in the x,y, and z directions. A diagram of these forces/torques applied to the sensor can be seen below in Figure 12.

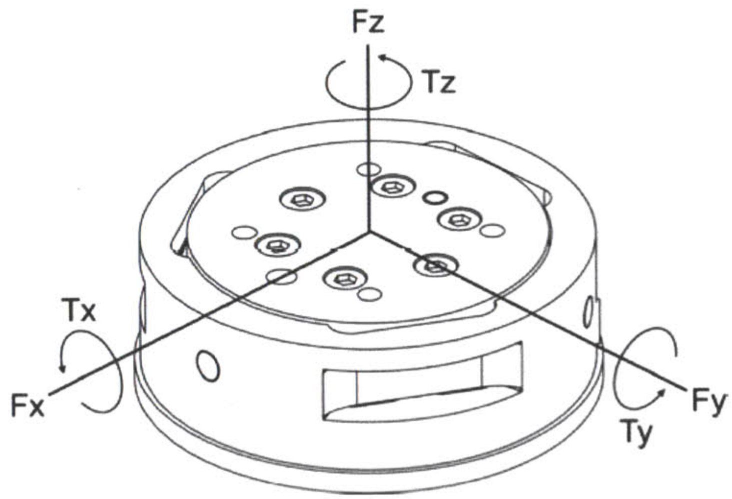


Figure 12: Diagram of Forces and Torques Applied to Sensor.

As stated before, the ATI Industrial Automation 6-axis force/ torque sensor came with data acquisition software. This software measures the different voltages output from the transducer and then converts these voltages to the respective force and torque components. A diagram of this outline can be seen below in Figure 13.

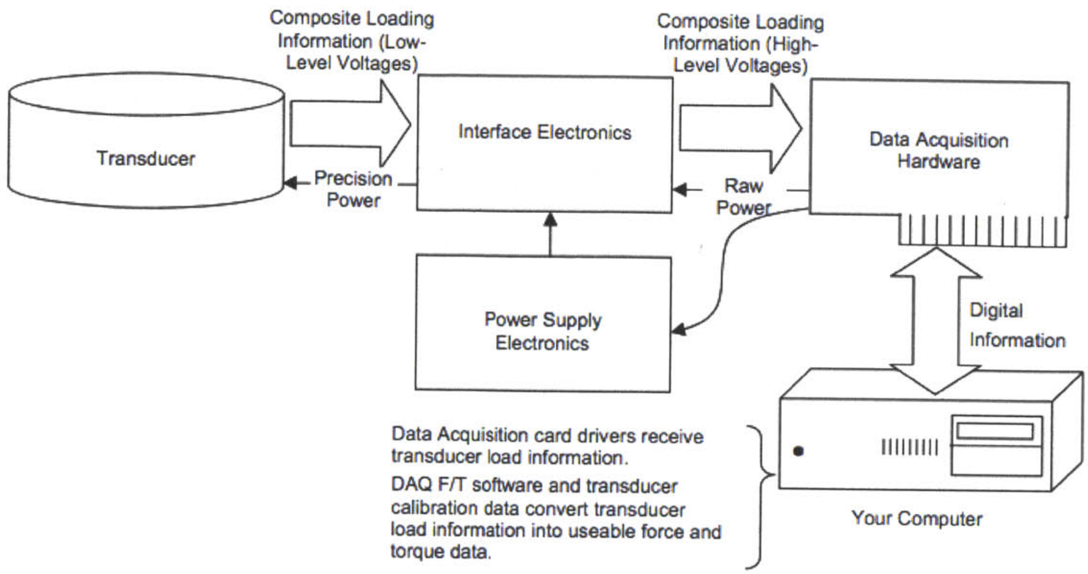


Figure 13: Diagram of Torque Sensor Data Acquisition Outline.

3.5 Torque Sensor

The torque sensor used was a Futek torque sensor model TFF500. The torque sensor was connected to the SCB-68 connector block and the DC power supply. A picture of the torque sensor can be seen below in Figure 14.

Figure 14: Futek Torque Sensor Model TFF500

Similar to how the 6-axis force/torque sensor works, the Futek torque sensor measures the voltage applied to the sensor and then converts the measured voltages to torque values. All of this calibration was done using given data and put into LabVIEW. A chart of the calibration data can be seen below in Figure 15.

Calibration Data

Test Temp .... 72.5 °F (22.5 °C)	**Relative Humidity** ...... 50.9 %
Excitation .... 15 (Vdc)	**Input Resistance** .... 350 (Ohms)
Zero .... 0.1637 (Vdc)	**Output Resistance** .... 350 (Ohms)

direction: TorqueCW

Rated Output ... 8.6479 (Vdc)	**ZeroReturn** .... 0.047 % of R.O.
Linearity .... -0.044 % of R.O.	

Figure 15: Futek Torque Sensor Calibration Data.

3.6 Sensors and Connections

All of the motors and sensors listed above resulting in a very complex diagram of multiple wires coming into and out of the SCB-68 connector block, DC power supply, the 4-Q-DC Servoamplifier ADS, the 6-axis force/torque sensor controller block, and the computer being used. This can be seen below in Figure 16.

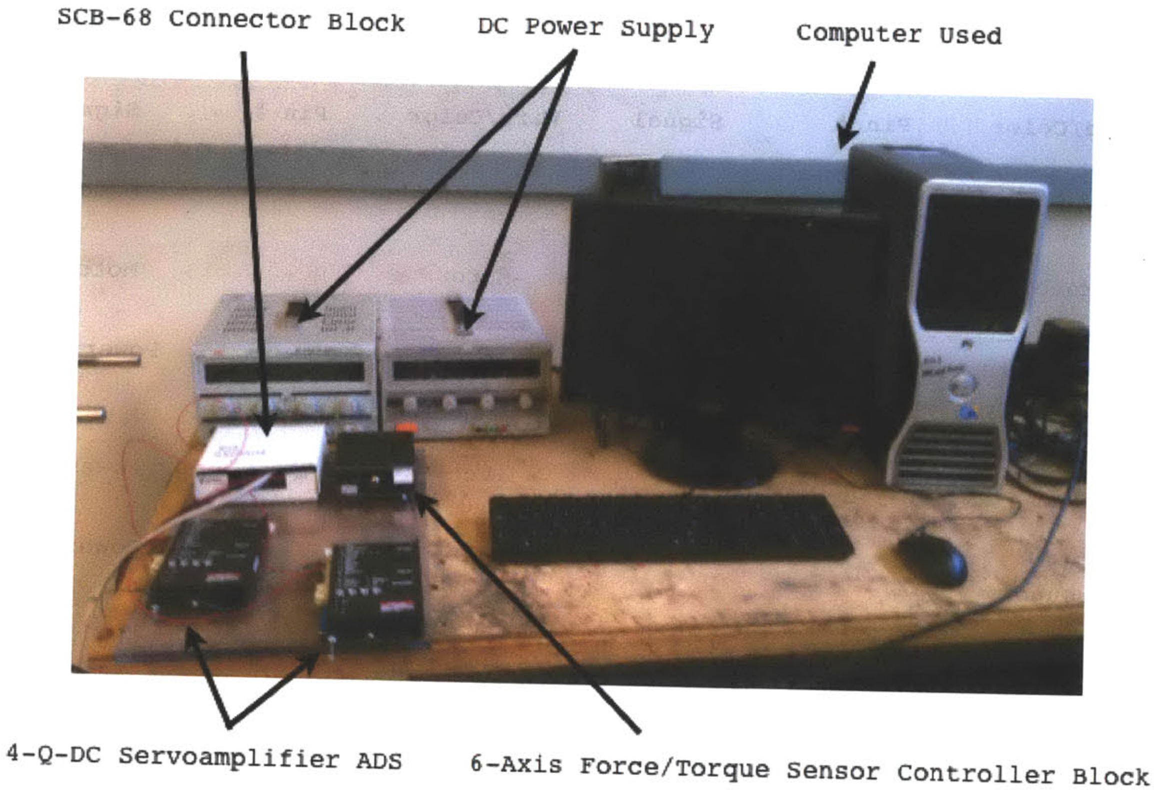


Figure 16: Picture of Motor and Sensor Controller Setup.

In order to increase organization and keep track of where all the different wires and coming from and going to, multiple charts were made. These charts can be seen below in Figures 17, 18, and 19.

Carriage Motor			Wheel Motor		
Wire/Color	**Pin #**	**Signal**	**Wire/Color**	**Pin #**	**Signal**
+Motor	-	Motor+	+Motor	-	Motor+
-Motor	-	Motor-	-Motor	-	Motor-
Ground Safety Earth	-	Power GND	Ground Safety Earth	-	Power GND
+Vcc	-	Power -	+Vcc	-	Power -
Power Ground	-	Power +	Power Ground	-	Power +
+Set Value/ Red	22	AO 0	+Set Value/ Red	22	AO 0
-Set Value/ White	55	AO GND	-Set Value/ White	55	AO GND
Enable/ Black	21	AO 1	Enable/ Black	21	AO 1
Gnd/Green	12	D GND	Gnd/Green	12	D GND
+Tacho Input	-	Motor Tacho +	+Tacho Input	-	Motor Tacho +
-Tacho Input	-	Motor Tacho-	-Tacho Input	-	Motor Tacho-
Monitor n/ White	33	AI 1	Monitor n/ White	33	AI 1
Monitor I	-	-	Monitor I	-	-
Ready	-	-	Ready	-	-
+12V/12mA OUT	-	-	+12V/12mA OUT	-	-
-12V/12mA OUT	-	-	-12V/12mA OUT	-	-
Gnd	-	-	Gnd	-	-

Figure 17: Chart of Carriage and Wheel Connections.

