Precision Closed-Loop Laser Pointing System for the Nanosatellite Optical **Downlink Experiment**

by

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ABSTRACT

The use of advanced small-satellite platforms has become increasingly more popular in the recent years. Several private companies are investing enormous capital into constellations of small satellites that are designed to provide highly dataintensive global services, such as rapid Earth imaging or fast worldwide Internet access. The scientific community is also interested in the development of miniature and high throughput platforms, for instance in the area of microwave radiometry or hyperspectral imaging.

The current state of the art nanosatellite radio frequency (RF) communications systems struggle to keep up with the increasing downlink demand and satellite data processing capabilities. Laser communications (lasercom) offers various advantages: increased bandwidth, smaller size, weight, power consumption, and a license-free spectrum.

While the narrow beamwidths allow lasercom to achieve higher data rates than RF, they, however, also result in higher pointing requirements for the spacecraft. Precision laser pointing systems have been successfully demonstrated on bigger satellites, but not on a nanosatellite scale, where the size and weight constraints are so severe. The Nanosatellite Optical Downlink Experiment (NODE) developed at MIT is a lasercom terminal designed to demonstrate the technologies required for a high-speed optical downlink using commercial off-the-shelf components within the constraints of a typical 3U CubeSat. NODE augments the bus attitude control system with a compact fine laser pointing stage to compensate for the spacecraft body pointing error.

This thesis focuses on the development and laboratory verification of the laser pointing system for NODE. A control scheme utilizing a miniature fast steering mirror (FSM) used to track a beacon uplink signal from the ground station is presented. An on-orbit FSM calibration algorithm is developed to improve the control robustness and precision. A novel sampling approach that enables closed-loop FSM control is proposed and implemented. The method focuses on simultaneous sampling of the beacon and an internal feedback signal on a single detector. Finally, a hardware-in-the-loop testbed is built in the laboratory with components that were selected for NODE, and the system is functionally verified and analyzed with regards to pointing accuracy. Experimental results show that the pointing requirements given by the mission link budget are met, and that the system performs reliably under various laboratory-simulated conditions.

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NOMENCLATURE

BDQ	Bias-Differential Quad-channel
BER	Bit error rate
COTS	Commercial off-the-shelf
DAC	Digital-to-analog converter
EDRS	European Data Relay System
FCC	Federal Communications Commission
FOV	Field of view
FPA	Focal plane array
FSM	Fast steering mirror
FWHM	Full width at half maximum
GPIO	General purpose input/output
GUI	Graphical user interface
ISS	International Space Station
LCT	Laser Communication Terminal
LEO	Low Earth orbit
LPF	Low-pass filter
MEMS	Microelectromechanical system
MIT	Massachusetts Institute of Technology
NICT	National Institute of Information and Communications Technology
NIR	Near-infrared spectrum
NODE	Nanosatellite Optical Downlink Experiment
OCTL	Optical Communication Telescope Laboratory
OGS	Optical ground station

PDF	Probability distribution function
PMC	Payload microcontroller
PPM	Pulse position modulation
PPP	Point-to-Point Protocol
PSF	Point spread function
PWM	Pulse width modulation
RF	Radio frequency
RMS	Root mean square
SNR	Signal-to-noise ratio
SOTA	Small Optical TrAnsponder
SPI	Serial Peripheral Interface
SSO	Sun-synchronous orbit
STAR Lab	Space Telecommunications, Astronomy, and Radiation Laboratory
SWaP	Size, weight and power consumption
TROPICS	Time-Resolved Observations of Precipitation structure and storm In- tensity with a Constellation of Smallsats
UART	Universal asynchronous receiver-transmitter
USB	Universal Serial Bus
WDM	Wavelength division multiplexer

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CHAPTER 1

Introduction

The use of small satellites has seen a vast increase in popularity in the recent years. Ride-sharing with bigger satellites has allowed much cheaper launch opportunities for smaller payloads as secondary cargo and opened the low Earth orbit (LEO) to more potential customers. Autonomous deploying mechanisms, such as the NanoRacks CubeSat Deployer on the International Space Station (ISS) or other specialized launcher adapters greatly facilitate the deployment of tens to hundreds of small satellites on a single launch, allowing customers to split the expense and access more frequent launch spots [1].

