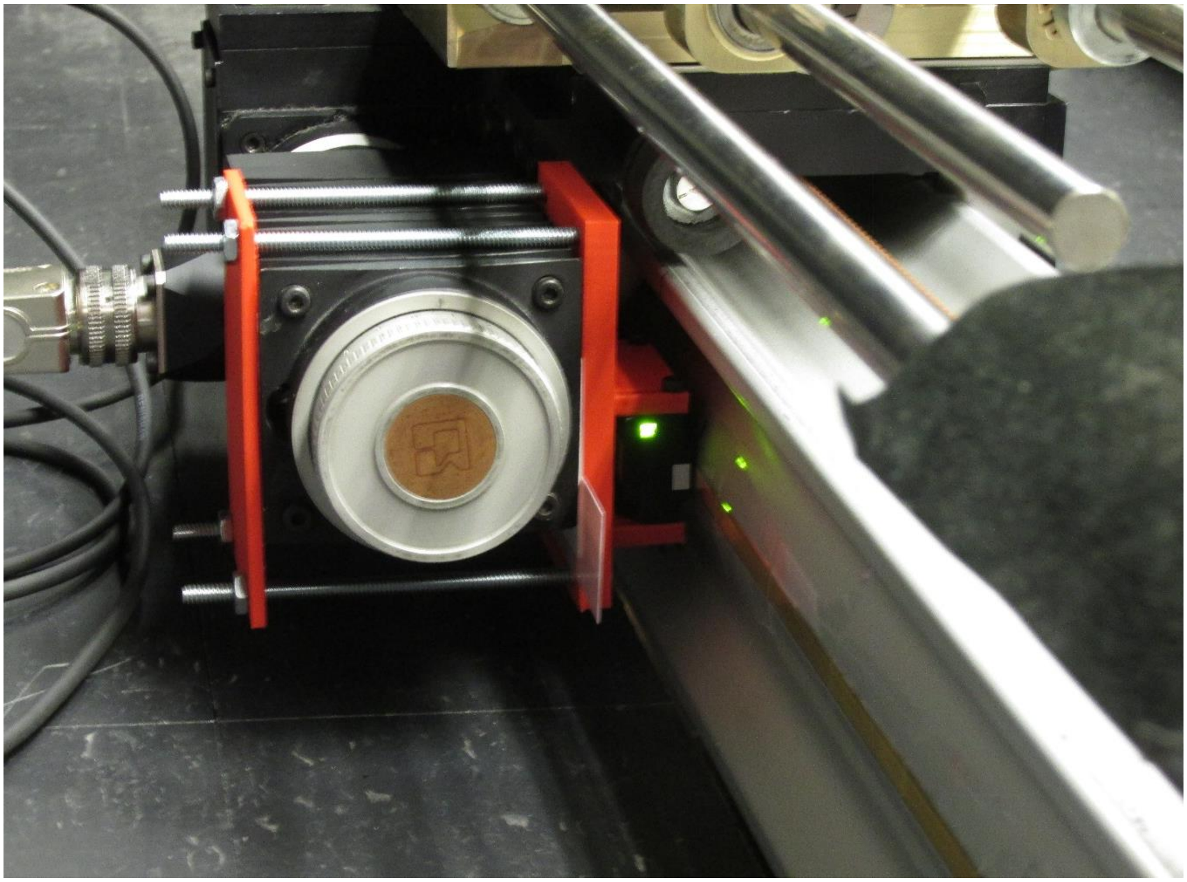
Quadrature Optical Linear Encoder Measurement System Development for Photometry Bench Modification



The Boeing Company Internship Final Report

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Abstract:

A quadrature optical linear encoder was analyzed to evaluate the feasibility of replacing the current working laser interferometer on the photometry bench located at the South Park Metrology Photometry Lab. The goal was to communicate with and install the encoder on the bench in order to compare its distance measurements to those of the laser interferometer. Communication to the encoder was made possible first with an Arduino Uno microcontroller, and finally with a National Instruments DAQ utilizing LabVIEW. A mounting fixture for the encoder was also developed, and a prototype was 3D printed for installation during proof of concept testing. The conclusion of these tests showed the encoder is capable of close bidirectional repeatability, but further tests need to be completed to remove irregularities which can potentially cause error outside of the required tolerances.