Linear Horizontal Encoder			Linear Vertical Encoder		
Wire/Color	**Pin #**	**Signal**	**Wire/Color**	**Pin #**	**Signal**
A/Green	37	PFI 8/P2.0	A/Green	42	PFI 3/P1.3
A Bar/ Yellow	-	-	A Bar/ Yellow	-	-
B/Grey	45	PFI 10/P2.2	B/Grey	46	PFI 11/P2.3
B Bar/Pink	-	-	B Bar/Pink	-	-
Z/Blue	3	PFI 9/P2.1	Z/Blue	1	PFI 14/P2.6
Z Bar/Red	-	-	Z Bar/Red	-	-

Figure 18: Chart of Horizontal and Vertical Linear Encoder Connections.

Wheel Torque Sensor				
Wire/Color	**Pin #**	**Signal**	**Wire/Color**	**Pin #**
+Signal/ Black	68	AI 0	+Signal/ Black	68
-Signal/Red	34	AI 8	-Signal/Red	34
+Exc/Grey	-	Power -	+Exc/Grey	-
-Exc/Brown	-	Power +	-Exc/Brown	-
+Sensing/ Purple	-	-	+Sensing/ Purple	-
-Sensing/ Green	-	-	-Sensing/ Green	-
+Teds/Orange	-	-	+Teds/Orange	-
-Teds/Blue	-	-	-Teds/Blue	-

Figure 19: Chart of Wheel Torque Sensor Connections

4. Experimental Setup

4.1 Start and Stop Program

In order to be able to restart the testbed and Mars rover wheel after each test it was decided to make a separate program. This program would allow for the user to start the program, with the carriage motor velocity set to zero. The user would then drag a dial left or right to allow for the carriage velocity to become negative or positive. A picture of the front panel and block diagram of this start and stop program can be seen below in Figures 20 and 21 respectively.

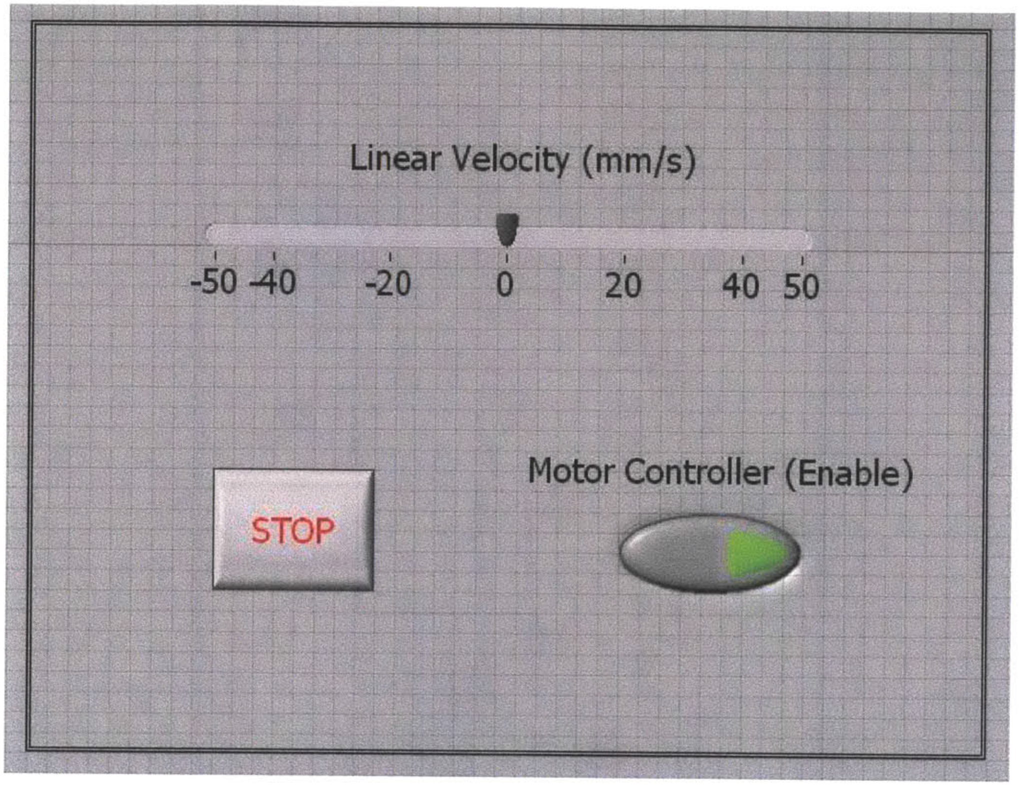


Figure 20: Front Panel of Start and Stop Program.

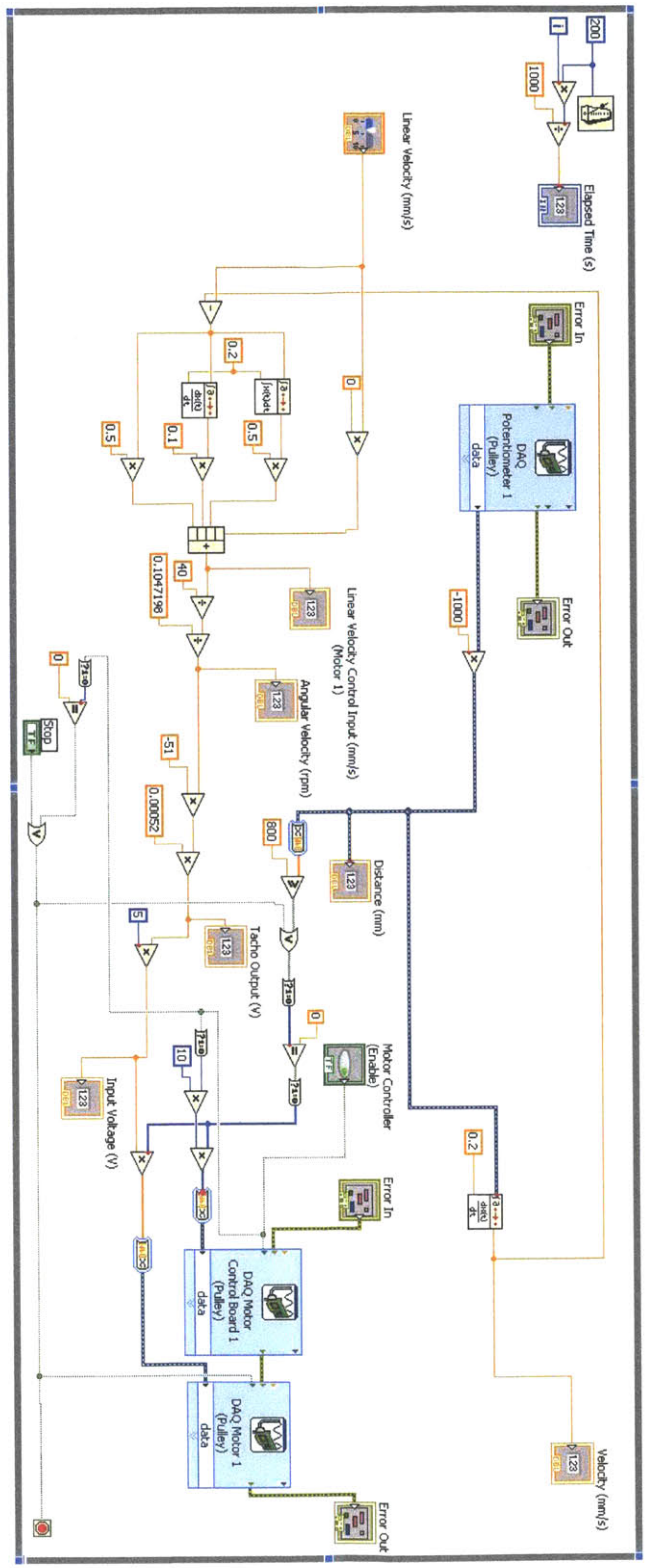


Figure 21: Block Diagram of Start and Stop Program.

It was decided to create a second program for reseting the testbed in order to ensure the safety of the user and the equipment being used. The main read and display program can be stopped in two different ways. It can be stopped by the user or can be stopped by different safety measure put into the program. When the main program is stopped it was found to be safer for the user be able to manually move the carriage back to its starting position. This would ensure that the carriage is not pushed past the testbed restraints and is also fully at its original starting position so that the horizontal linear encoder is reading the correct distance the carriage is moving from the starting end of the testbed. The parts that make up the start and stop program will be explained in the read and display program section since the start and stop program is a less complicated version of the read and display program.

4.2 Read and Display Program

The read and display program is the main LabVIEW program that was used to control and acquire data from the testbed. As stated earlier the LabVIEW program was designed to allow the user to control and view the actions of the testbed. On the display screen all of the different sections are separated by labels.

There is a section called, "Timing and Other Parameters."

This section contains the sampling frequency and amount, and the distance and velocity stop conditions.

There is a section called, "Test Control Parameters." This section contains the settings for the carriage velocity, desired slip, and the motor voltage controller button.

There is a section called, "Readings." This section contains the readings for the distance and velocity the carriage is traveling, the sinkage of the rover wheel, and also the force and torque values from the 6-axis force/torque sensor. This section also contains the setting for the wheel torque.

There is a section called, "6-Axis Sensor Parameters." This section just contains the calibration file that the 6-axis force/torque sensor uses to convert the voltage values to the respective force and torque values.

The next windows graph/display the different real time data occurring. There are windows displaying the 6-axis force/torque data, carriage displacement data, carriage velocity data, wheel torque data, motor velocity data, and 6-axis raw voltage data. These sections can all be seen on the front panel of the read and display program shown below in Figure 22.

