Development of a Fine Pointing System for the Segmented Aperture Interferometric Nulling Testbed (SAINT)

Matthew Cosby[1], Dr. Brian Hicks[2]

[1]University of Michigan, Ann Arbor; [2]University of Maryland, College Park

Introduction

While launch vehicle capabilities and difficulty of manufacture limit the size of single monolithic primary mirror telescopes placed into space, segmented mirror telescopes can push the limits of space-based sensitivity and resolution. In the hunt for exoplanets orbiting very closely to their respective stars, the extremely precise image resolution and sensitivity required to perform coronagraphy motivates the use of these segmented aperture arrays in future space-based telescopes.

A coronagraphic fine pointing system (FPS) stabilizes telescope optical beam jitter to a residual level only a fraction of a typical stellar angular diameter for propagation through starlight suppression optics. In the Segmented Aperture Interferometric Nulling Testbed (SAINT) and visual nulling coronagraph (VNC), jitter is caused by environmental dynamics such as mechanical vibrations, local air temperatures, and acoustics. The FPS controls the tip and tilt axes of a Physik Intrumente (PI) fast steering mirror (FSM)[1] to stabilize image locus on the PixeLINK angle tracker camera (ATC) detector[2].

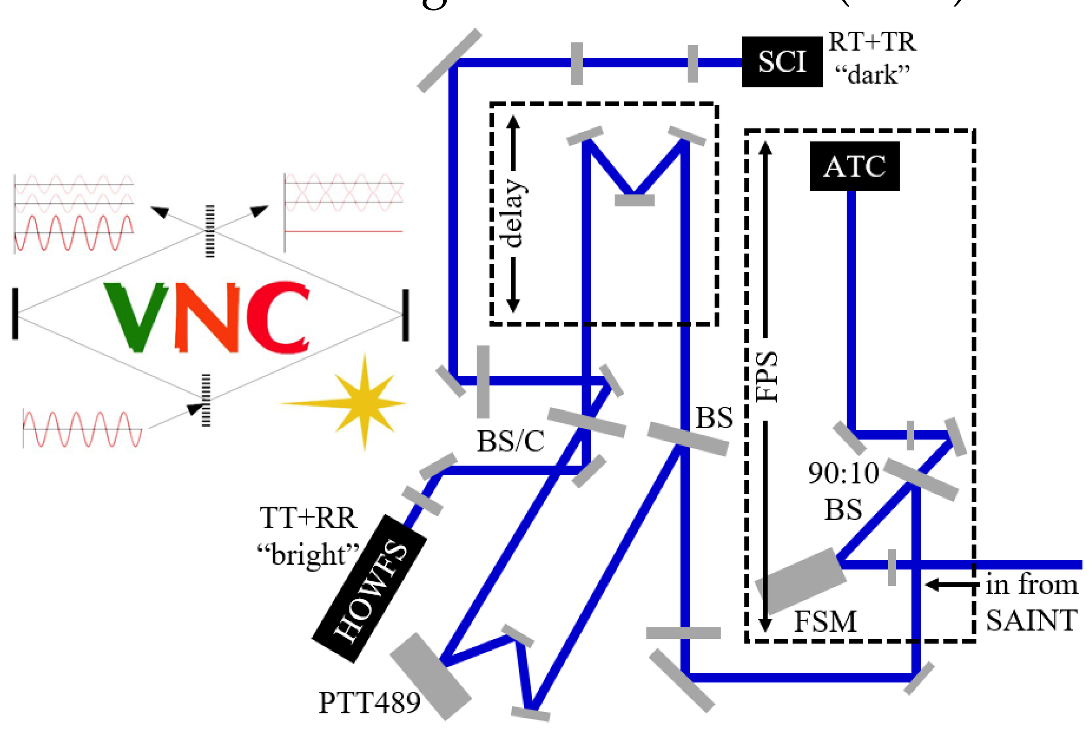

Figure 1: Ray trace of the VNC receiving light from SAINT noting the positions of the FSM and ATC in the beam path.

