Calibration report for DPI galvo and artificial eye

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Introduction

On September 21, 2020, Ruei and I did some testing of the galvos and drivers that we had in the lab at the time. We figured out that there was a combination of galvo and driver that seemed to work. We did this testing because we needed to determine whether we had a system cable of moving the DPI artificial eye at low frequencies, which was required for trying to get the DPI back in function. These preliminary tests suggested that we did have a working system, but it would need to be calibrated.

At the beginning of October, I conducted a rigorous calibration of the DPI galvo to figure out the conversion from input voltage to rotation amplitude at a given frequency. The first calibration I did suggested that a rotation amplitude of 1 arcmin could not be achieved at 1 Hz with the equipment we had: even with the function generator set to its lowest voltage of 0.05 V, the rotation amplitude was around 5 arcmin. After realizing this, I decreased the gain until this small amplitude of 1 arcmin at 1 Hz could be achieved.

Next, I conducted a full calibration over a range of input voltages from 0.05 V to 4.0 V at frequencies of 1 Hz, 5 Hz, 10 Hz, 40 Hz, and 60 Hz. First, I did a calibration with a laser pointer attached to the galvo. This enabled me to determine the relationship between the galvo rotation angle—measured by looking at the beam deflection on the calibration grid—and the encoder voltage. After determining that this relationship was stable and constant over the frequencies tested, I used this information in the final calibration process, which involved the galvo with the artificial eye mounted to it. This process ensured that the final calibration was done with the actual payload instead of the laser, which has a different mass and geometry.

The remainder of this report explains the steps of the calibration process, the data processing, and the final calibration data.

Calibration grid for measuring laser deflection

A custom calibration grid was made to simplify the calibration process. First, the distance from the laser to the target was determined by finding a suitable location for doing the calibration. I decided to use the optical table in the AO room to mount the galvo, and I determined the distance based on this configuration. A target distance of 3 meters was chosen based on the available space in the room. The calibration grid was designed to have lines spaced by 1 arcmin with line widths of 0.25 arcmin at the target distance of 3 meters. Since only small angles were used in this calibration, the small-angle approximation was used to make the design of the calibration target simpler. This approximation, defined as $\tan\theta \approx \theta$ for small θ (where θ is in radians), introduces less than 0.1% error for angles less than 3° in magnitude. For the angles used in this calibration (+/- 1.5° maximum angle), the error introduced by this approximation is less than 0.025%.

Using this approximation means that the same spacing between adjacent lines can be used across the whole angular scanning range (instead of adjusting the spacing according to $\tan\theta$). For a distance of 3 meters, the physical distance that the beam would traverse at the target location for a rotation of 1 arcmin is given by

$$d = (3\text{m})\tan(1\text{ arcmin}) = 0.8727\text{ mm}$$

The target was therefore designed with a center-to-center line spacing of 0.8727 mm, which corresponds to lines every 1 arcmin at a distance of 3 meters.