Introduction:

The photometry bench is a device used to determine the accuracy of various light property measuring devices. The bench is approximately 18 feet long. Three motor driven carriages ride along an X95 aluminum profile (See Figure 1). Carriage 1 is used to mount and position the photometry device under test. Carriages 2 and 3 mount to baffles which block out unwanted light during tests. A calibrated lamp is used as the light source, and is placed at one end of the bench. A calibrated laser interferometer is placed at the other end and measures the position of Carriage 1. As the device under test moves on the carriage to various distances on the bench, there exists a corresponding measurement: color temperature, candescence, foot-candles, etc. The position of the device under test is critical for determining whether photometry measurement equipment is within specified tolerances. This project aimed to replace the laser interferometer with a new lower cost system, while still maintaining the required positioning accuracy.

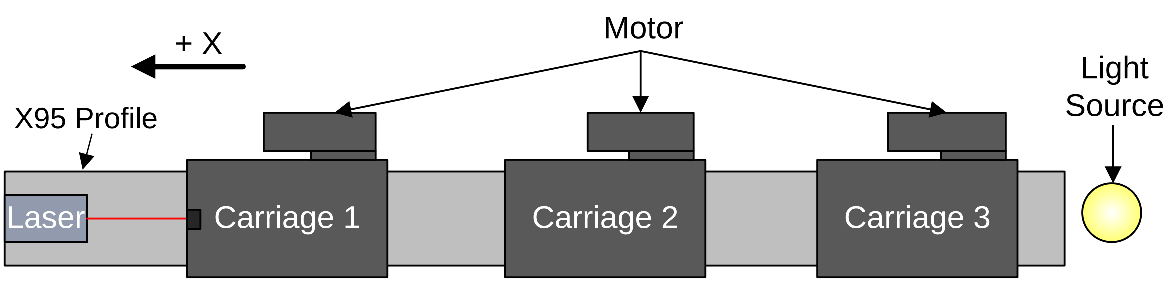


Figure 1 - Top Down view of Current Photometry Bench

A quadrature optical linear encoder was chosen for its precision distance measuring capabilities. It works by using optical principles. A marked scale of a certain pitch is laid down. A readhead, containing an infra-red LED, shines a light onto the scale at an angle. The scale reflects the light back to the readhead, and passes through an index grating to a photo detector. This grating filters the signal and produces a sinusoidal signal, which is then converted to a square wave, based on the location of the readhead on the scale. [1] The scale contains two channels, A and B (See Figure 2). These channels produce two digital square waves 90° out of phase (quadrature). These signals can then be used to determine the direction the encoder is traveling (+ x-axis or – x-axis).

Requirements for the new encoder system included repeatability, accuracy to within ±1 mm, bidirectional counting in the +x and – x directions, a reset feature, and easy to use interface.

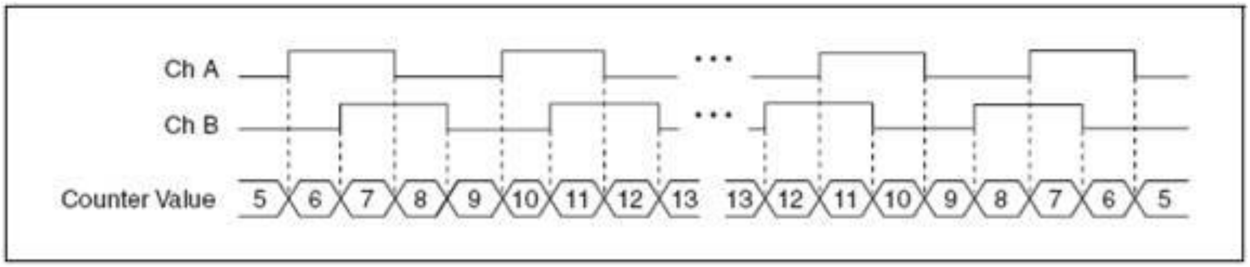


Figure 2 - Encoder square waves 90° out of phase and quadrature encoding. [2]

Procedures:

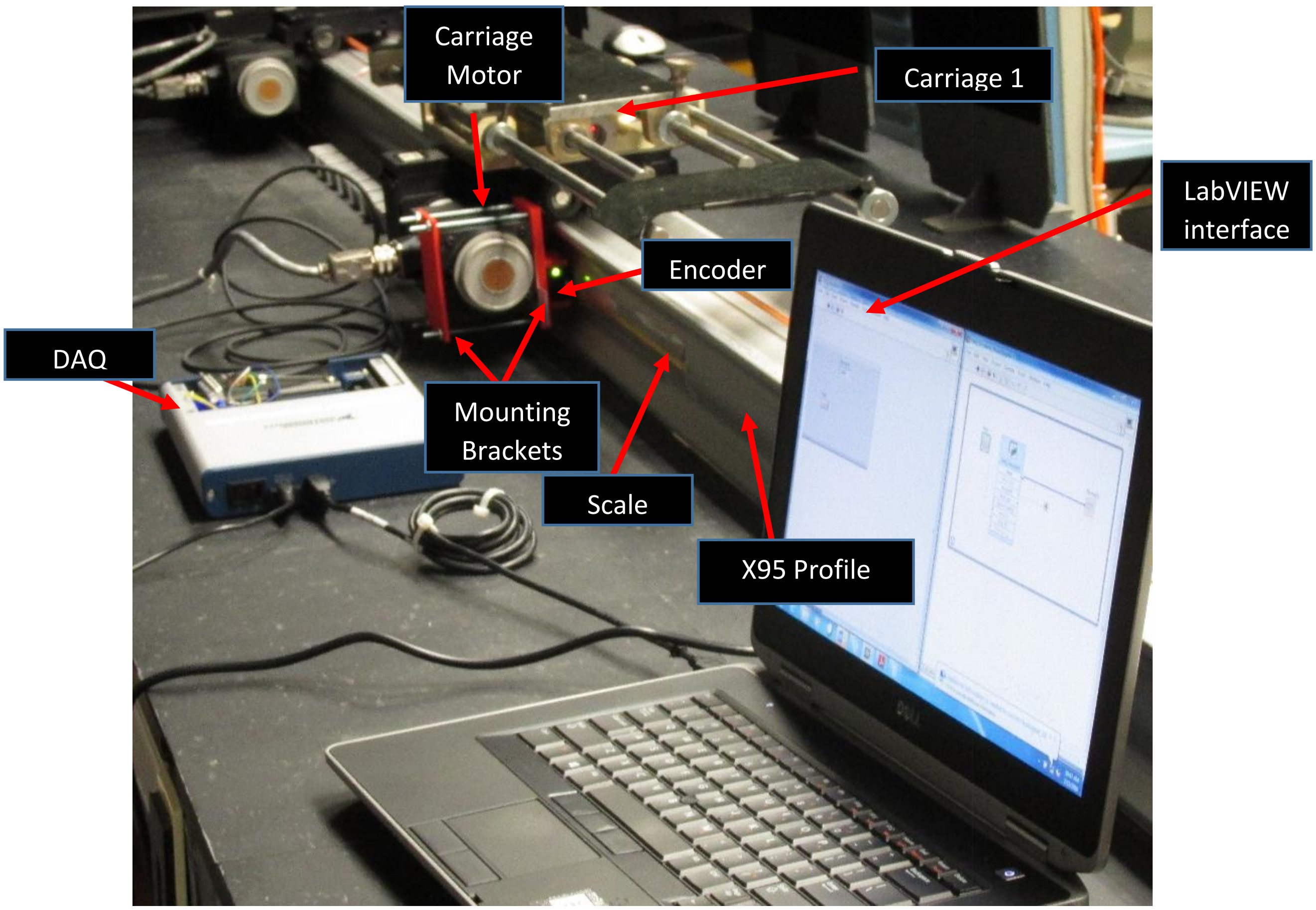
Arduino Uno Microcontroller Setup:

Laser Comparison: This test was performed to validate that the Arduino could communicate with the encoder. First, the 15 pin ribbon cable was stripped and the exposed wires soldered. Next, the corresponding power, ground, A channel, and B channel pins were wired to the Arduino board. The LCD display and push button were wired to the Arduino as well. The ribbon cable was then connected to the encoder's 15 pin cable. A calibrated laser was used for comparison. The encoder was mounded to an x-y stage and a small ~1 inch scale was mounted to a flat plate underneath the encoder. Next, the laser beam was referenced to the encoder. The encoder was then translated along the scale. The counted distance could then be noted on the serial port and compared to that of the laser and LCD display.