1.1 Increasing Downlink Demand in LEO

With easier access to space and quick pace of technological improvement, the satellite builders pursue faster, iterative development cycles. This paves the way for more advanced and miniaturized technologies into their payloads with increasing processing power and data acquisition capacity. There are multiple examples which illustrate how immensely data-intensive LEO applications of small satellites can be with currently available technology.

In the category of scientific missions, a constellation currently being designed at the MIT Lincoln Laboratory, called TROPICS, aims to use CubeSats to provide rapidly updated data for weather models. The twelve planned satellites will continually scan the swath of atmosphere below using microwave radiometers and produce data at a steady rate of about 16 kbps, thus, generating about 1.5 GB of information to be downlinked per satellite per day [2].

Another even more data-intensive application of high scientific interest is hyperspectral imaging, where the inclusion of additional frequency channels in the collected imagery substantially increases the output data rate. A disaster monitoring mission depicted by Tsitas and Kingston proposes a multispectral CubeSat

imager for tracking the progress of a flood, generating 127 Mb of compressed data every second of operation [3]. A mission outlined by Mandl et al. equips a Cube-Sat with an even more sophisticated hyperspectral imager that would produce raw data rates on the order of Gbps, collecting over a terabyte of information over one orbit, assuming enough power is available for continuous operation [4].

In the category of commercial missions, several private companies are currently developing constellations of small satellites designed to provide various attractive global services, focused mainly on remote Earth sensing and worldwide lowlatency Internet connectivity.

Planet (formerly Planet Labs), a startup focused on rapid Earth imaging, has already launched over a hundred CubeSats weighing below 5 kilograms, and equipped with 3-5 meter resolution imaging capabilities. The satellites, called Doves (see Figure 1.1), contain an optical telescope that occupies most of the space in its 3U bus [5]. Each Dove takes a roughly 4 MB sized image every second, and together, the constellation acts as a line scanner for the whole Earth. In its full capacity, Planet plans to operate up to 150 satellites in a Sun-synchronous orbit (SSO) and provide access to sub-daily new imagery of the entire planet. To accomplish this goal, it must downlink approximately 6 TB of images every day. As of 2016, the company was capable of downlinking 550 GB of imagery per day over its X-band downlinks, with a data rate of up to 84 Mbps [6].



Figure 1.1: A Dove - Planet's rapid-imaging CubeSat [7].

Other, more enormous commercial constellations are being developed with the goal of providing worldwide low-latency Internet connectivity from LEO. One of such proposals came from OneWeb, a company which recently successfully obtained a license from the Federal Communications Commission (FCC) to operate its constellation of 720 small satellites [8]. With an outlined capacity of ten ter-

abits per second, it is also a good example of how the data throughput from small satellites is rapidly increasing.

1.2 Nanosatellite Communications Constraints

As the number of small satellites in orbit grows and their downlink demand is getting higher, pressure is put on their on-board communications systems and the ground-based receiver infrastructure. There are, however, fundamental constraints in increasing the downlink rates from nanosatellites using currently available technology.

The primary engineering constraint of a small satellite platform is its size, weight and power consumption (SWaP). SWaP is fundamental to on-board communications systems, as more power and size generally means higher performance communications capability. As the link capacity inherently depends on the channel bandwidth and the signal-to-noise ratio (SNR), the higher the received power is, the higher the chance is to achieve fast downlink rates.

We can analyze the constraints further by looking at the simplified version of the link equation, also called the Friis transmission formula:

$$P_{Rx} \propto \frac{P_{Tx} A_{Tx} A_{Rx}}{\lambda^2 R^2} \tag{1.1}$$

where P_{Rx} is the received power, P_{Tx} is the transmitted power, A_{Tx} is the transmitter aperture area, A_{Rx} is the receiver aperture area, λ is the wavelength and R is the distance between the receiver and the transmitter.

It can be seen that most of the terms in play are difficult candidates for radical improvement, either due to SWaP or cost constraints. P_{Tx} is fundamentally limited by the available power on the satellite (e.g. photovoltaic technology). A_{Tx} is constrained by the size and mass of the satellite, while a high A_{Rx} antenna would be very costly for a nanosatellite operator. R is given by the orbit, and so is essentially constrained by physics. The only term where order-of-magnitude improvements are technologically feasible is the wavelength/frequency.