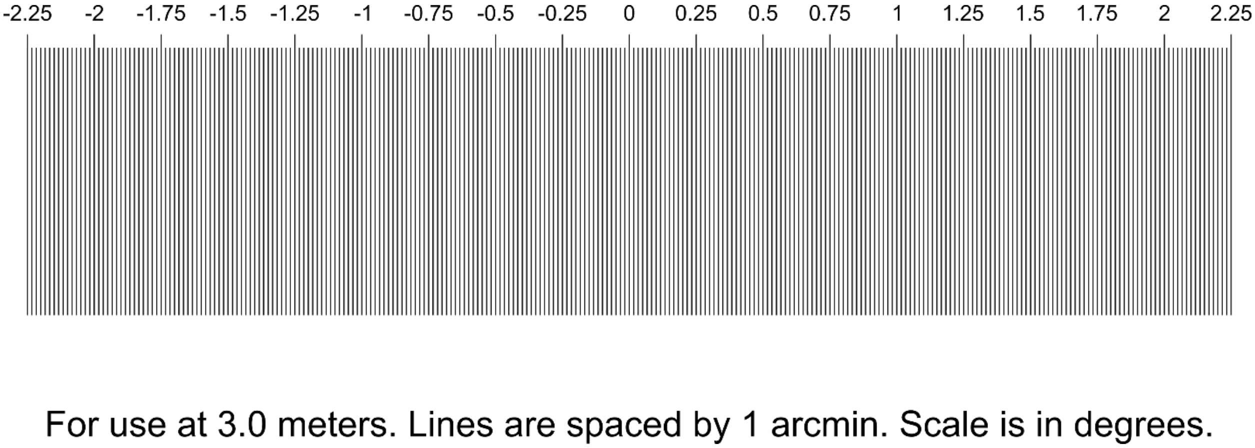


Figure 1: Custom calibration grid used for calibrating the DPI galvo. The grid was designed for use at 3 meters, and lines are spaced by 1 arcmin. The scale at the top is in degrees.

The calibration grid was designed in a vector graphics drawing program (Inkscape) and was printed without scaling to preserve the dimensions of the lines. After it was printed, it was carefully measured with a ruler to ensure that the proper scaling had been preserved.

Calibration setup

The calibration target was taped to the wall with the center of the grid at the height of the laser aperture. This ensured that the laser beam was normally incident on the center of the target at the 0° position: the starting/resting position. The galvo was attached to the optical table such that the distance from the center of the rotation axis (galvo shaft) to the calibration target was 3.000 +/- 0.001 m.

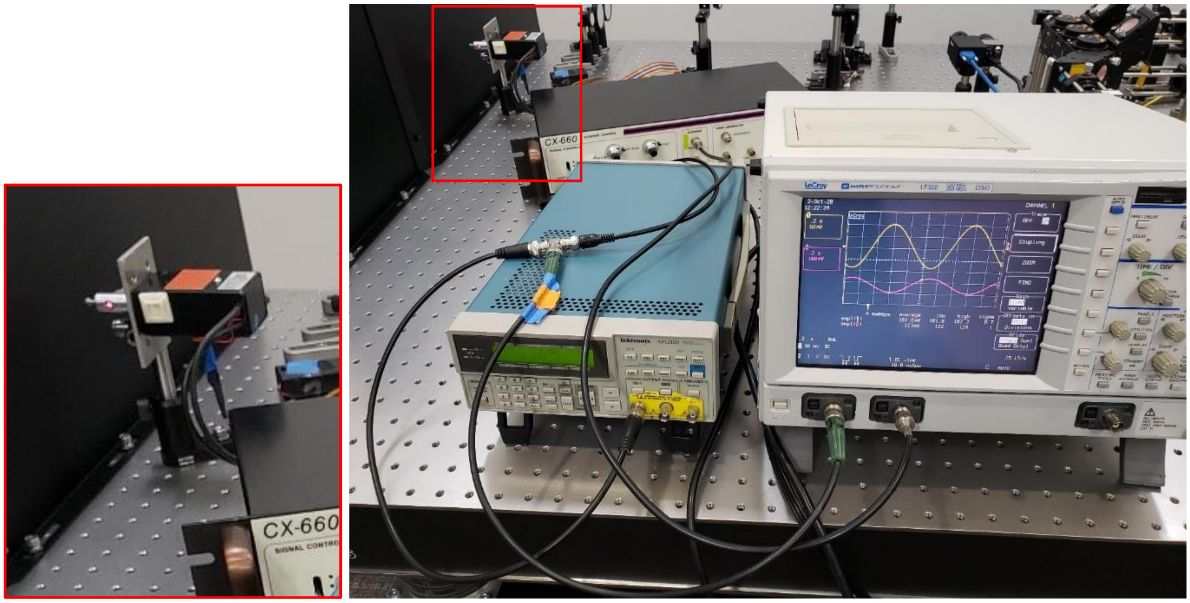


Figure 2: Setup in the lab showing how the hardware was configured for the calibration process. The inset on the left shows the galvo, mounted horizontally for purely vertical rotations. The red laser pointer is attached to the galvo shaft using a metal adapter, and the laser aperture is visible as a red dot in the middle of this adapter. The picture on the right shows the function generator (left) attached to the galvo driver (back) and oscilloscope (right). The yellow trace on the oscilloscope is the input voltage (from the function generator), and the magenta trace is the encoder voltage from the galvo driver, showing that the galvo is following the sinusoidal input voltage, but with a phase delay.