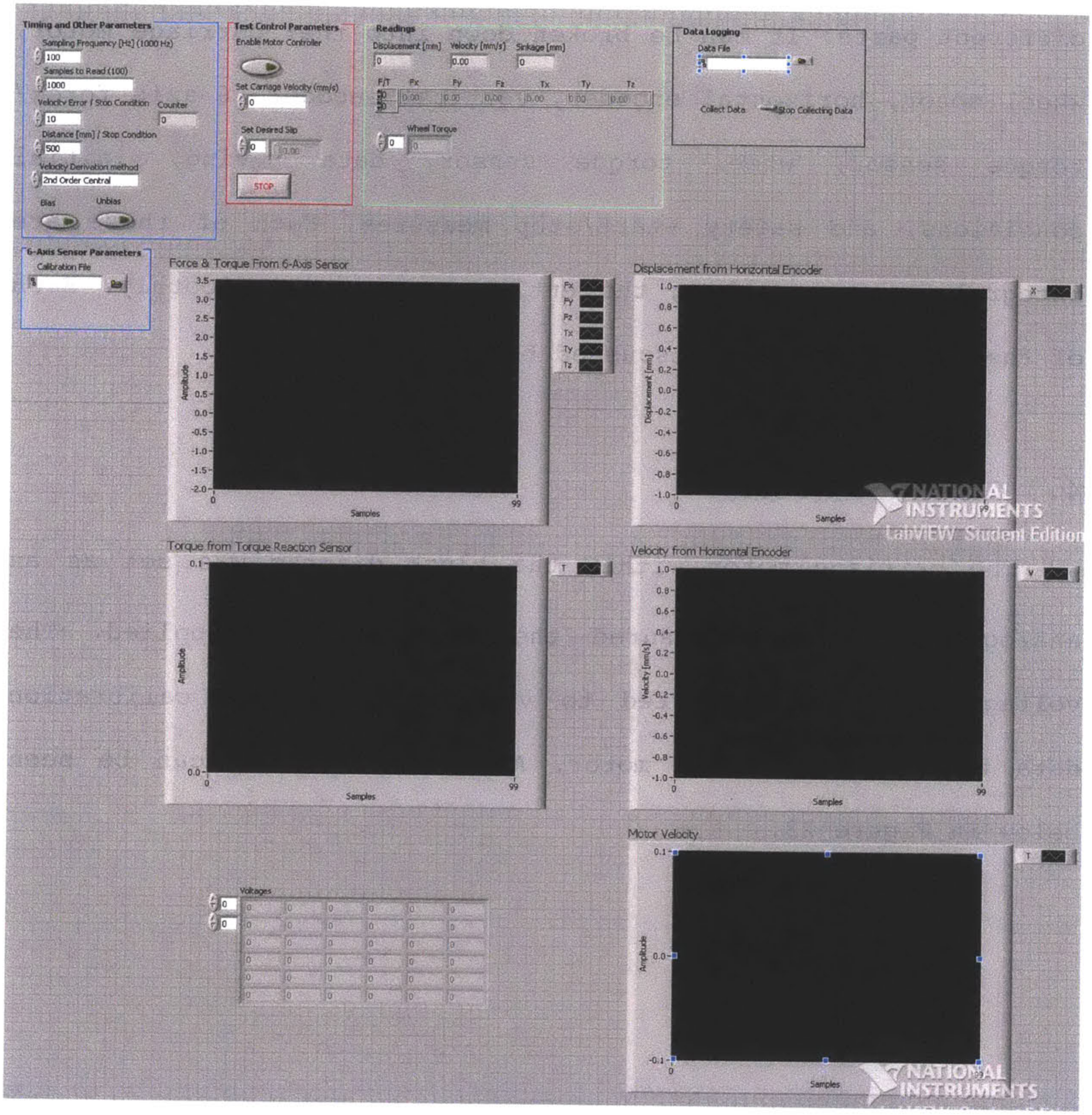


Figure 22: Front Panel of Read and Display Program.

The block diagram allowing for the sections displayed on the front panel to work correctly is very complex. In order to simplify things the block diagram can be broken down into many different parts. It can be broken down into the: carriage motor, wheel motor, horizontal encoder, vertical encoder, 6-axis force/ torque sensor, wheel torque sensor, data saving, initial conditions, and safety start/stop measures. Each of these are integral parts in making the entire program run smoothly. Each of these parts will be discussed below.

4.3 Carriage Motor

The carriage motor within the block diagram was set as an analog output that measured the voltage being applied. The voltage was then converted to velocity using the calibration data that came with the motor. A picture of this can be seen below in Figure 23.

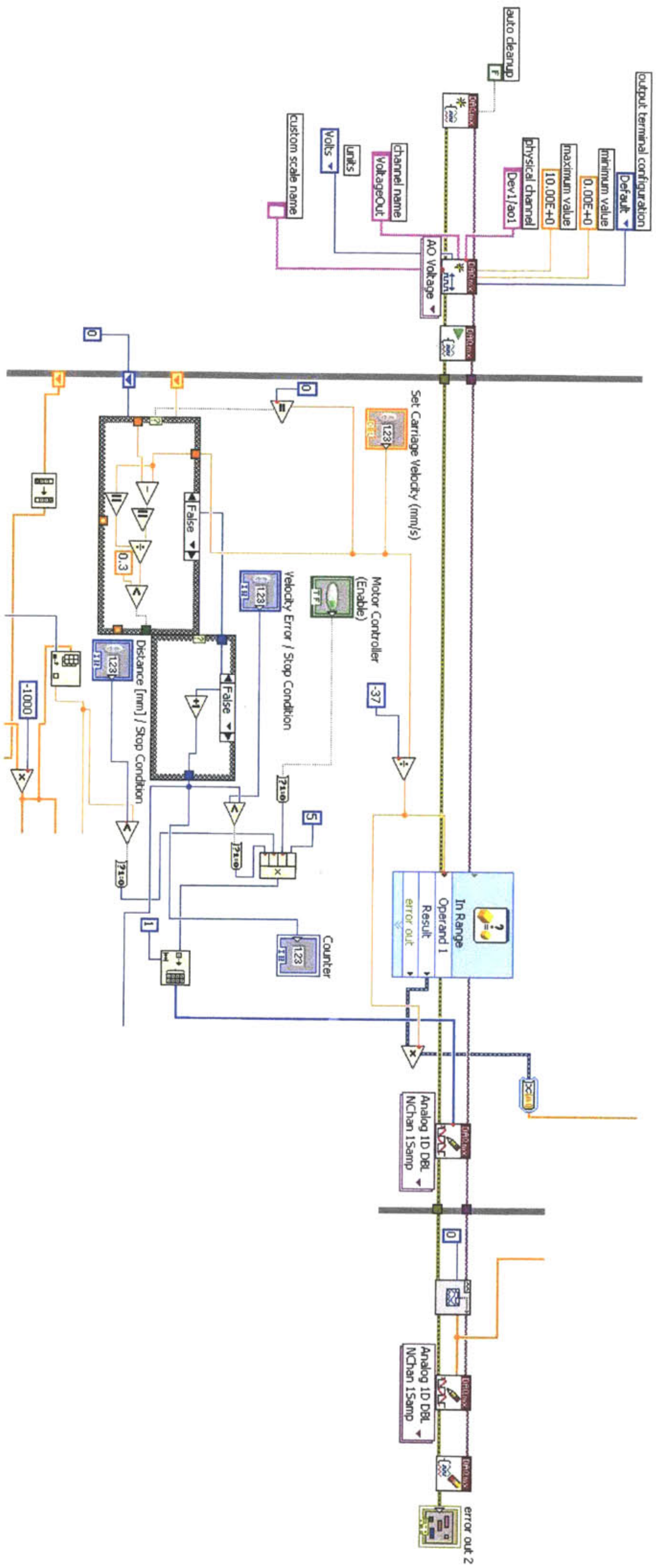


Figure 23: Picture of Carriage Motor Components.

4.4 Wheel Motor

The wheel motor within the block diagram was set as an analog output that measured the voltage being applied. The voltage was then converted to velocity using the calibration data that came with the motor. A picture of this can be seen below in Figure 24.