FPS Controller Design

The SAINT-VNC FPS is a proportional-integral-derivative (PID) controller whose purpose is to actively correct for errors in optical beam location. Corrective signals corresponding to the image locus error, its time rate of change, and its the residual value over time are applied to the tip and tilt axes of the FSM, precisely maintaining beam position on the detector.

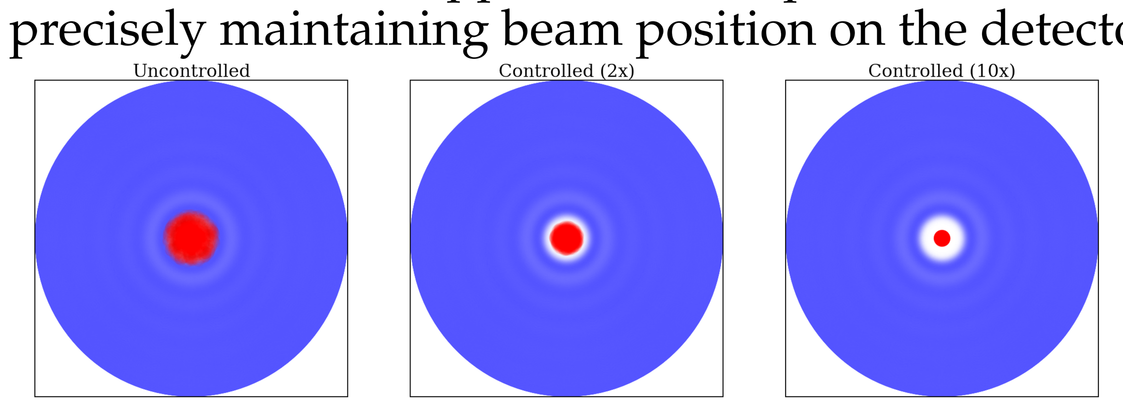

Figure 2: Schematic effect of pointing stabilization relative to on-sky null transmission. In pointing dominated systems, a 10× jitter reduction may enhance image contrast 100-10,000×.

In retrieving beam position, the system uses the ATC to capture a frame containing the beam and calculates its centroid of signal intensity in pixel-space. Each centroid is compared to that of the desired beam location, and errors in the horizontal (x) and vertical (y) pixel-space are stored. Capture rate, centroid computation time, and subsequent control bandwidth are driven by the ATC image size. Frame dimensions and corresponding control bandwidths are shown in Table 1.

Table 1: Notable control loop event durations show that frame capture and centroid computation drive the bandwidth.

Frame [pix]	Capture [ms]	Compute [ms]	Command [ms]	Freq [Hz]
1280 × 1024	18.50	31.60	0.04	20
1024 × 768	12.54	19.12	0.04	31
800 × 600	6.05	15.54	0.04	46
640 × 480	7.27	11.69	0.04	53
320 × 240	6.41	11.59	0.04	56
256 × 256	1.51	7.62	0.04	109
128 × 128	0.99	5.09	0.04	163
64 × 64	1.14	6.82	0.04	125
32 × 32	1.72	6.21	0.03	126

Prior to entering the controlled mode, the FPS commands a sequence of increasing and decreasing voltage signals to both axes in order to compute the local voltage-pixel response. Due to the alignment of the FSM axes, a voltage signal sent to either axis causes a response in both image axes. The roughly linear responses are then computed via least squares fitting and the solution of the two-dimensional linear system.

Once the response is computed, the FPS enters controlled mode using the standard PID control structure, with gains, k_P, k_I, and k_D, tuned via a similar method to that described in Csencsics & Schitter 2017[3], resulting in the following most favorable values in terms of jitter mitigation:

$$C_{PID} = k_P + k_I/s + k_D s$$
$$k_P = 0.200, k_I = 0.698, k_D = 0.004.$$

Results and Conclusions

The SAINT-VNC FPS attenuates pointing jitter to achieve the precision required to perform coronagraphy. In its current state, the system can command at 163 Hz. However, capabilities of a particular actuator in the system have limited testing to 5 Hz providing beam precision within 0.911 pixels of commanded, as shown in figures 3 and 4. In extended duration, deviations in the uncontrolled state would continually propagate while the controlled state would remain pointed.