Historically, the majority of CubeSat-sized missions have flown with lower frequency (UHF or S-band) communications systems, with data rates of up to 3 Mbps [9]. A few organizations are developing transceivers in the higher frequency X and Ka-bands. As mentioned, Planet is flying X-band transmitters and has registered spectrum for theoretical downlinks of up to 200 Mbps [9]. Syrlinks has also developed commercially available X-band radios for CubeSats [10, 11]. However, the licensing of the high-frequency RF spectrum that is necessary for faster downlinks is a huge bottleneck. Especially for projects with a limited budget and a fast development cycle, obtaining a portion of the spectrum in the higher bands is extremely difficult and can take longer than the time needed to design, manufacture and test the whole satellite [12, 13]. In general, the situation in the overcrowded RF spectrum is expected to worsen as more satellites enter into orbit and licensing organizations such as the FCC struggle to keep up with the demand [14].

In conclusion, the small satellite platform lacks a convenient and scalable highrate communications solution.

1.3 Laser Communications

Lasercom is one of the key contenders in providing next generation high-rate space communication links. It utilizes laser beam propagation in free space as the signal carrier, often in the visible or near-infrared (NIR) spectrum. This makes laser downlinks and uplinks feasible, as the Earth's atmosphere is sufficiently transparent at these wavelengths, similarly as in the radio "window" (Figure 1.2).



Figure 1.2: Opacity of the Earth's atmosphere to electromagnetic radiation [15].

The orders-of-magnitude shorter wavelength is the core benefit of lasercom, because it enables narrower beams given the same effective aperture size. With a narrower beam, the energy density of the signal increases, which leads to more efficient SWaP utilization. The spectrum is also attractive because of the enormous bandwidth that it encompasses. In fact, the entire bandwidth of the RF spectrum can fit within a small window of the NIR spectrum portion that is utilized for lasercom. Since the carrier frequencies are on the order of terahertz, there is an extensive amount of bandwidth available. The second significant benefit is that this spectrum is nearly unregulated. Since the narrow beamwidths present negligible risk of interference, the only regulations on lasercom in general are imposed with regards to eye safety [16]. For lasercom downlinks, however, the transmitted power is spread out over a larger area, and thus is far below the maximum permitted exposure limit. Safety has to be, however, considered for the case of uplinks since the power is concentrated on the ground.

With the narrow beamwidths, however, lasercom becomes challenging to implement due to the accurate pointing that needs to be established between the transmitter and the receiver. Depending on the beamwidth (divergence) used, the required pointing accuracy is usually beyond the satellite's body pointing capability, and so fine pointing stages have to be implemented [17]. This is especially challenging for nanosatellites, given the strict SWaP constraints.

Another obvious issue of lasercom is its susceptibility to atmospheric effects. Cloud coverage can lead to absorption, or even complete obstruction of the downlink line of sight. Atmospheric turbulence also leads to undesired variations in signal intensity, phase, and direction [18]. These effects are primarily mitigated by site selection and ground station diversity [19, 20]. Studies have shown that a combination of three or more sites can lead to a downlink availability higher than 90% [21].

Table 1.1: Summary of key advantages and challenges in the implementation of lasercom.

Advantages			
+ Better SWaP utilization: higher gain with smaller terminals			
+ Highly directional: interference or interception is unlikely			
+ Regulatory benefits: free spectrum and essentially unlimited bandwidth			
Challenges			
 Precision pointing required 			
– Atmospheric channel impairments			
– Eye safety regulations for uplink			

Ultimately, if the outlined challenges can be solved, the benefits of lasercom can be extremely advantageous, especially for small satellite platforms. The ability to downlink more data with less SWaP, and the advantage of free spectrum allocation, can enable a wide variety of new interesting scientific as well as commercial missions, that are either impossible or very difficult to implement with currently available nanosatellite communications technology.

1.4 Thesis Objective and Structure

To demonstrate the feasibility and benefits of using lasercom on a nanosatellite platform, the MIT Space Telecommunications, Astronomy, and Radiation Laboratory (STAR Lab) is currently developing a CubeSat communications payload called the Nanosatellite Optical Downlink Experiment (NODE). NODE targets a 10-100 Mbps optical downlink, with the primary aim of demonstrating a variety of technologies that are necessary to enable scalable high-rate lasercom within a highly SWaP constrained environment. One of the technologies is a compact fine laser pointing stage that augments the host satellite's body attitude determination and control system (ADCS).