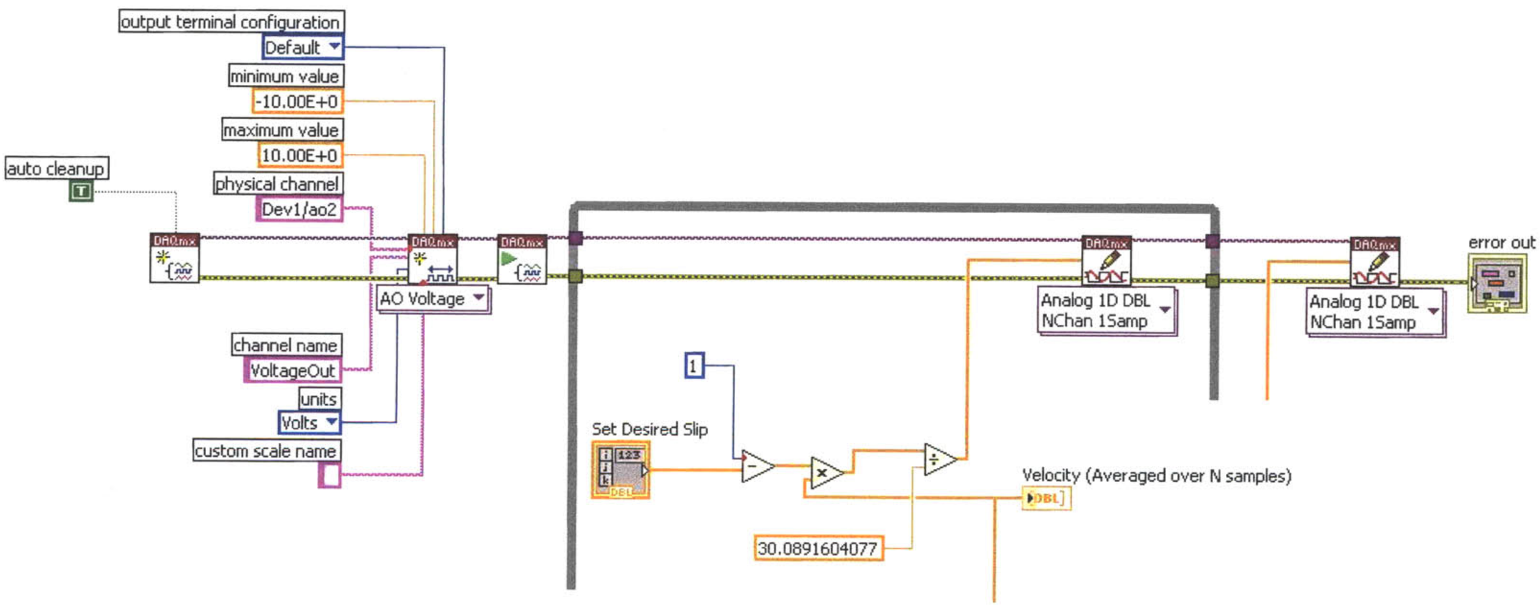


Figure 24: Picture Wheel Motor Components.

4.5 Horizontal Encoder

The horizontal encoder within the block diagram was set as linear counter input. The encoder encoded linear position into a digital signal that was decoded into displacement using calibration data that came with the encoder. A picture of this can be seen below in Figure 25.

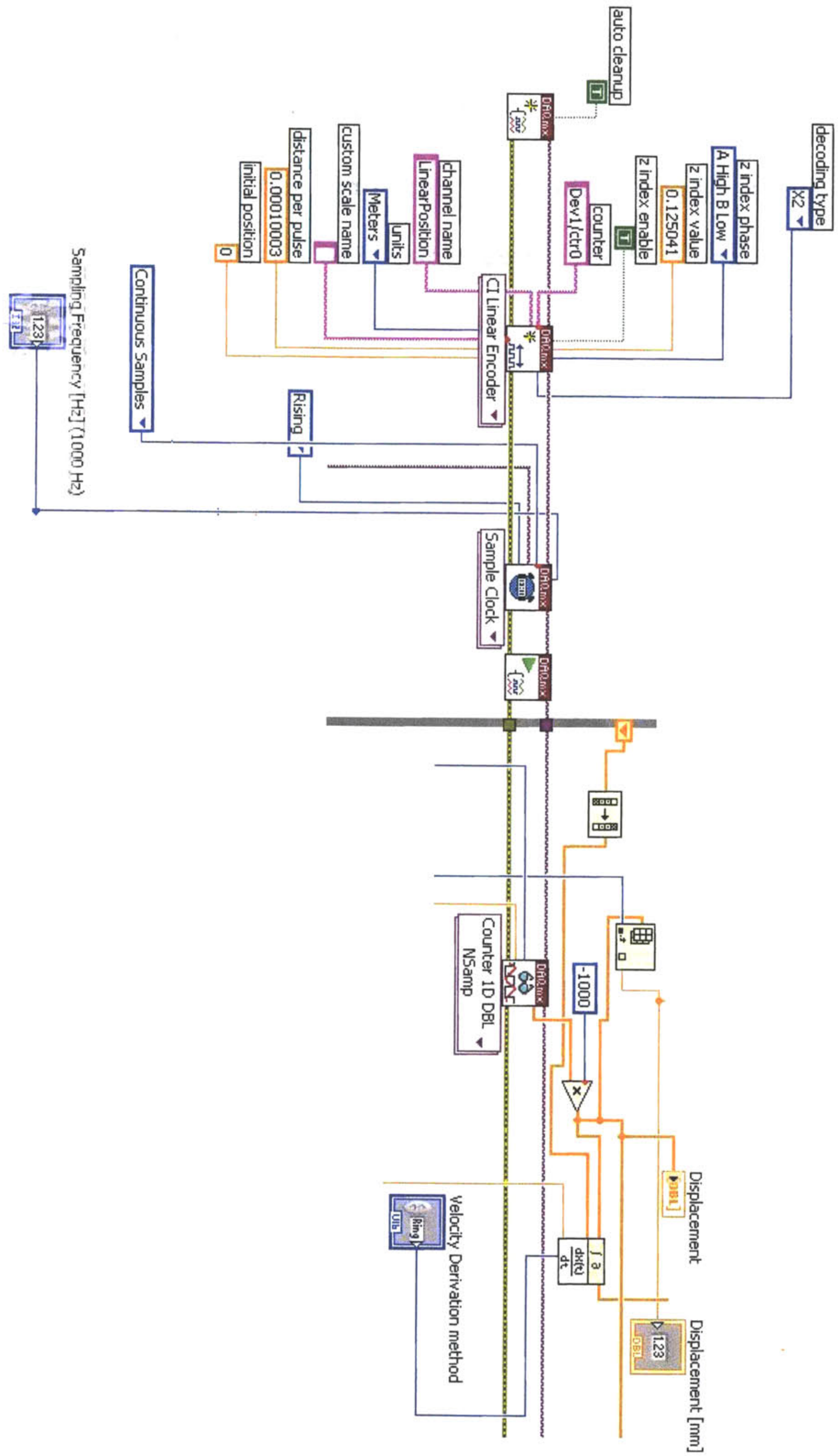


Figure 25: Picture of Horizontal Encoder Components.

4.6 Vertical Encoder

The vertical encoder within the block diagram was set as linear counter input. The encoder encoded vertical position into a digital signal that was decoded into displacement using calibration data that came with the encoder. A picture of this can be seen below in Figure 26.

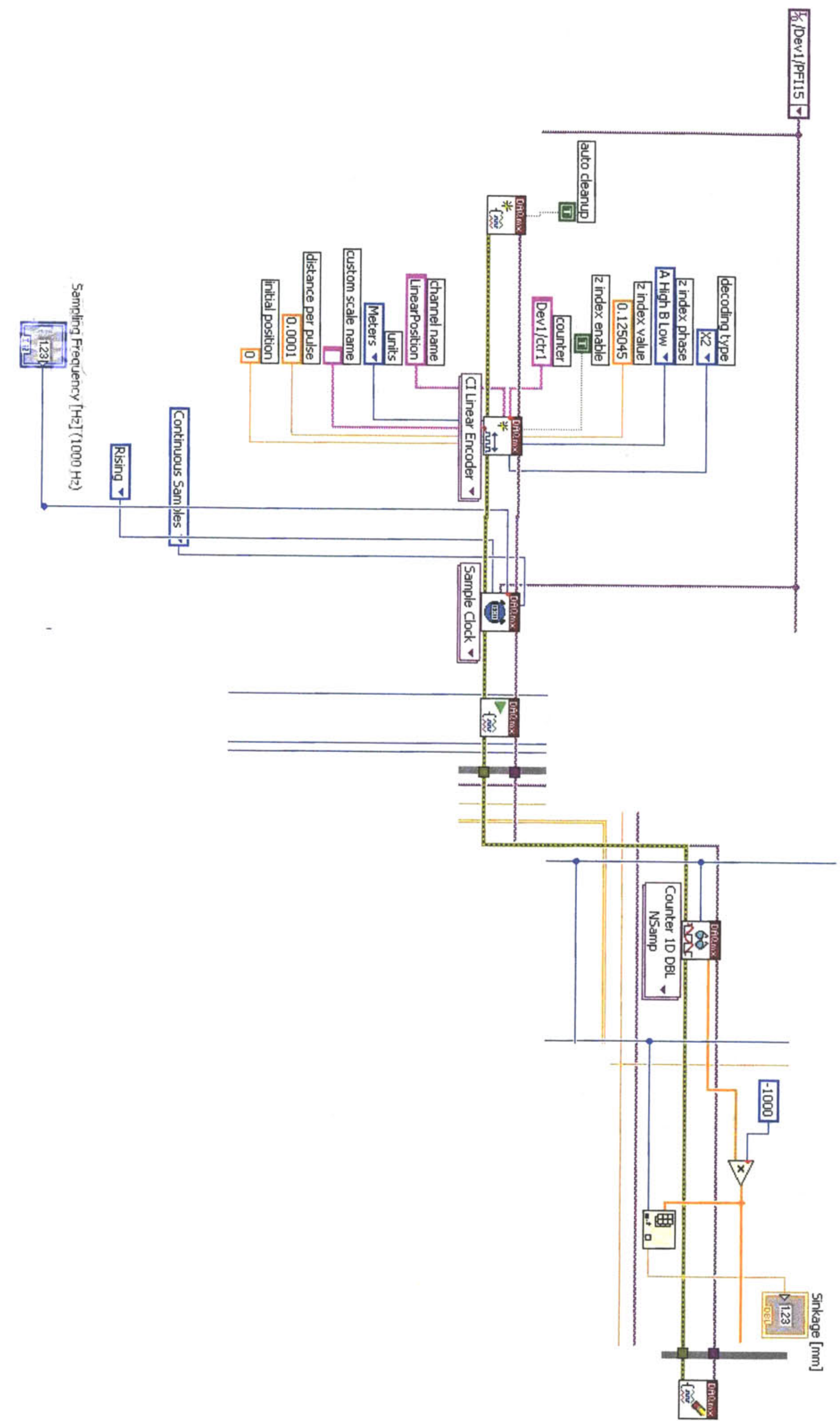


Figure 26: Picture of Vertical Encoder Components.