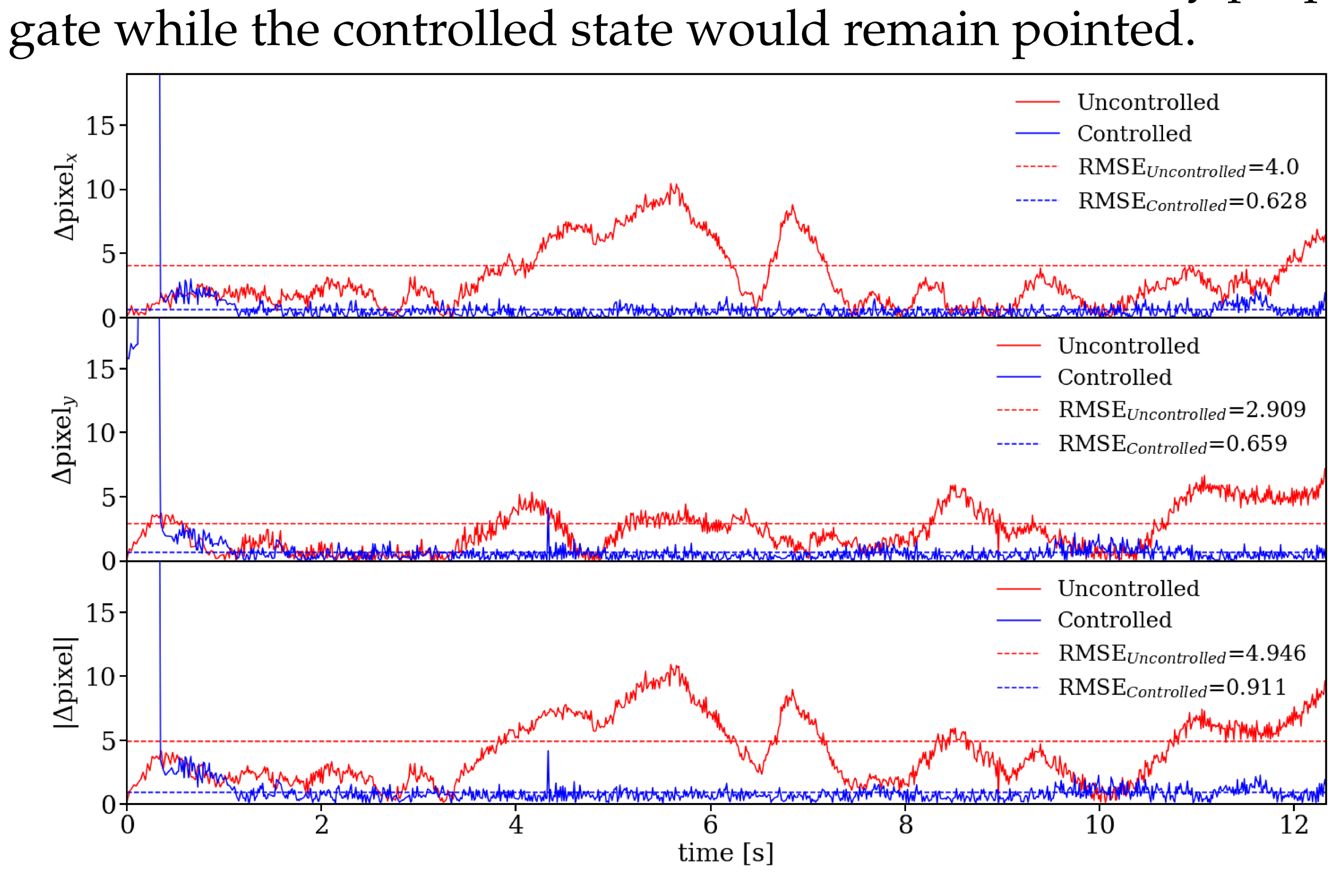

Figure 3: Presently, the FPS mitigates jitter to 0.628 and 0.659 pixels in the x- and y-axes(top, middle) respectively, achieving pointing within 0.911 pixels(bottom) of commanded.

