Development of optical imaging system for LIGO test mass contamination and beam position monitoring

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Summary of Previous Work

Presently, an imaging system—consisting of a DSLR camera with telephoto lens—exists for viewing the surfaces of the end test masses of the LIGO interferometer. The system is used for monitoring large angle scattering from the test mass surfaces, which are thought to be due to imperfections of the surface coating and particulate contamination. The goal of this project is to calibrate the camera system so that the amount of scattering in the images from the camera can be quantified. Additionally, this project also aims to set up a similar camera system for monitoring the input test masses at the corner station.

As of the last report, a preliminary attempt to calibrate the Nikon DSLR camera used in the camera system has been made. Total pixel counts from the camera images were found to be linear with respect to the number of photons incident on the camera, which was calculated from the wavelength of the laser (1064 nm), the laser power used, and the nominal exposure time (1/2000 s). However, there was a positive intercept in the linear fit—which suggested a non-zero pixel count even when no photons are incident on the camera sensors—that remained to be explained. The transmissivity of the camera lens/telescope used in the camera system was also not yet determined.

As for the input test mass camera system, only the cabling and electrical connections for the telescope for the focuser had been determined. The stepper motor for the focuser could be controlled by manually writing to individual bits from the Beckhoff TwinCAT software, and a user-friendly interface had yet to be developed.

Work Done on Camera Calibration

Work done on camera calibration since the last report consisted of checking the preliminary calibration against actual images of the test mass surfaces when the infrared light is resonating in the interferometer, calibrating the lens, and attempting to determine how the actual exposure time compares to the manufacturer's nominal exposure time.

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Checking calibration and investigating exposure times

Even though the transmissivity of the camera lens and the viewport have yet to be determined, it was still possible to check if the preliminary calibration was applicable to the images from the test masses: Since the red, green, and blue channels had independent calibration curves, they should yield similar values for number of photons incident at the same camera setting.

However, it was found that power drop-off from the center of from the scattering bodies is very sharp, such that in images taken at slower shutter speeds such that more of the scattering is visible, the center pixels were saturated and therefore could not be used (Figure 1, left). In images taken at very fast shutter speeds such that no pixels are saturated, only the center of the scattering bodies are visible (Figure 1, right), resulting in barely any bright pixels that we can work with.

Figure 1: Image of LHOY ETM with 2 W input at ISO 200 with 1/2 s exposure time (left) and 1/5000 s exposure time (right).

Using the unsaturated image to check our calibration, it was found that it gave negative power due to the yet to be explained positive intercept in the calibration curve; the total pixel count was less than the total pixel count for no photons incident on the sensor, according to our calibration.

Moreover, in addition to the values being negative (and therefore obviously wrong) the values from the red and blue channels were also inconsistent with the value from the green channel. It is unclear why this is the case, but could be a combination of there being too few bright pixels in the image, and issues with the original calibration.

In order to increase the number of bright pixels we can see on images of the test mass without running into the problem of saturation, we considered merging several images taken with different exposure times to create a high dynamic range (HDR) image: Saturated pixels in a long exposure image are replaced with values of unsaturated pixels at a shorter exposure time, scaled by a certain amount and, perhaps, adjusted by some offset.

To determine how much the the pixel values at a shorter exposure time must be scaled and adjusted by when replacing a saturated pixel at a longer exposure time, we need to determine how accurate the nominal exposure times are:

Given that total pixel count is linear with respect to the number of photons incident and the number of photons incident is proportional to actual exposure time, the total pixel count is linear with respect to the actual exposure time. Therefore, if the actual exposure time is linearly related to nominal exposure time, the total pixel count of the same scene ought to be linear with respect to the nominal exposure time.

To test this hypothesis, we took images of a DC power source at different shutter speeds; a DC power source was used to avoid the flickering from AC power sources.

Repeating calibration measurements

Since we only used three "bright" frames and three "dark" frames per setting, there may have been incomplete cancellation of noise in the dark pixels, which may have contributed to the positive intercept in the preliminary calibration, we repeated the calibration measurements for selected settings.

Since images taken at ISO 200 saturated very quickly, we would probably favour lower ISO settings for future images of the test masses. Therefore, we repeated calibration measurements at ISO 100—this time averaging over 100 "bright" frames and 100 "dark" frames. We also increased the size of the laser beam using a biconcave lens to increase the size of th laser spot in the frame so that there is no longer overwhelmingly more dark pixels than bright pixels. This will hopefully reduce the contribution of dark pixels to spurious positive counts. By increasing the size of beam, we were also able to use power settings on the laser that are an order of magnitude higher than before. This was beneficial because the laser power was more stable at higher power.

Lens calibration

In addition to efforts to improve and figure out the problems with the initial calibration, we also calibrated the camera lens and the telescope that are/will be used in the camera system. We investigated the following lens:

- AF-S DX Nikkor 55-300 mm f/4.5-5.6G ED VR (currently in use for ETM cameras)
- Tamron SP 150-600 mm f/5-6.3 Di VC USD (planned replacement for Nikkor lens at ETM cameras)
- Celestron EdgeHD 8" Schmidt-Cassgrain telescope (to be used for ITM cameras)

The camera lens were calibrated by keeping the lens aperture wide open, and measuring the power of the input laser light and the power of the laser light after it passes through the lens. To ensure that the output beam was not clipped by the aperture, we aligned the beam with the lens axis to the best of our ability using iris diaphragms and visually inspected the output beam profile for fringing patterns. The same alignment procedure was also used for the telescope.