After the initial setup was completed, the laser and galvo driver were turned on so that the beam position could be fine-tuned. The galvo was rotated in its mount to bring the resting position of the galvo to the 0° position on the alignment target. Then the angular beam width was measured using the calibration grid. To make measurement of the beam position easier, the laser pointer was rotated in its mount until the beam was aligned with its narrowest width in the direction of the calibration grid (the beam is slightly elliptical, so the shortest beam width was used to make localizing the beam position easier and less prone to error). A white card was used to find the edges of the beam, and then the calibration grid was used to measure the beam rotation based on the location of the beam edges during rotation.

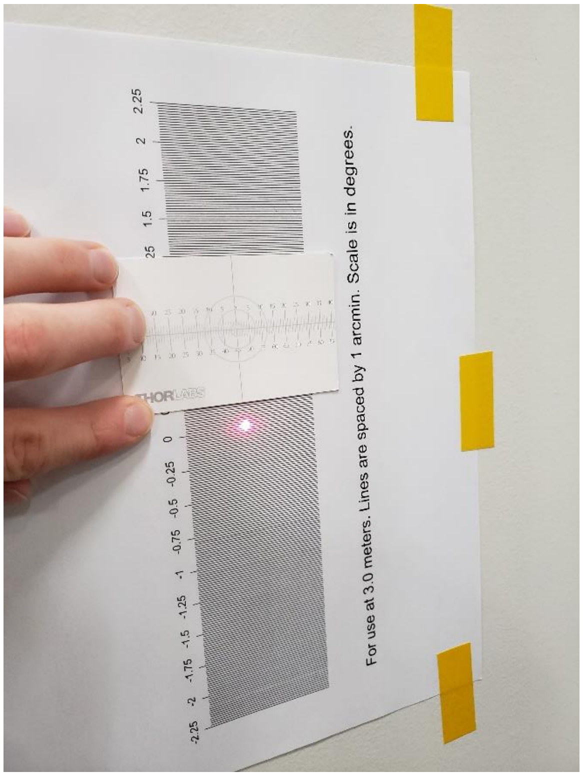


Figure 3: The alignment grid taped to the wall with the laser beam centered at the 0° rotation position. A white card was used to find the edges of the beam. These measurements were then used to determine the rotation angle of the beam.

Collecting calibration data

Using the setup described above, the calibration was collected. The input voltage was increased from 0.05 V to 4.0 V in 18 steps. At each voltage, the angular position of the top of the beam and the bottom of the beam were recorded in a spreadsheet. This process was repeated for each of the five frequencies tested (1 Hz, 5 Hz, 10 Hz, 40 Hz, and 60 Hz). The amplitude of the rotation was calculated as

$$a = \frac{p_{top} - p_{bottom} - w}{2}$$

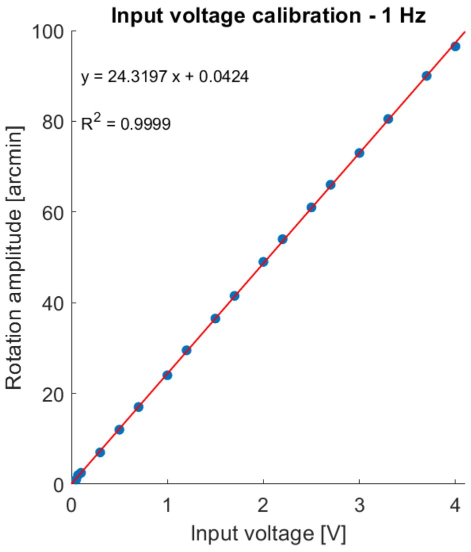
where a is the rotation amplitude in arcmin, p_{top} is the angular position in arcmin of the top edge of the beam at the top of rotation cycle, p_{bottom} is the angular position in arcmin of the bottom edge of the beam at the bottom of the rotation cycle, and w is the beam width in arcmin. For example, an input voltage of 1 V at 1 Hz resulted in the beam traversing between +27 arcmin and -26 arcmin on the calibration target. Here +27 arcmin is the position of the top edge of the beam at the top of the rotation cycle, so $p_{top} = 27$. The bottom edge of the beam at the bottom of the rotation cycle was -26 arcmin, so $p_{bottom} = -26$. The beam width was measured to be 5 arcmin, so $w = 5$. Plugging in these values, we get