4.7 6-Axis Force/Torque Sensor

As stated before the 6-axis force/torque sensor came with its own software. It had its own LabVIEW program that recorded and displayed the forces and torques. This program was broken down and pieces were taken and put into the read and display program. The different pieces taken were modified and added onto in order to get the 6-axis force/torque sensor to read and display the forces and torques in sync with the rest of the sensors.

The 6-axis force/torque sensor was set as an analog input that returned voltage. The calibration file that came with the 6-axis force/torque sensor software was used in order to covert the voltages to the respective forces and torques. The 3 forces and torques were separated into single arrays then bundled together in order to be displayed neatly in the table format when being saved to a different file. The important force components used for the testbed were the force components in the X and Z directions. This can be seen below in Figures 27, 28, 29, and 30.

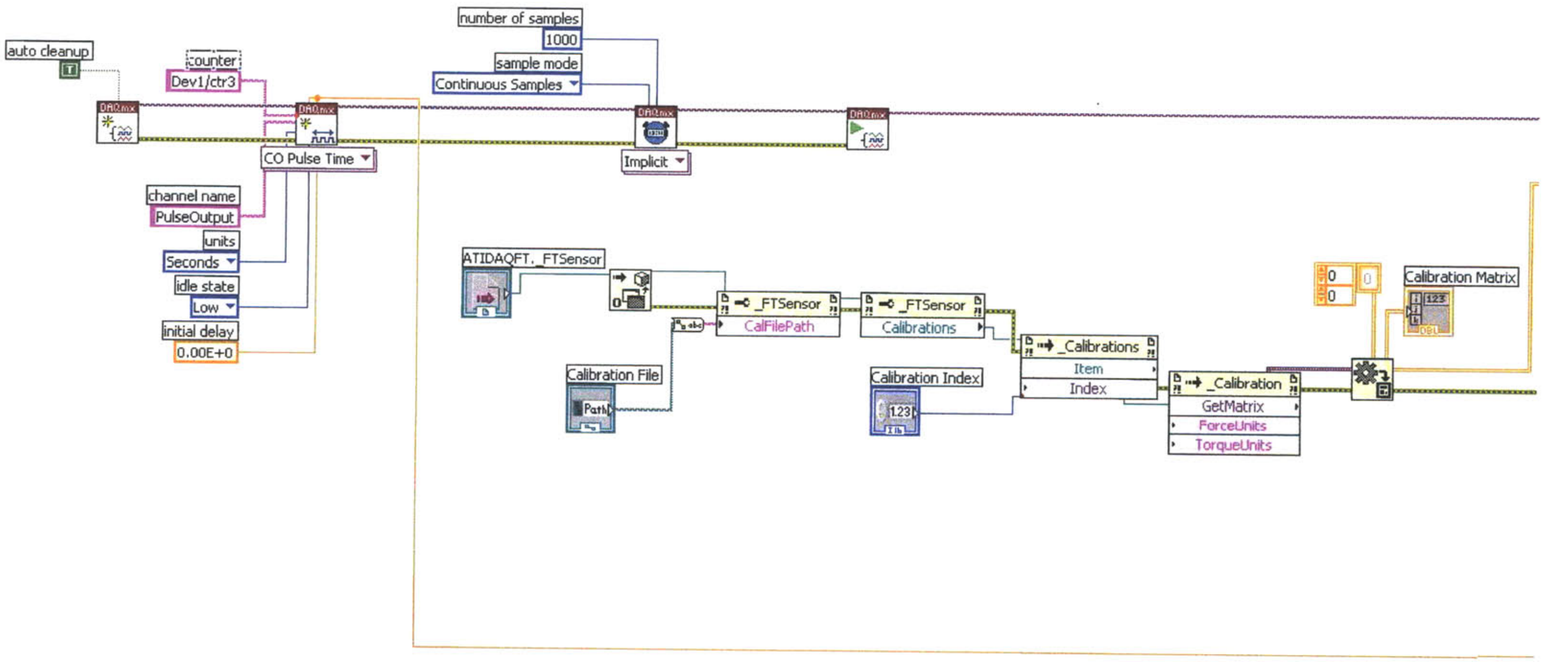


Figure 27: Picture 1 of 6-Axis Force/Torque Sensor Components.

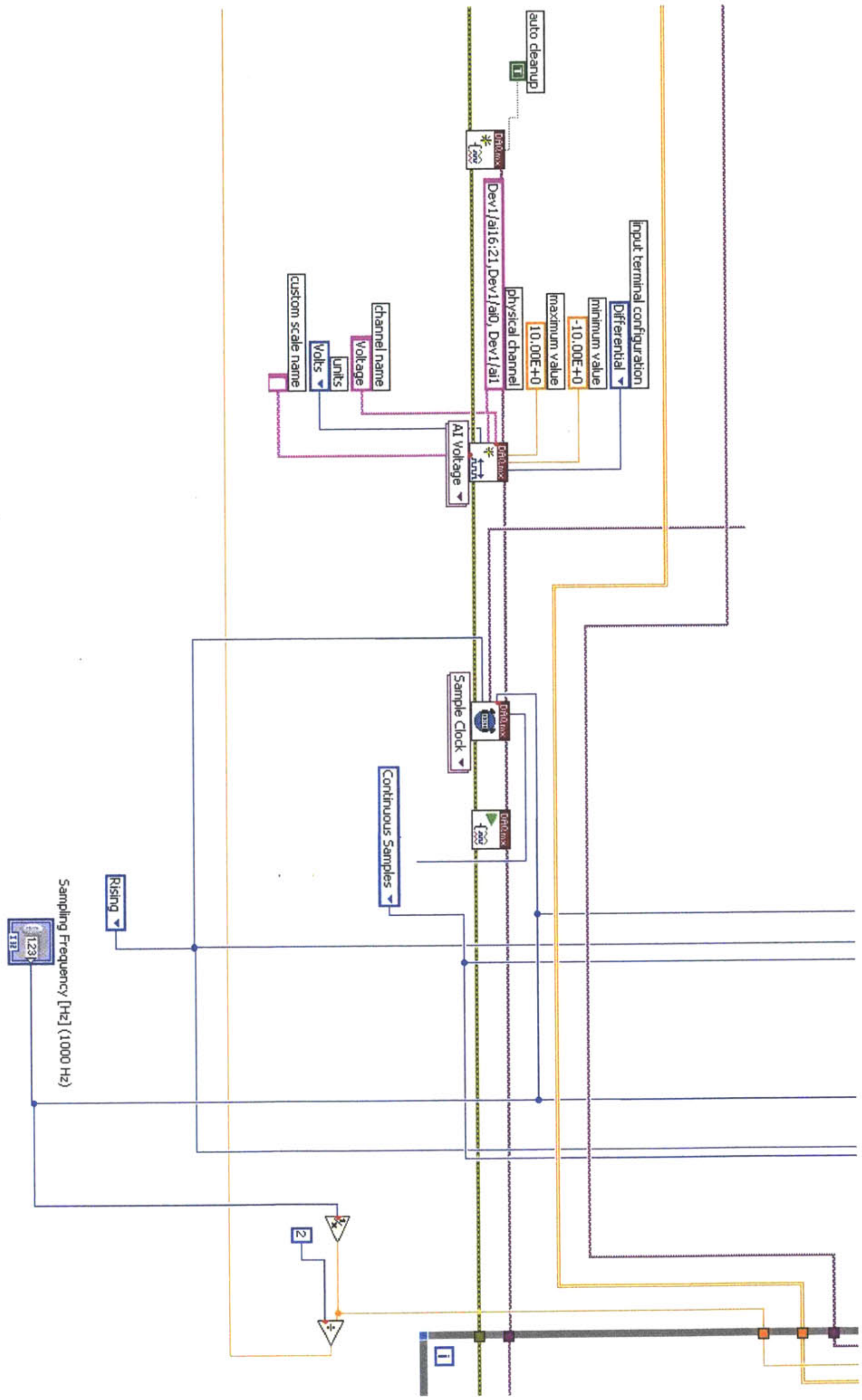


Figure 28: Picture 2 of 6-Axis Force/Torque Sensor Components.