Transmissity is given by $\text{transmissivity} = \dfrac{\text{outputpower}}{\text{inputpower}}$. Data from the lens calibration is given in Table 1.

Lens	Input power (mW)	Output power (mW)	Transmissivity
Nikkor	9.8 ± 0.1	1.95 ± 0.01	0.199 ± 0.003
Tamron	8.27 ± 0.01	1.15 ± 0.01	0.139 ± 0.001
Celestron	8.29 ± 0.01	2.81 ± 0.01	0.339 ± 0.002

Table 1: Transmissivities of the lens used in the camera system

Work Done on ITM Camera System

Work done on the input test mass camera system consisted of testing the range of velocities the stepper motor can support, and developing the PLC program for controlling the focuser as well as the GUI for remote focusing to switch between viewing infrared and green light from the control room.

It was found, in the process of testing the range of velocities that the stepper motor can support, that the magnitude of the signed integer "Velocity" is not actually absolute velocity, but rather a percentage of a configuration variable which sets the maximum number of steps per second, i.e. the maximum velocity. For instance, when maximum velocity is set to 1000 steps per second, and velocity is set to 4000 (i.e. 40%) the stepper motor moves at the same speed as when the maximum velocity is set to 4000 steps per second, and velocity is set to 1000 (i.e. 10%).

As the Beckhoff controller that we are using (EP7041-2002) only supports the velocity control interface for PLC, position control loops using velocity control and timing pulses will have to be written to support moving to position presets for focusing on the infrared (1064 nm) light and the green (532 nm) light. Presently, velocity control can be used to jog the focuser, and has been tested with a rudimentary GUI (Figure 2).

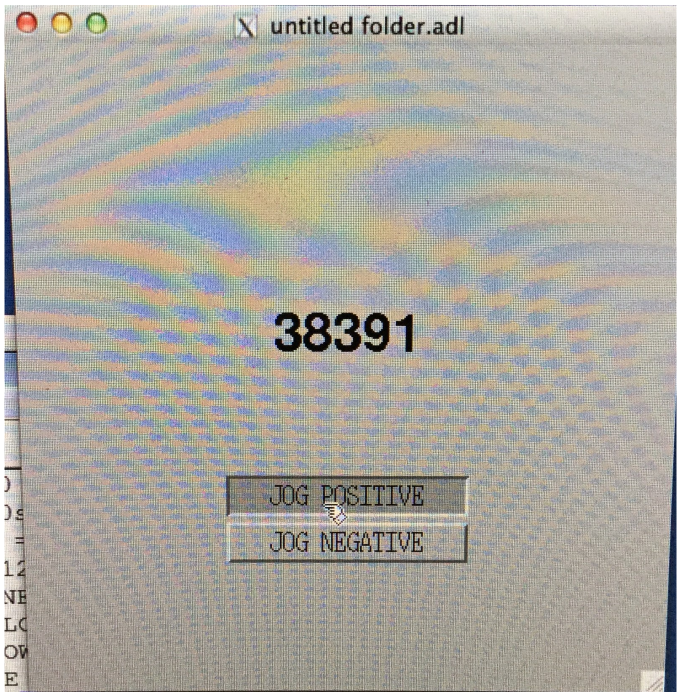

Figure 2: Rudimentary GUI for testing focuser jog control.

The number displayed in Figure 2 is the stepper motor internal counter readout, which should indiciate the position of the stepper motor. However the internal counter is a 16-bit integer and therefore overflows after $2^{16} - 1 = 65535$. For the full range of motion of the focuser, the counter overflows about four or five times, which means that this value cannot be used directly for position control and for storing position presets. To solve this problem, a function to compute the new position after moving based on the the final and initial values of the internal counter value and how many times the counter over- or underflows was written. The value is then retained as a 32-bit integer—the absolute position—which should be able to handle the focuser's full range of motion without overflowing.

Presently, bugs in the aforementioned function for computing the new position is the main problem hindering the implementation of position control.

Further Work and Goals

Camera Calibration

Further work on the camera calibration part of the project consists of analysing the new power calibration data to determine if the positive intercepts persist, and analysing data from the exposure time measurements to determine the relation between nominal and actual exposure time.

Additionally, I also plan to check how much the dark pixel counts still contribute to the calibration images after the dark frame is subtracted by summing over the images with the laser spot masked out. This is to determine how well subtracting the dark frame actually cancels out the dark counts from the bright frames, and therefore also the quality of the calibration.

Moreover, in order to better understand the noise due to the dark counts, I plan to take completely dark images at various shutter speeds to determine whether the total dark pixel values is dependent on shutter speed.

Finally, I plan to check—where possible—that the calibrations for the various components of the camera system make sense. For the new calibration for the camera sensor at ISO 100, this means acquiring a new set of images of the end test masses at ISO 100 to check how well (if at all) the new power calibration works. For the telescope, which is a relatively simple optical system, I will attempt to compare the measured transmissivity to a theoretical estimate based on manufacturer's specifications for the materials used in the optical elements (if available).

ITM Camera System

Due to some issues that have arisen that require the ITM camera housing to be re-machined, physical installation of the camera system at the ITM is unlikely to happen within the next month. Therefore, the goal for the next few weeks is to complete the development of the control software and the GUI interface, and to leave comprehensive documentation for the the cabling connections as well as software cofiguration for use when the system is ready to be physically installed.

I will also explore the possibility of integrating the focuser control program and user interface into the existing infrastructure before the installation of the camera hardware.