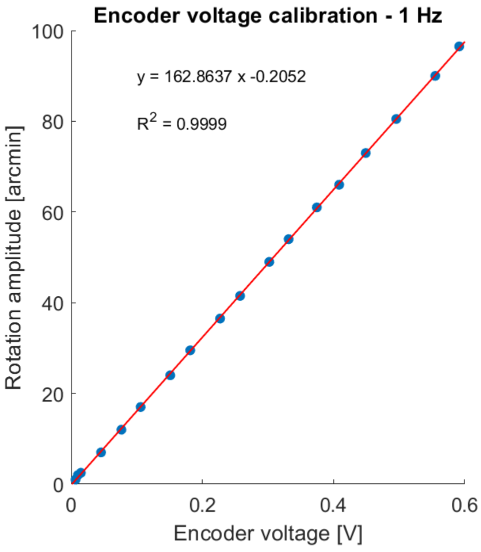
$$a = \frac{27 - (-26) - 5}{2} = 24 \text{ arcmin}$$

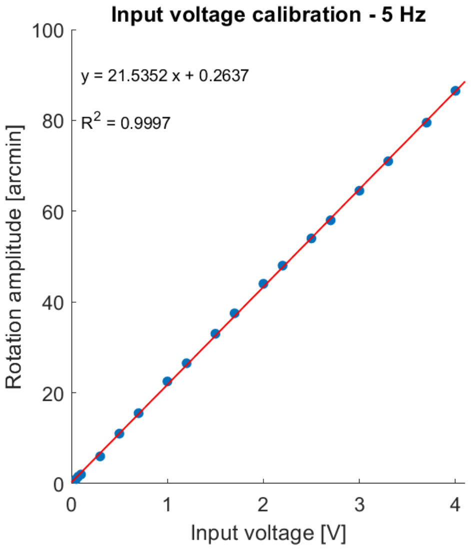
The top and bottom positions were measured to the nearest arcmin. The equation above is effectively the average of two amplitudes (top amplitude and bottom amplitude), so the uncertainty of these measurements was +/- 0.5 arcmin. The data was collected in an Excel spreadsheet. In addition to recording the measured amplitude, the encoder voltage, measured with the oscilloscope, was also recorded. This enabled two calibrations to be conducted: one for the relationship between input voltage and rotation angle, and the other between encoder voltage and rotation angle.

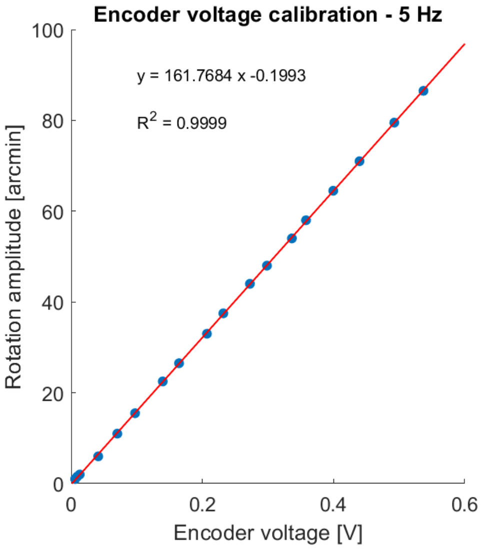
Data analysis and first calibration results

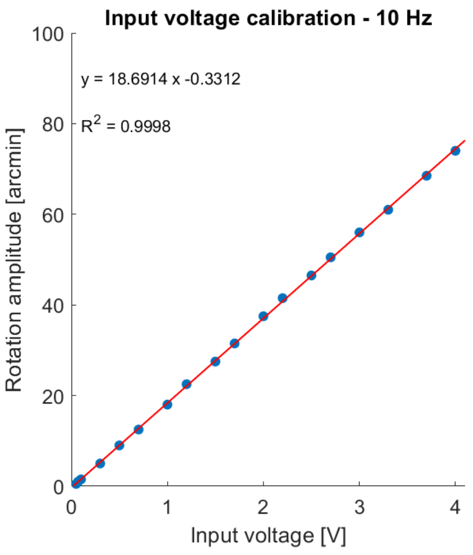
The data was processed using a custom MATLAB script. After reading in the data, a linear regression was computed for both calibrations. Figures were then generated for each of the five frequencies tested. The results are shown in the figures below.