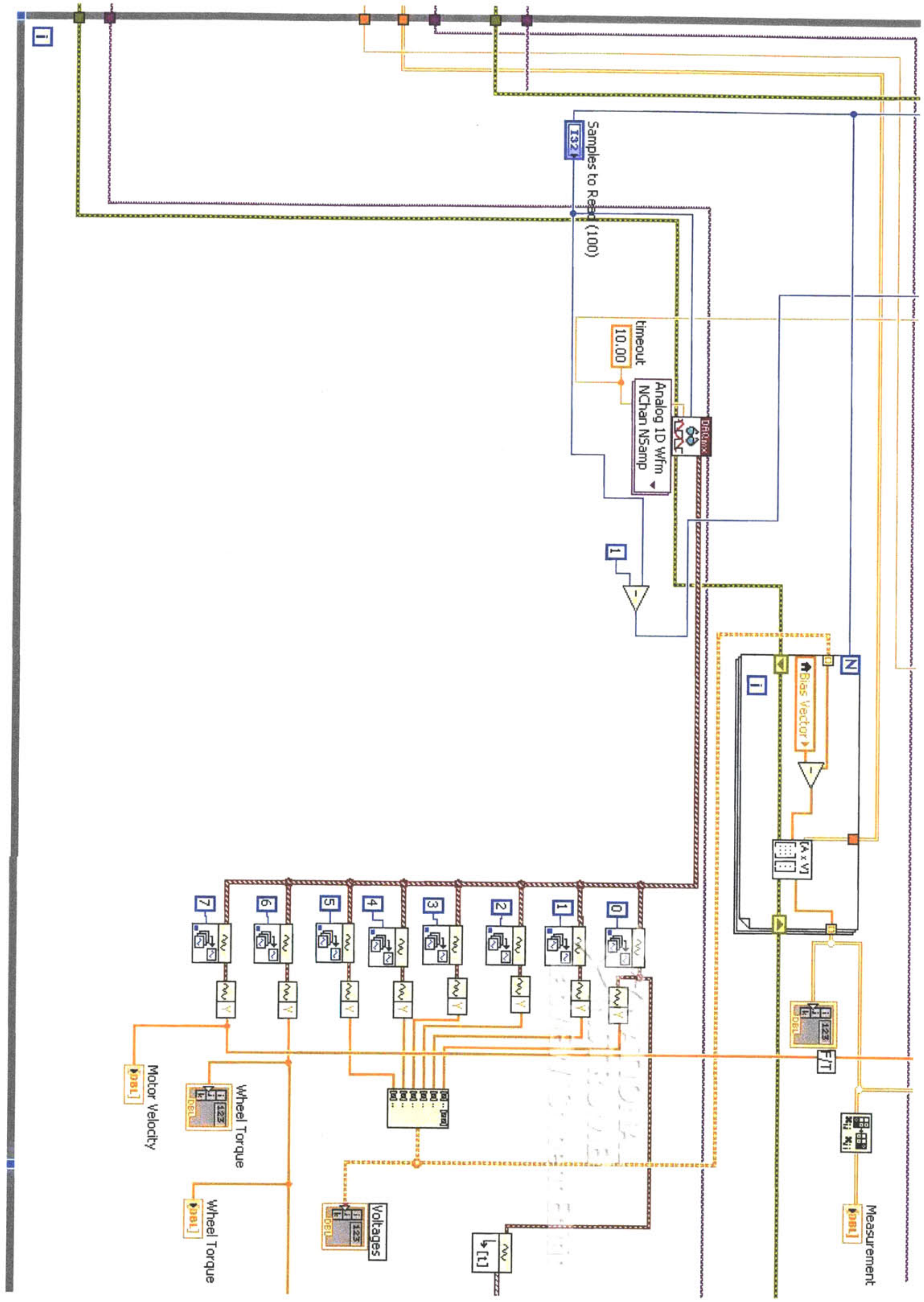


Figure 29: Picture 3 of 6-Axis Force/Torque Sensor Components.

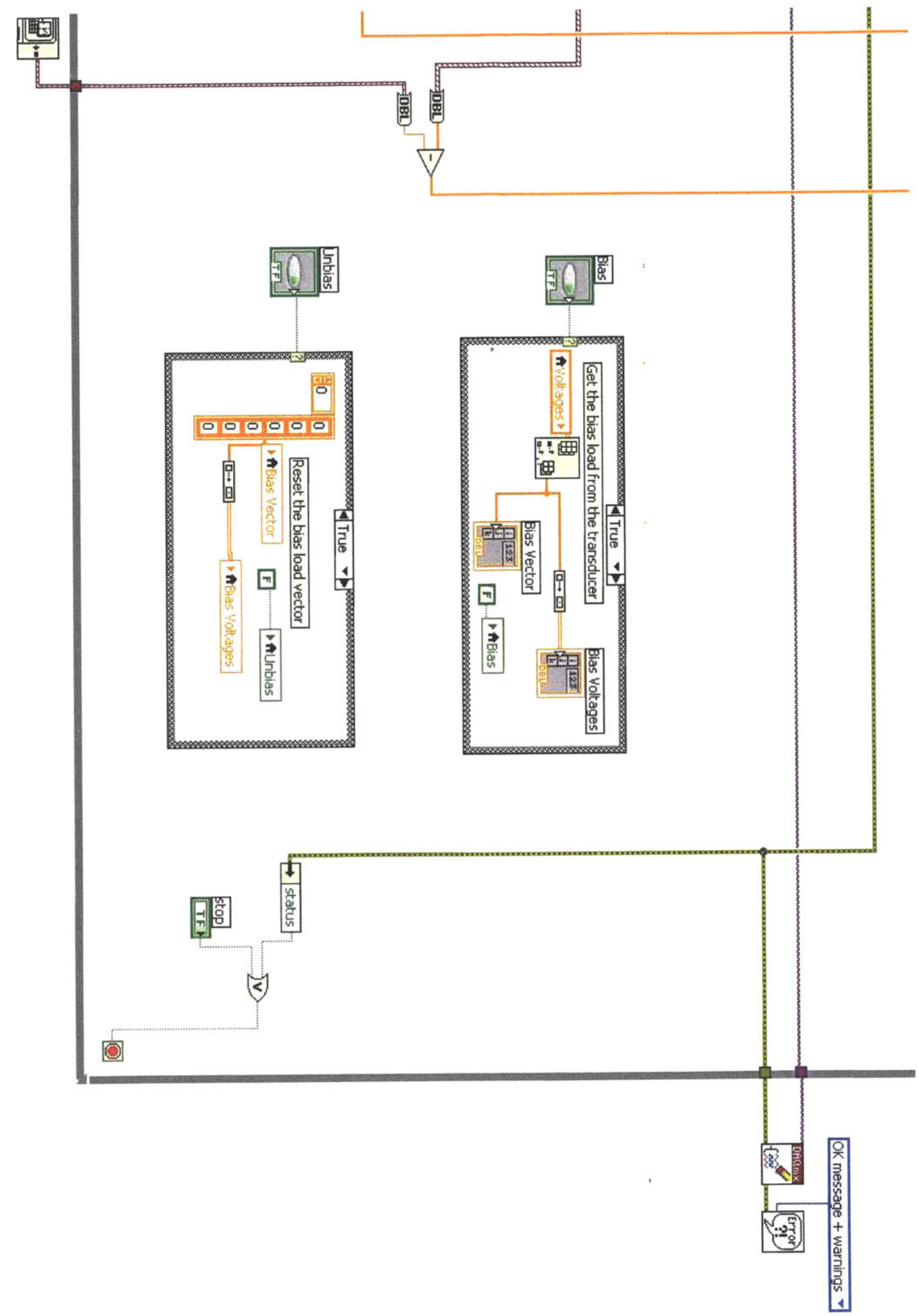


Figure 30: Picture 4 of 6-Axis Force/Torque Sensor Components.

4.8 Wheel Torque Sensor

The wheel torque sensor within the block diagram wast set as an analog output that returned voltage. The voltage was then converted to velocity using the calibration data that came with the torque sensor. A picture of this can be seen below in Figure 31.

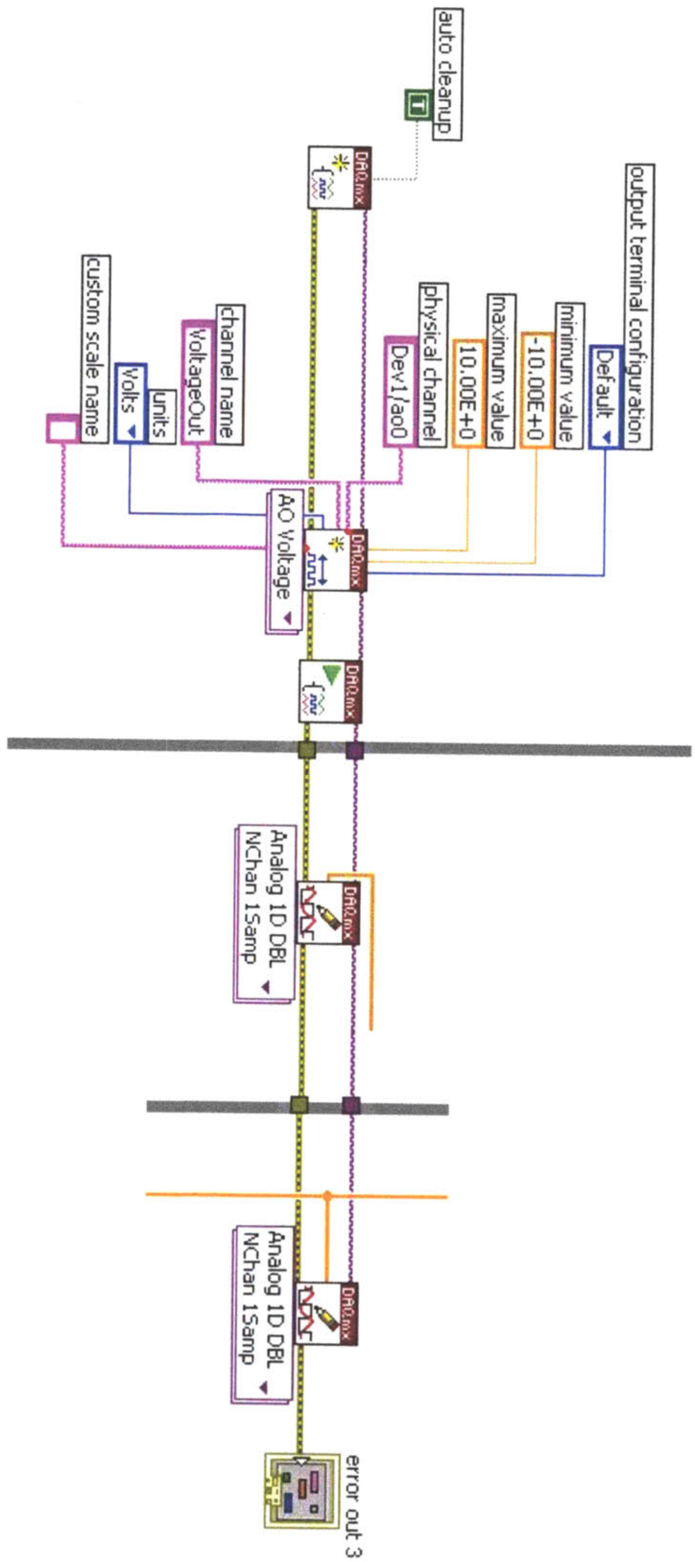


Figure 31: Picture of Wheel Torque Sensor Components.