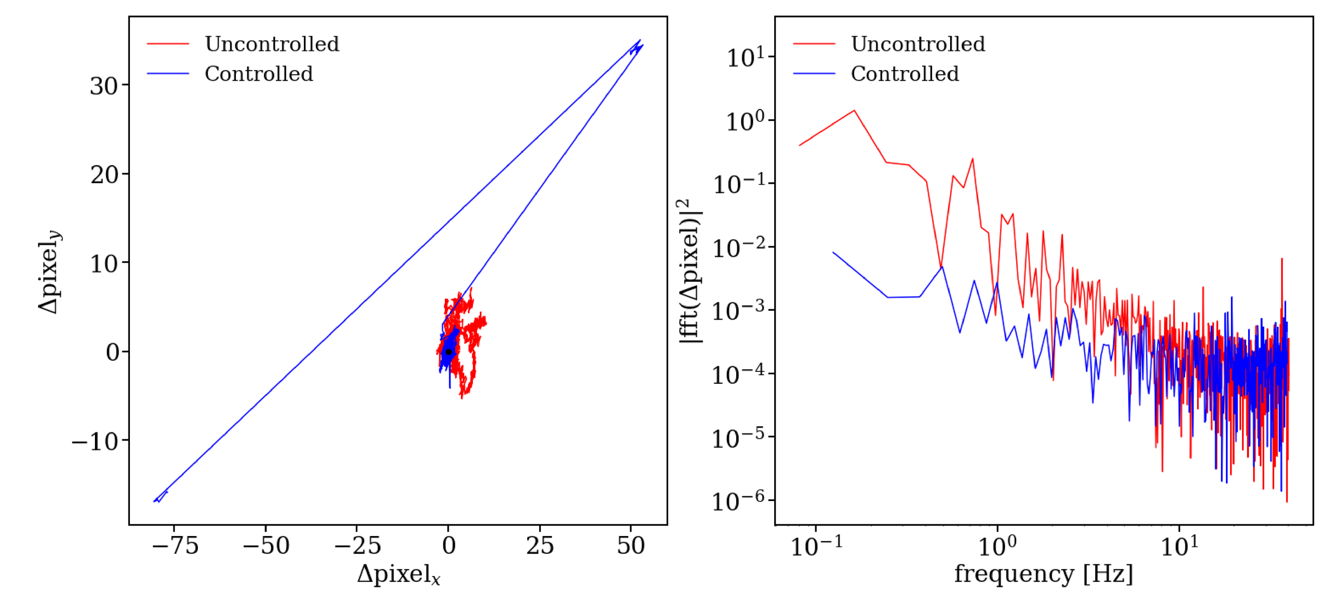

Figure 4: The x- and y-axis locations of the beam on the detector(left) display the drastic image locus correction immediately following the initial command and the precise pointing achieved via the system thereafter while in its controlled state. The effectiveness of the FPS is also made apparent in the corresponding power spectrum(right).

The pointing capability of a FPS depends heavily on the frequency at which error corrections can be commanded. That of the SAINT-VNC system is no exception, as is detailed in table 2 below. When considering the very high frequency optical jitter associated with such a system, commanding at a high rate is vital to stabilizing the beam locus. Achieving the maximum controller bandwidth was thus of paramount importance when evaluating controller performance.

Table 2: Comparison of expected FPS precision at multiple bandwidths assuming the beam full width at half maximum (FWHM) to be ∼80 pixels. Values in red are projected.

Control Bandwidth	5	20	53	109	163	[Hz]
RMS Error (x)	0.628	∼0.40	∼0.20	∼0.10	∼0.05	[pix]
RMS Error (y)	0.659	∼0.40	∼0.20	∼0.10	∼0.05	[pix]
RMS Error (mag)	0.911	∼0.57	∼0.28	∼0.14	∼0.07	[pix]

The most favorable pointing precision is expected to result from the highest commanding frequency established. Concerning future improvements to the controller bandwidth and pointing precision as a whole, along with correcting actuator performance, it is possible that enhancements can be made to the controller software. Of particular importance are refinements to the centroid computation time as the frame capture duration is largely driven by hardware capabilities.

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