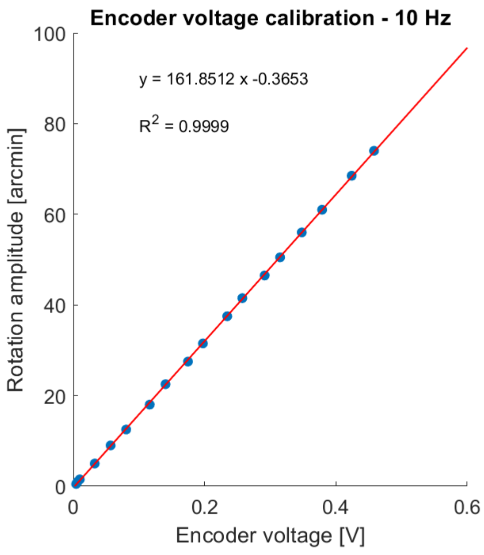


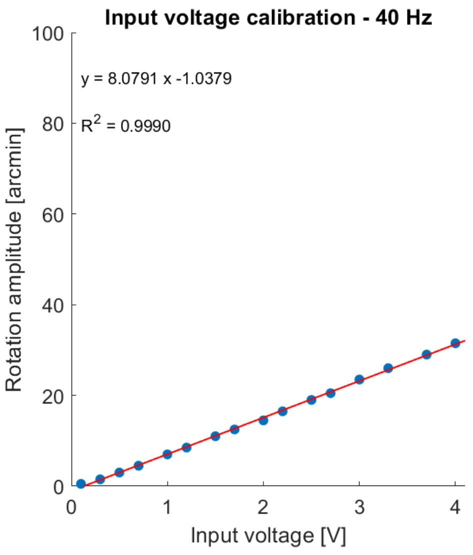


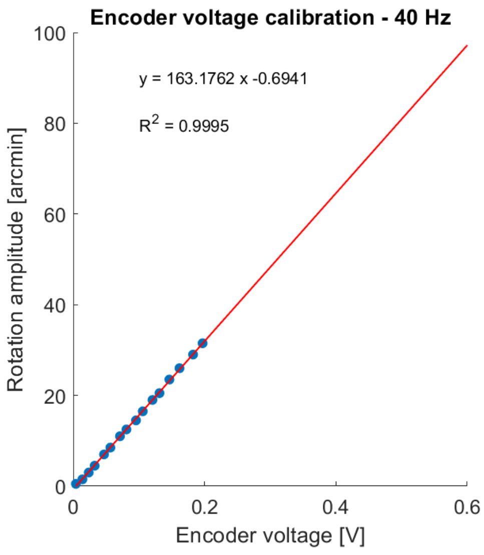


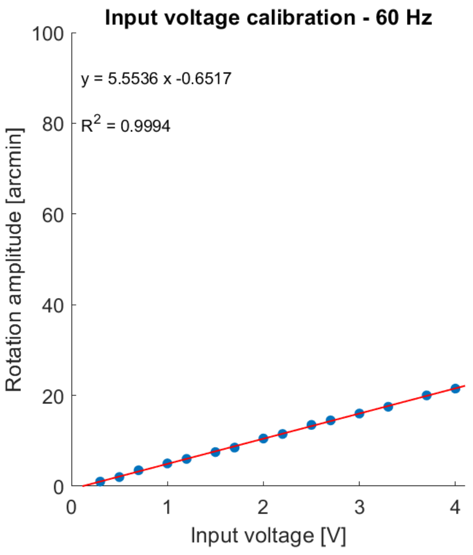


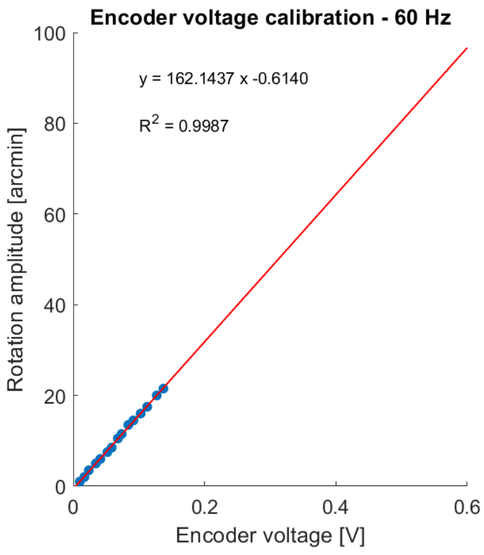

Input voltage calibration - 10 Hz
y = 18.6914 x -0.3312
R^2 = 0.9998
Rotation amplitude [arcmin]
0
20
40
60
80
100
0
1
2
3
4
Input voltage [V]