This thesis focuses on the fine pointing system of NODE. Although NODE, including its pointing subsystem, is essentially past the design review, there is no integrated hardware setup of the subsystem developed yet. While some components of the system were individually tested, a general hardware-in-the-loop testbed of the pointing system is needed to develop and verify the fine pointing algorithms. Thus, the primary goal of this work is to advance the technology readiness level of the system by developing such setup, with emphasis on the following sub-objectives:

- 1. Assemble the optics and electronics of the fine pointing system based on the NODE design in the laboratory.
- 2. Develop embedded pointing control algorithms for the system hardware.
- 3. Research how the inclusion of an internal calibration laser can improve the pointing accuracy and robustness.
- 4. Verify the precision of the fine pointing system under the expected host satellite body pointing disturbance.

The thesis is structured into five major chapters. The next chapter focuses on further research background on the topic and on the NODE system-level architecture. Chapter 3 covers all theoretical aspects of the development process (i.e. mainly sub-objectives 2 and 3). Chapter 4 focuses exclusively on the practical and experimental aspects of the work (objectives 1 and 4). The last chapter summarizes the achieved results, the thesis contributions, and discusses future work.

CHAPTER 2

Background

In this chapter, we investigate prior successful demonstrations of fine laser pointing on satellites, and compare their approach with the challenges associated with a nanosatellite implementation. Afterwards, we present the NODE system-level architecture and derive the fine stage pointing precision requirement. Lastly, a recapitulation of previous research that has been carried out in STAR Lab with regards to the fine pointing system is given, with emphasis on takeaways that are linked to the objectives of this thesis.

2.1 Fine Pointing on Prior Missions

In the recent years, a large number of different lasercom links have been demonstrated, in scenarios including LEO-to-ground [22, 23], LEO-to-LEO [24], GEOto-ground [25, 26], GEO-to-LEO [27, 28], deep space-to-ground [29], groundto-deep space [30], GEO-to-aircraft [31], aircraft-to-ground [32, 33], aircraftto-aircraft [34], and stratospheric balloon-to-balloon [35]. Several interesting projects are also in development for demonstration in the near future [36–42].

The vast majority of the successful missions utilize some kind of fine pointing mechanism to improve the beam pointing accuracy. While most of the missions are outside the scope of NODE in terms of targeted usage area or SWaP, two systems with comparable utilization and parameters are highlighted here for analysis.

The first notable system is the Laser Communication Terminal (LCT), developed by the German company Tesat Spacecom. LCT is a more generic design that was successfully used on multiple missions. The first generation of LCT was launched in 2001 to demonstrate lasercom links between LEO and GEO, but also successfully completed a LEO downlink measurement campaign [43]. Recently, the second generation of LCT was implemented, as part of the European Data Relay System (EDRS) mission. EDRS is a constellation of GEO satellites designed to relay data between LEO satellites and ground stations that would be otherwise outside the satellite's line of sight. Under EDRS, LCT successfully demonstrated 1.8 Gbps links between Sentinel-1 in LEO an Alphasat in GEO in 2014 [44].

The LCT pointing system consists of 4 independent pointing stages on top of the host spacecraft body pointing capability. This includes a two-axis gimbal assembly, a coarse FSM, a fine FSM, and ultimately a mirror dedicated for point-ahead angle compensation on the downlink [45]. LCT is by design a bidirectional system, so the transmitted signals also provide pointing feedback to the receiver sides. Altogether, the coarse gimbal assembly and the three steerable mirrors enable a RMS pointing accuracy of 100 μ rad [43]. LCT weighs 56 kilograms and during peak transmission consumes 160 W of power, and so is deployable only on medium to large satellite platforms.

The second notable system is the Small Optical TrAnsponder (SOTA), developed by Japan's National Institute of Information and Communications Technology (NICT). SOTA is a lasercom terminal designed to fit on a host microsatellite bus called SOCRATES. SOTA augments the bus ADCS with two pointing stages: a gimbal assembly and an FSM. It incorporates four different downlink lasers, two of which are used for communications at different wavelengths [46].



Figure 2.1: On the left, the LCT, made by Tesat Spacecom, with an aperture diameter of 13.5 cm [47]. On the right, the NICT-designed SOTA, as part of the SOCRATES spacecraft, with an aperture diameter of only 5 cm (images are not drawn to scale) [48].