Caliper Comparison: This test was to validate the Arduino could operate at the required maximum speed of 0.707 ft/s. Next, the corresponding power, ground, A channel, and B channel pins were wired to the Arduino board. The LCD display and push button were wired to the Arduino as well. The ribbon cable was then connected to the encoder's 15 pin cable. Next, a 12 inch sample scale was mounted to a flat plate. A digital caliper was used to approximately measure 244 mm and this distance was indicated on the flat plate. The encoder was then placed on the spacer provided by Renishaw and aligned on the scale. Next, the Arduino was connected to the computer via USB, and the code was uploaded to the board. The encoder was hand driven along the scale 244 mm. The counted distance could then be noted on the serial port and LCD display.

USB-6366 DAQ Setup:

First, the photometry bench laser was turned on and allowed to warm up. Next, the centerline of the X95 aluminum profile was found using digital calipers and a straight edge. The centerline was marked and a 1 foot sample of the scale was overlaid on the profile and secured with clear tape. *Renishaw provided a one foot sample, so this is what was used. It prevented having to cut any of the existing scale for testing purposed.* Next, the head of the optical encoder cable was removed so the wires were exposed and the corresponding power, ground, A channel, and B channel pins were wired to the USB-6366 DAQ. The DAQ was then connected to a power supply and the USB port to a laptop. The encoder was then mounted to carriage 1 and aligned with the scale. An oscilloscope was also connected to the DAQ to monitor the signal during testing. After, the photometry bench laser was zeroed. The LabVIEW program was then started. Carriage 1 was then hand driven and motor driven during the series of tests, and the laser value displayed was compared to that of the encoder. See Figure 3 for USB-6366 DAQ setup and bench testing.



Materials:

1) Renishaw RGH22X30D00A Quadrature Optical Linear Encoder
2) Renishaw RGS20-S Scale Kit
3) Arduino Uno Microcontroller (initial setup)
4) Arduino C Software (initial setup)
5) NI USB-6366 DAQ
6) NI MAX Software

7) LabVIEW Software
8) CATIA 3D modeling software (design of fixtures)
9) 15 pin Ribbon Cable
10) Breadboard
11) Wires
12) 220 ohm Resistor
13) Push Button

Results and Discussion:

Testing began with the Arduino Uno as it was easily available, cheap, and sufficient for initial proof of concept and communication purposes. No issues were seen during the initial laser comparison test, so the caliper comparison test was done to validate the results at higher speeds. This proved beneficial because it was discovered that the Arduino was not be able to operate effectively at higher speed (therefore higher frequencies). The required clock counter frequency was calculated and it was determined that a more powerful controller was needed.

The solution was using the NI-6366 DAQ, which had a counting clock speed of 10 MHz and 2+ counters. The series of tests, tested conditions beyond the normal expected operational uses of the photometry bench. The motor driven results, fell within the 1 mm specification, with a standard deviation of the error averaged 0.13 mm. There were some irregularities during testing such as: driving the motor beyond the testing region of the scale, some alignment errors, as a laser was not used for this process, inconsistent green light readings from the encoder readhead, less rigidity than ideal due to the material of 3D printed mounting fixture, the incorrect fixture fasteners being used, and the fixture not being completely clamped down. Despite all of these irregularities, during the motor driven tests, the encoder still performed within ±.1mm 80% of the time, which is stricter than the stated specification of ±1 mm.

Table 1: Motor Driven Error Data

Forward Error Standard Deviation (mm)	Backward Error Standard Deviation (mm)	Fast Repeat (x10) Error Standard Deviation (mm)	Average Error (mm)
0.15	0.096	0.13	0.13

Other sources of uncertainty include:

Scale Error

- linearity ± 3 µm/m± 0.75 µm/60 mm [3]
- pitch

Resolution

Signal Processing

- from readhead (±0.15 µm) [4]

- from DAQ

Mounting Errors

- pitch ±1° [4]
- yaw ±0.5° [4]
- roll ±1° [4]
- curvature of rail (4° from centerline)
- straightness of scale
- alignment of bracket

Vibrations

- motor
- movement: operating 100 m/s² max @ 55 Hz to 2000 Hz [4]
- carriage

Power Supply 5V ±5% [4]

Temperature

- Storage: -20 °C to +70 °C [4]
- Operating: 0 °C to +55 °C [4]

Humidity

- Storage 95% maximum relative humidity (non-condensing) [4]
- Operating 80% maximum relative humidity (non-condensing) [4]

Acceleration: operating 500 m/s² [4]

Shock: 1000 m/s², 6 ms, ½ sine [4]

The primary concern with the 0.125545 average standard deviation is this indicates the encoder skipped some counts. On this small (1 foot) scale, the skipping did not prove to produce results outside of the tolerance. However, on a large scale these skipped counts could possibly cause greater error.