4.9 Data Saving

As the program was being run, the data being displayed was being stored in an array. After the program was stopped, the data in the array was saved onto a separate file. The data being saved was, the time elapsed, the distance the carriage traveled, the velocity the carriage traveled at, the 3 forces and 3 torques exerted on the wheel that was recorded by the 6-axis sensor, and the torque applied to the wheel that was recorded by the torque sensor.

The carriage motor data, wheel torque data, and the 6-axis force/torque data were all put inside the analog voltage input block. The data then was split into single arrays for each sets of data. All of the 6 sets of data were then combined into one big array. From there the array was put into a table format. The user was able to set when data was being recorded when the program was being run by a switch called, "Collect Data." The user was also able to set where the data recorded was being saved to. A picture of these data saving components is shown below in Figures 32, 33, and 34.

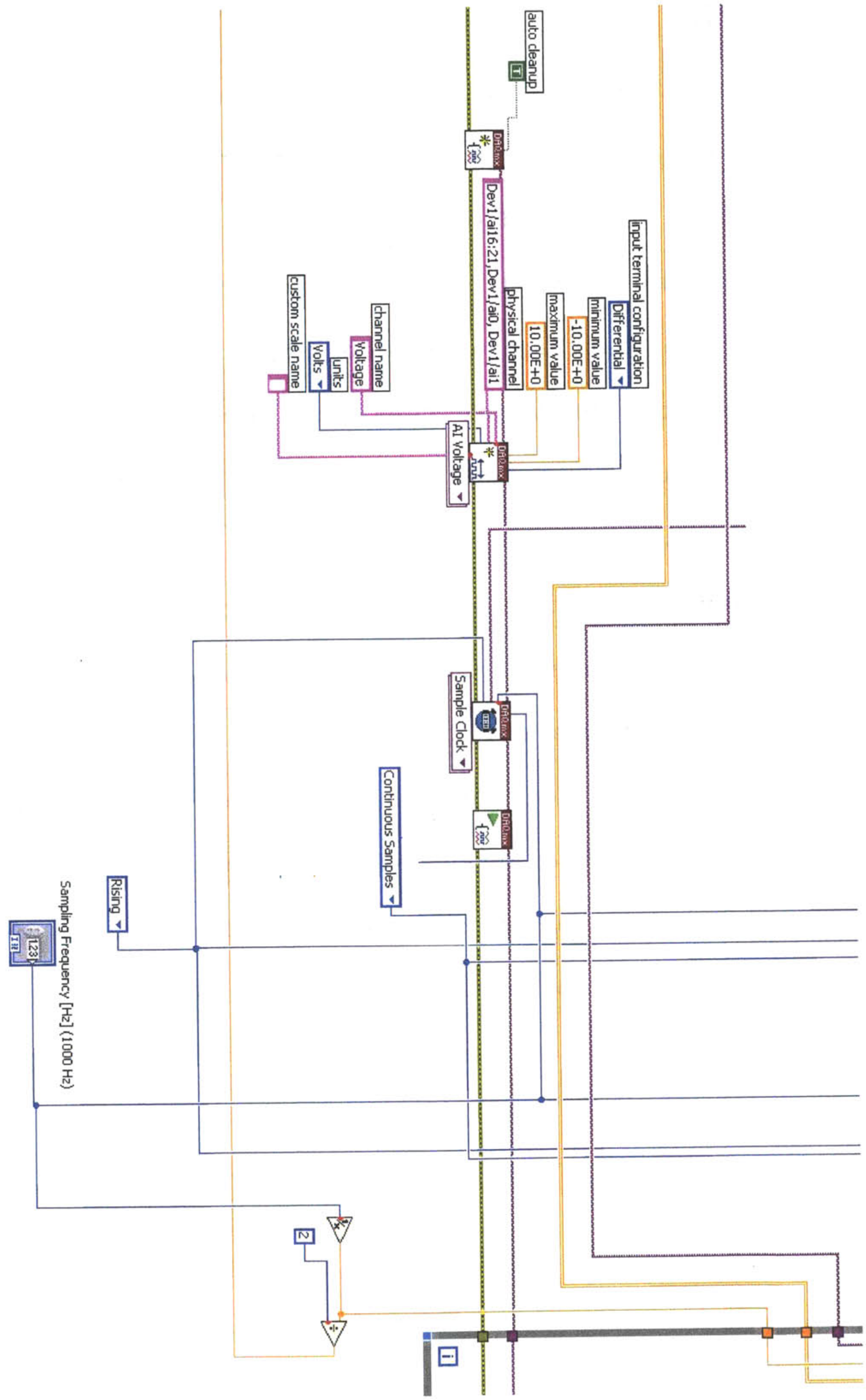


Figure 32: Picture 1 of Data Saving Components in Block Diagram.

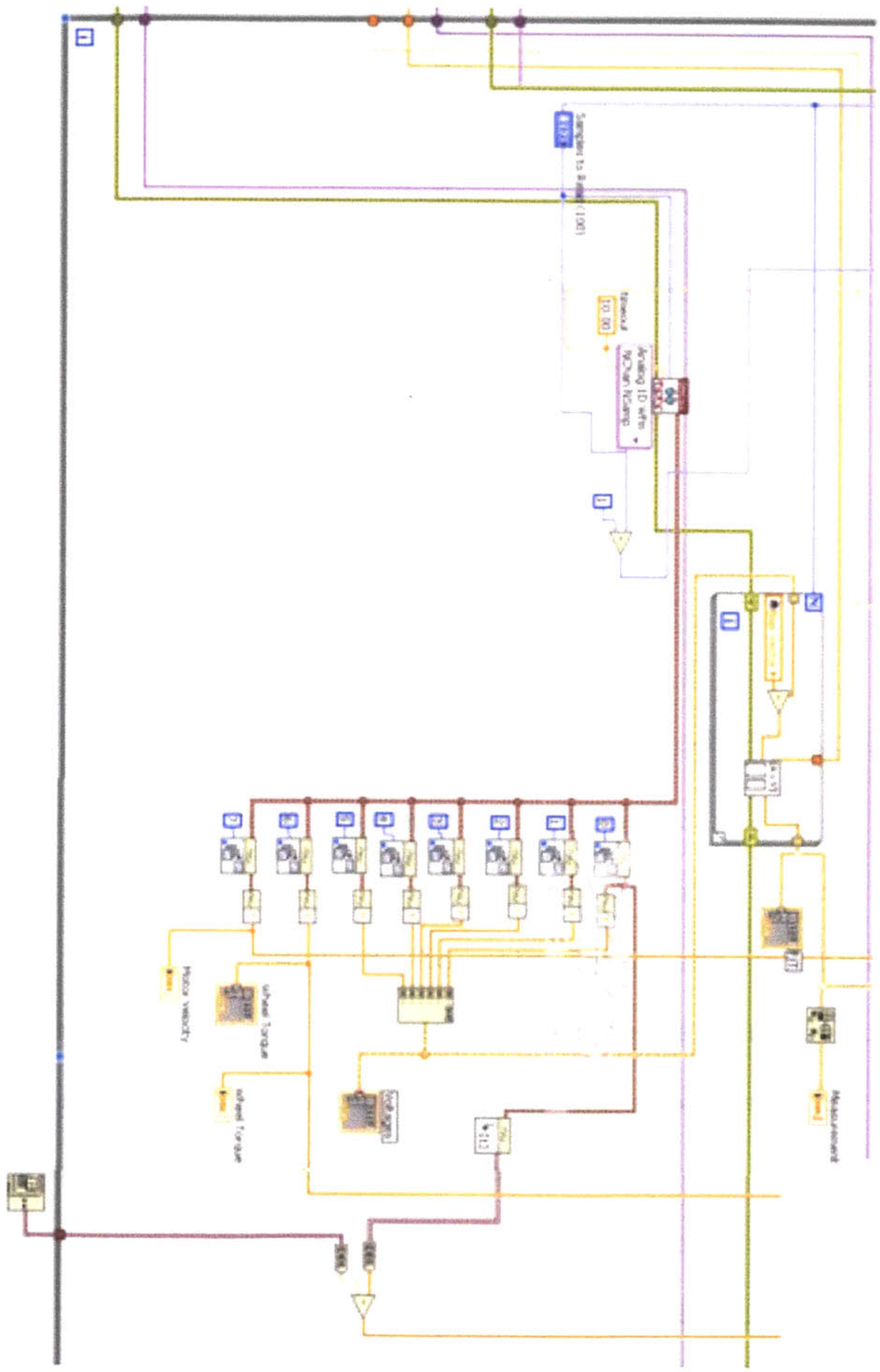


Figure 33: Picture 2 of Data Saving Components in Block Diagram.