Encoder voltage calibration - 10 Hz
y = 161.8512 x -0.3653
R^2 = 0.9999
Rotation amplitude [arcmin]
0
20
40
60
80
100
0
0.2
0.4
0.6
Encoder voltage [V]


Input voltage calibration - 40 Hz
y = 8.0791 x -1.0379
R^2 = 0.9990
Rotation amplitude [arcmin]
0
20
40
60
80
100
0
1
2
3
4
Input voltage [V]


Encoder voltage calibration - 40 Hz
y = 163.1762 x -0.6941
R^2 = 0.9995
Rotation amplitude [arcmin]
0
20
40
60
80
100
0
0.2
0.4
0.6
Encoder voltage [V]


Input voltage calibration - 60 Hz
y = 5.5536 x -0.6517
R^2 = 0.9994
Rotation amplitude [arcmin]
0
20
40
60
80
100
0
1
2
3
4
Input voltage [V]


Encoder voltage calibration - 60 Hz
y = 162.1437 x -0.6140
R^2 = 0.9987
Rotation amplitude [arcmin]
0
20
40
60
80
100
0
0.2
0.4
0.6
Encoder voltage [V]

These calibration curves show a high degree of linearly over the range of angles tested. The lowest R^2 value was greater than 0.998. These results show that the calibration for input voltage and rotation angle changes significantly with frequency: at higher frequencies, the slope is much lower compared to the slope at low frequencies. However, the calibration for the encoder voltage and rotation angle is very consistent across frequencies. This agrees with the expectation because the encoder voltage is supposed to be a measurement of the galvo's rotation, and this should correspond to the measured rotation angle regardless of the frequency.

The results for the encoder voltage and rotation angle calibrations were averaged across the five different frequencies to improve the accuracy of this measurement. The average slope was found to be 162.36 arcmin/V, with a standard deviation of 0.63 arcmin/V. The average intercept was -0.42 arcmin, with a standard deviation of 0.23 arcmin. These averaged values were used to generate the equation for converting from encoder voltage to rotation amplitude. Here it's important to note that all amplitudes are single-sided amplitudes: half of the peak-to-peak values. The equation for converting from encoder voltage amplitude to rotation amplitude was found to be