Conclusions:

The Arduino Uno caliper comparison set up could count properly, and had a functional reset button, however it could not keep an accurate count at higher speeds, due to its low clock frequency, as determined through the Nyquist aliasing theory. Accuracy and precision was achieved during the hand and motor driven optical encoder photometry bench tests using the DAQ which had a higher clock speed. All of the tests produced results within 1 mm based on the uncertainty analysis. This is within an allowable amount as the photometry bench requirements. The average standard deviation of the motor driven tests was higher than that of the hand driven test. This indicated a loss of counts during the motor driven tests. The quadrature optical linear encoder will be a suitable replacement for the laser interferometer as it is less expensive if the accuracy and precision can be ensured through more ridged and standardized tests for repeatability. These tests would also validate these measurements over the full range of the photometry bench.

References:

[1] Renishaw plc, 2016, “How it works,” http://www.renishaw.com/en/rgh22-incremental-encoder-system-with-rgs-linear-scale--6443

[2] National Instruments, 2013, “Encoder Measurements: How-To Guide,” http://www.ni.com/tutorial/7109/en/

[3] Renishaw plc, 2010, “RGS20-S, RGS20-PC, RGS40-S, RGS40-PC,” data sheet

[4] Renishaw plc, 2008, “RGH22 series readhead,” data sheet

Appendix:

A1: Optical Encoder Photometry Bench Test: Hand Driven Data

Forward			
Calipers (mm)	Laser (mm)	Encoder (mm)	Delta (mm)
302.16			
Trial 1	302.9	302.9	0
Trial 2	301.7	301.7	0
Trial 3	302.3	302.3	0
Trial4	300.9	300.9	0
Trial 5	303	303	0
		Standard Deviation	0
Backward			
Calipers (mm)	Laser (mm)	Encoder (mm)	Delta (mm)
302.16			
Trial 1	302.2	302.2	0
Trial 2	307.5	307.5	0
Trial 3	301.9	301.9	0

Trial 4	304.3	304.3	0
Trial 5	301.9	301.9	0
		Standard Deviation	0
Return to Zero			
Calipers (mm)	Laser (mm)	Encoder (mm)	Delta (mm)
302.16			
Trial 1	1.1	1.1	0
Trial 2	0	0.0	0
Trial 3	-1.6	-1.6	0
Trial 4	-1.9	-1.9	0
Trial 5	-2.2	-2.2	0
		Standard Deviation	0