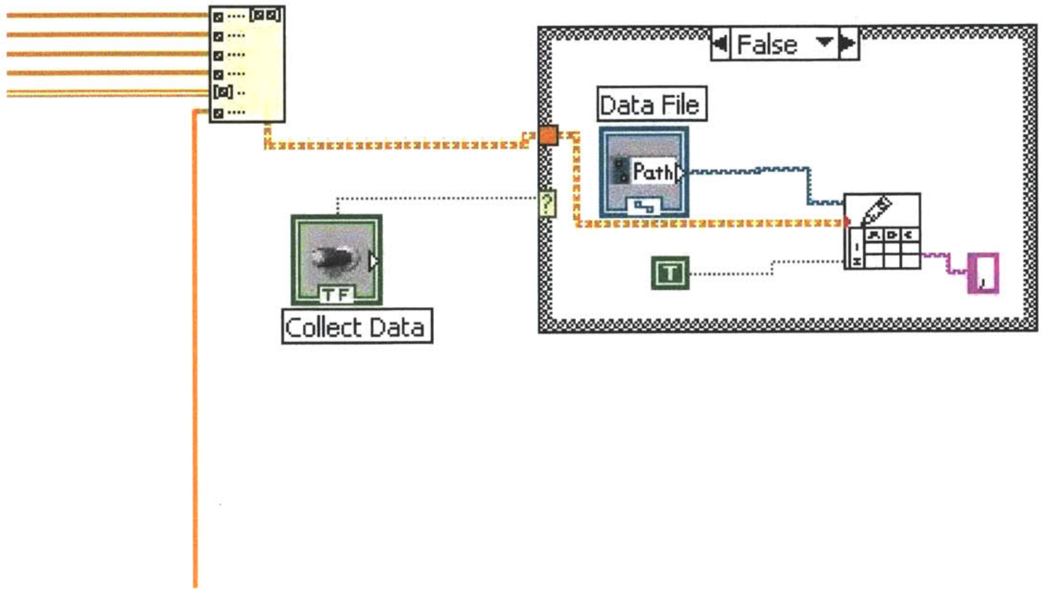


Figure 34: Picture 3 of Data Saving Components in Block Diagram.

4.10 Initial/Safety Conditions

There were 6 initial conditions set, for when the program was run each time. These conditions were set for both safety measures and for the simplicity of the user.

The first initial condition was setting the carriage velocity to zero. This was done in case the program is stopped before the carriage velocity is set to zero. This will make sure the carriage doesn't start moving when the program is started.

The second initial condition was setting the motor controller to false. The motor controller switch is what allows voltage from the DC power supply to be sent to the motor. Setting the motor controller to false is another safety measure to ensure that the carriage doesn't start moving when the program is started.

The third initial condition was setting the amount of samples for the program to read when it is plotting the 6-axis force/torque data. Setting the samples to read means setting the size, in samples, of each chuck of data that is read from the 6-axis force/torque data. This was set to 100 as a reasonable number for the user to use in case they don't know how many samples they want to read.

The fourth initial condition set the sampling frequency. This was set to 100 Hz also as a reasonable number for the user to use in case they don't know what they want to use as the sampling frequency.

The fifth initial condition set the velocity error stop condition. This condition is for safety purposes. If the carriage input velocity is off from the actual velocity by a certain amount, the motor will stop. The error was initial set to 10 as a reasonable number to use. This error value was good because if the horizontal carriage reached the end of the test bed and the user had not stopped or reversed the carriage, the carriage would stop from this condition in about 3 seconds.

The sixth initial condition set the distance stop condition.

If the carriage travels a certain distance the motor will be stopped. This was to ensure that the user doesn't allow the carriage to hit the end of the testbed. This was set to 500mm, a safe distance from the end of the testbed.

A picture of the 6 initial conditions and the code behind them from the block diagram of the read and display program in LabVIEW is shown below in Figures 35 and 36 respectively.

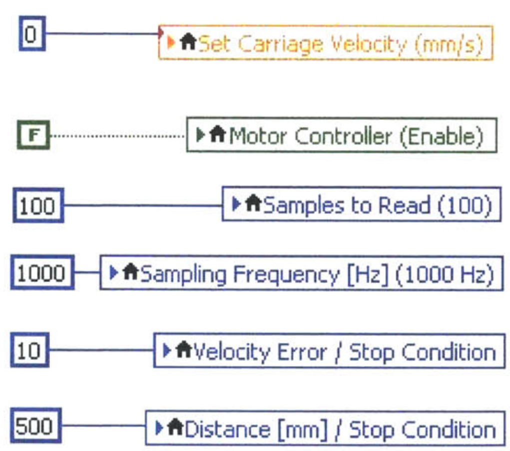


Figure 35: Picture of Initial/Safety Conditions from Block Diagram

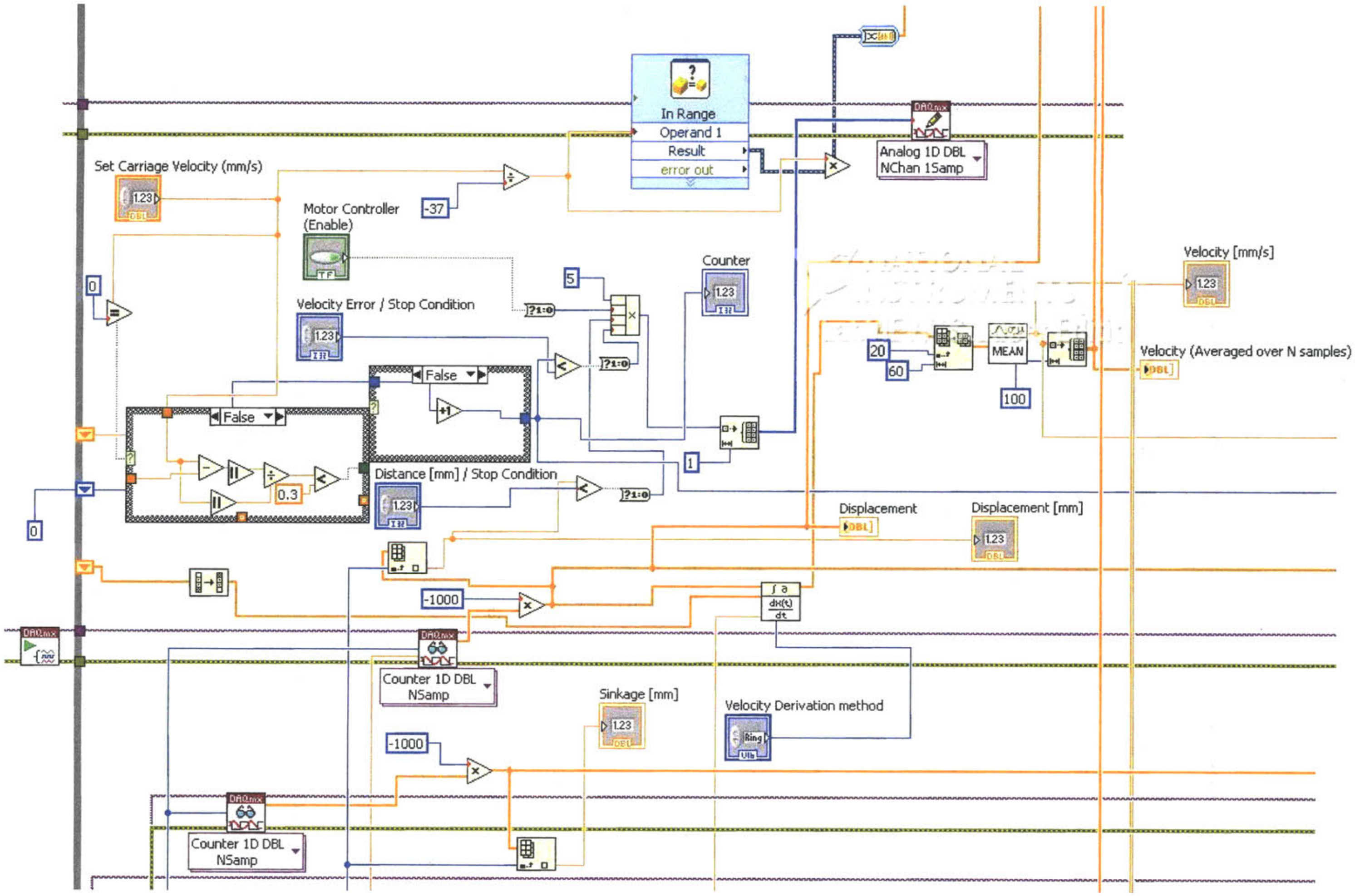


Figure 36: Picture of Initial/Safety Conditions Components.

5. Conclusion

As stated before, the objectives of this thesis were to integrate a testbed enabling the examination of the interaction of Mars rover wheels on a mars soil simulant and to create a program to control the testbed. The testbed itself was extremely complex, consisting of 2 motors, 2 linear encoders, a 6-axis force/torque sensor, and a torque sensor. As previously stated these were the integral components that were integrated into the testbed and controlled using a program created in LabVIEW.

The LabVIEW program created had components of each of the motors and sensors listed above. These components were more specifically known as: the carriage motor, the wheel motor, the 6-axis force/torque sensor, and the wheel torque sensor. Each of these components were integrated into LabVIEW using calibration data that came with each individual motor or sensor.

The most important user controlled features within the LabVIEW program consisted of the user being able to input a desired carriage velocity, a desired slip value between the wheel and the soil, and a location where to save the data recorded,

There were also multiple initial and safety conditions set within the LabVIEW program that was to ensure the safety of the user and testbed. There was also a second LabVIEW program created in order to reset the testbed carriage in its initial start position at the end of each test to ensure consistency.

Future work on this project would be completely assembling the entire testbed to its final state and adjusting certain constants in the LabVIEW program based on the final testbed parameters. After the LabVIEW program was adjusted, tests could be run to examine the interaction of the Mars rover wheels on the mars soils simulant. From these tests, the LabVIEW program's complete accuracy and precision would be checked.

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