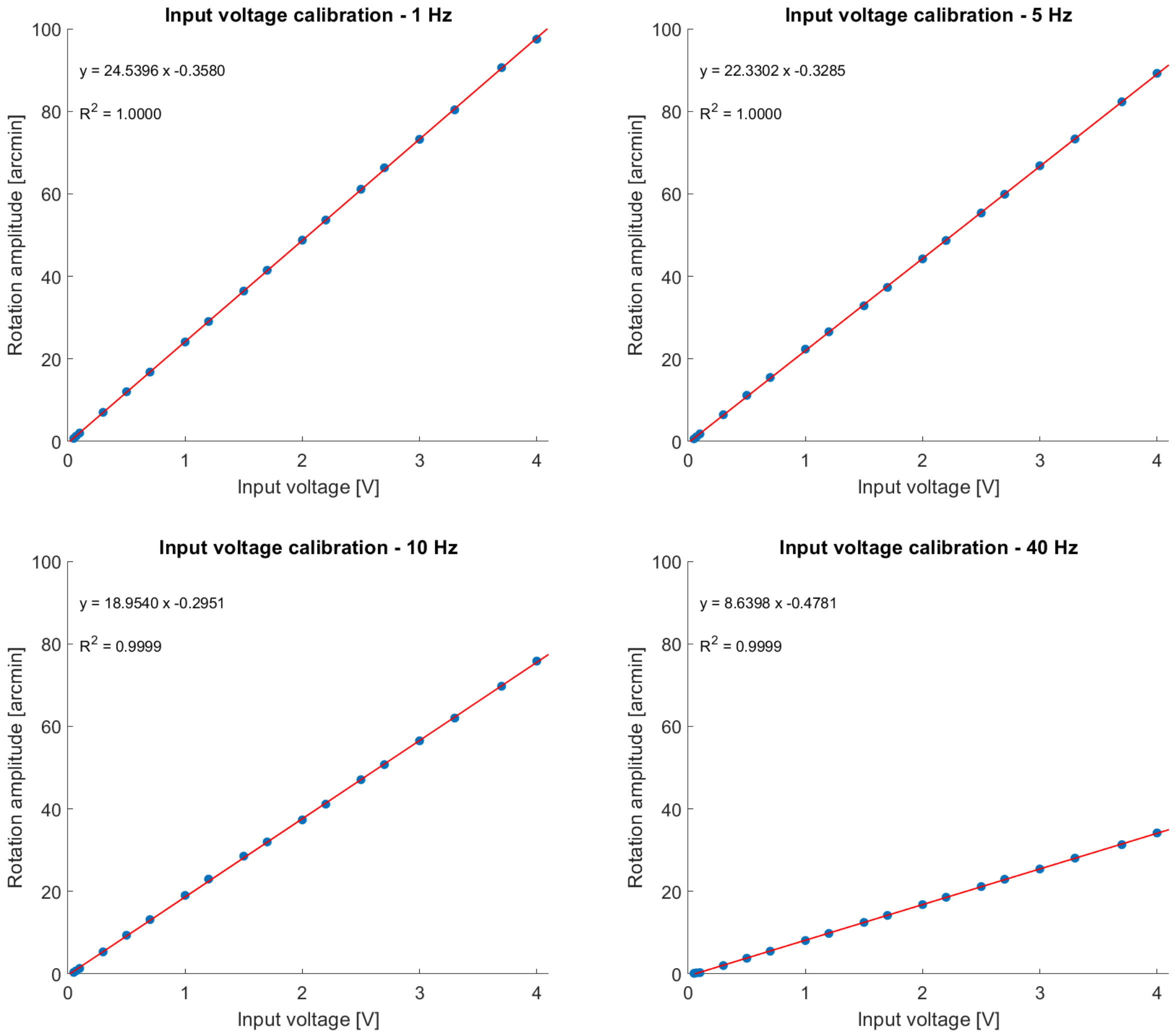
$$a = 162.36\, V_{enc} - 0.42$$

with

V_{enc}	encoder voltage amplitude, measured with oscilloscope (V)
a	rotation amplitude (arcmin).

Final calibration results

With the calibration equation above, we now have a way to convert from measured encoder voltage to rotation amplitude. This means we can replace the laser with the artificial eye and repeat the calibration process to get the final calibration data to convert between input voltage amplitude and rotation amplitude. This is an important step in the calibration process because it ensures that the final calibration is conducted with the exact payload that will be used in the experiment (changes in payload mass or geometry can affect the motion characteristics). For the final calibration, the DPI artificial eye was mounted to the galvo shaft. The same range of input voltages was used, and the encoder voltages were collected in an Excel spreadsheet. Then the equation above was used to convert these measured encoder voltages to rotation angles. Finally, this data was processed in MATLAB using a similar procedure to the first calibration. Results from the final calibration are shown in the figures below.

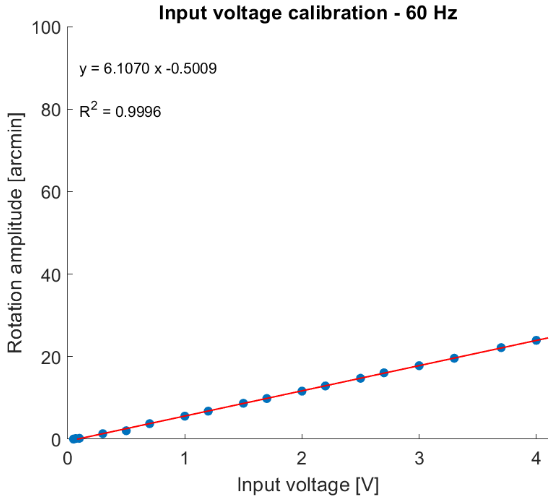


Input voltage calibration - 1 Hz

Input voltage calibration - 5 Hz

Input voltage calibration - 10 Hz

Input voltage calibration - 40 Hz



Input voltage calibration - 60 Hz

Figure 4: Final calibration figures relating input voltage to rotation amplitude for the DPI galvo with the artificial eye installed. One calibration curve was generated for each of the five frequencies tested. The red lines are linear regressions, with parameters for the linear fit displayed in the top left of each graph.