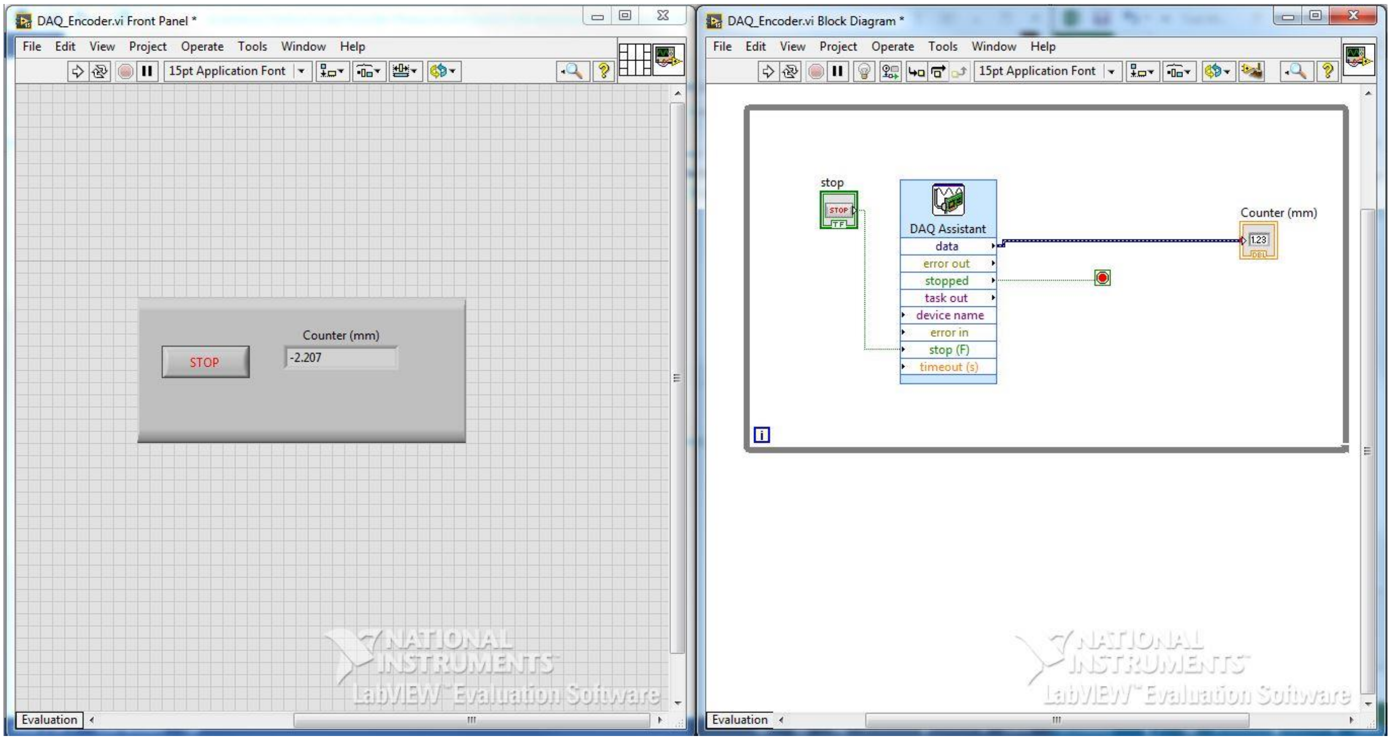
A2: Optical Encoder Photometry Bench Test: Motor Driven Data

Forward					
	Laser (mm)	Encoder (mm)	Notes	Delta (mm)	Percent Error
Trial 1	309.9	309.8		-0.051	0%
Trial 2	219.3	219.4		0.093	0%
Trial 3	321.1	321.1		0	0%
Trial4	34.3	34.3		-0.037	0%
Trial 5	----	196		0	0%
Trial 6	299.7	299.7		-0.061	0%

Trial 7	286.1	286.1		-0.038	0%
Trial 8	118.9	118.5	fast burst	-0.424	0%
Trial 9	280.6	280.2	fast burst	-0.41	0%
Trial 10	147.6	147.6	fast burst	-0.016	0%
Trial 11	285.1	285.1	fast burst	0.002	0%
Trial 12	273.5	273.5	fast length	-0.018	0%
Trial 13	278.6	278.5	fast length	-0.141	0%
Trial 14	7.1	7.1		-0.025	0%
Trial 15	298.8	298.6	fast length	-0.235	0%
			Standard Deviation	0.150759	
Backward					
	Laser (mm)	Encoder (mm)	Notes	Delta (mm)	
Trial 1	-7	-7		-0.015	0%
Trial 2	-4	-4		-0.02	0%
Trial 3	7.4	7.4		0.001	0%
Trial 4	41.4	41.3		-0.069	0%
Trial 5	-8.8	-8.7		0.099	1%
Trial 6	38.3	38.2		-0.063	0%
Trial 7	-10.6	-10.6		-0.014	0%
Trial 8	206.1	206.2	fast burst	0.051	0%
Trial 9	115.4	115.4	fast burst	-0.02	0%

Trial 10	30.2	30.2	fast burst	-0.039	0%
Trial 11	9.4	9.5		0.051	1%
Trial 12	39.1	39	fast length	-0.143	0%
Trial 13	3.1	3		-0.125	4%
Trial 14	38.7	38.7		-0.019	0%
Trial 15	41.6	41.3	fast length	-0.304	1%
			Standard Deviation	0.10328	
Fast Repeat (x10)					
	Laser (mm)	Encoder (mm)	Notes	Delta (mm)	
	71.2	71.3		0.073	0%
Trial 1	42.2	42.2		0.003	0%
Trial 2	70	69.8		-0.232	0%
Trial 3	197.8	197.8		-0.002	0%
Trial 4	57.8	57.8		0.024	0%
Trial 5	108.3	108.5	went past region	0.205	0%
Trial 6	85.5	85.5		-0.004	0%
			Standard Deviation	0.121499	

A3: LabVIEW Front Panel and Block Diagram



A4: CATIA Bracket Assembly