These results once again show a high degree of linearity. The same decrease in slope with increasing frequency is exhibited, which highlights the fact that the calibration changes significantly with frequency: different calibration curves and equations are required for different frequencies. There was a small change in slope for this final calibration compared with the calibration with the laser pointer. The slope increased by 0.48 arcmin/V on average, with the smallest increase of 0.22 arcmin/V occurring at 1 Hz, and the largest increase of 0.80 arcmin/V occurring for 5 Hz. While this is a small change in slope, it is significant over the range of voltages tested: the average slope change of 0.48 arcmin/V corresponds to a difference of 1.9 arcmin over the input voltage range tested (0.05 V to 4.0 V). Since the rotation measurement uncertainty is +/- 0.5 arcmin, this difference is well above the noise floor. This suggests that the decision to do the final calibration with the artificial eye instead of the laser was a good choice.

Equations for converting between rotation amplitude and input voltage are summarized in the table below. The variables and their corresponding units are:

V_{in} function generator voltage amplitude (V)

a rotation amplitude (arcmin).

Table 1: Equations for converting between input voltage and rotation amplitude for the DPI galvo when used with the DPI artificial eye.

Frequency	Arcmin to voltage	Voltage to arcmin
1 Hz	$V_{in} = 0.0408a + 0.0146$	$a = 24.5396V_{in} - 0.3580$
5 Hz	$V_{in} = 0.0448a + 0.0147$	$a = 22.3302V_{in} - 0.3285$
10 Hz	$V_{in} = 0.0528a + 0.0148$	$a = 18.9540V_{in} - 0.2951$
40 Hz	$V_{in} = 0.1157a + 0.0553$	$a = 8.6398V_{in} - 0.4781$
60 Hz	$V_{in} = 0.1637a + 0.0820$	$a = 6.1070V_{in} - 0.5009$

In addition to the equations shown in Table 1, lookup tables were generated for common rotation amplitudes and input voltages. These tables are meant to provide a quick reference for easily setting the DPI galvo and artificial eye to a specified rotation amplitude, or for determining the rotation amplitude for a given input voltage.

Table 2: Input voltage (V) lookup table for common rotation amplitudes at different frequencies.

Rotation amplitude (arcmin)	1 Hz	5 Hz	10 Hz	40 Hz	60 Hz
1	0.055	0.059	0.068	0.171	0.246
2	0.096	0.104	0.120	0.287	0.410
5	0.218	0.239	0.279	0.634	0.901
10	0.422	0.463	0.542	1.213	1.719
15	0.626	0.686	0.806	1.791	2.538
30	1.237	1.358	1.598	3.528	
60	2.460	2.702	3.180		
90	3.682	4.045			

Table 3: Rotation amplitude (arcmin) lookup table for common input voltages.

Input voltage (V)	1 Hz	5 Hz	10 Hz	40 Hz	60 Hz
0.05	0.9	0.8	0.7	0.0	0.0
0.1	2.1	1.9	1.6	0.4	0.1
0.25	5.8	5.3	4.4	1.7	1.0
0.5	11.9	10.8	9.2	3.8	2.6
1	24.2	22.0	18.7	8.2	5.6
2	48.7	44.3	37.6	16.8	11.7
3	73.3	66.7	56.6	25.4	17.8
4	97.8	89.0	75.5	34.1	23.9

Conclusion

The DPI galvo has been calibrated for use with galvo driver and the DPI artificial eye. This report summarizes the calibration process: the design of the calibration grid, the initial calibration procedure, the data processing steps, the final calibration with the artificial eye installed, and the final calibration results. Supplemental documents will be uploaded to the AP Lab Wiki, along with this report. This report should provide a framework and practical steps for other calibration procedures in the future. If you have questions about any of these results, email Ben Moon at b.moon@rochester.edu.