SOTA utilizes a beacon uplink laser from the ground station for precision pointing feedback, and while it is locked, achieves a pointing accuracy of about 150 μ rad, based on measurements of pointing losses [49]. The lasercom terminal weighs only 5.9 kg and consumes 40 W of power. Since it launched in 2014, SOTA successfully demonstrated several lasercom downlinks from LEO at 10 Mbps.

While SOTA has been one of the most compact lasercom satellite terminals demonstrated so far, its SWaP is still beyond what nanosatellite platforms can offer. A typical 3U CubeSat weighs no more than 4 kilograms and typically consumes only 10 to 20 W. In order to address the satellite platforms of this scale, further miniaturization and SWaP reduction of the terminals is necessary, and thus heavy mechanisms such as gimbals have to be inevitably avoided. In Table 2.1, the key design parameters of LCT and SOTA are summarized, and compared with the targeted parameters of NODE.

Design parameter	LCT 2 nd Gen.	SOTA	NODE
Link type	LEO-GEO-ground	LEO-ground	LEO-ground
Wavelength (nm)	1064	976/1550	1550
Data rate	1.8 Gbps	1/10 Mbps	10-100 Mbps
Range (km)	< 45000	< 1000	< 1000
Mass (kg)	56	5.9	0.6
Transmitted power ¹ (W)	2.2	0.27/0.04	0.2
Power consumption (W)	160	40	15
Aperture diameter (cm)	13.5	5	2.54
# of pointing stages ²	5	3	2
Pointing accuracy ³ (μ rad)	100	~150	< 100 (exp.)

Table 2.1: Key design parameters of LCT and SOTA vs. targeted NODE parameters.

¹Average transmitted power values.

²This number includes the host spacecraft ADCS.

³Root mean square (RMS) pointing accuracy.

2.2 NODE Architecture

NODE aims to advance the state of the art in nanosatellite communications and provide a high-bandwidth downlink that is compatible with the SWaP constraints of a typical CubeSat. It is designed to occupy approximately 1U, and so serve as a potential communications payload for different host CubeSats. The first generation has a baseline goal of a 10 Mbps link rate and a stretch goal of 100 Mbps. It was, however, designed to be scalable, and so much higher data rates are envisioned in the next generation, once the fundamental technology and design is successfully demonstrated in flight.

To increase the affordability and performance, commercial off-the-shelf (COTS) components are used in the design where feasible. This also led to the choice of the downlink wavelength of 1550 nm, as its wide usage in the fiber optics industry caused wide availability of COTS components, such as optical fiber amplifiers [50]. Apart from the downlink 1550 nm laser, the NODE design also utilizes an uplink beacon laser to facilitate precise pointing. The beacon is transmitted from the optical ground station (OGS) and detected on an on-board detector, so that the fine pointing stage has accurate knowledge of the OGS location, and can track it by steering an FSM. The host satellite also contains a regular bi-directional radio to be used for telemetry transmission.



Figure 2.2: Illustration of beacon detection on-board NODE [51].

2.2.1 Concept of Operations

The operational concept of NODE can be split into three major phases. In the first phase, the whole satellite will begin a slew maneuver to point towards the OGS using the bus ADCS. This ensures that the OGS will be within the beacon detection system field of view (FOV) at all time. In the next phase, the OGS will begin to track the satellite as it as passes over, and transmit the beacon navigation signal. Once the beacon is acquired on the NODE detector, the fine pointing stage will begin the third, tracking phase, during which it will lock onto the signal and initiate the laser downlink.



Figure 2.3: The three operational phases required to initiate a lasercom downlink. In the first phase the whole satellite body slews towards the OGS, so that the uplink beacon is within the detector's FOV. After the beacon is acquired, the fine pointing stage is initiated, and will track the beacon signal with high precision. Finally, the laser downlink is initiated [52].

The primary targeted OGS for the downlink demonstration is the Optical Communication Telescope Laboratory (OCTL) operated by the NASA Jet Propulsion Laboratory, located at the Table Mountain Observatory in California. OCTL has a one meter receiver aperture, which will facilitate downlinks up to an expected rate of 100 Mbps. OCTL also includes a powerful 9 W beacon laser with a wavelength of 976 nm, for which the NODE beacon detection system was designed.

Simultaneously with NODE, STAR Lab is also developing an amateur portable optical ground station of its own to be used as a compact receiver. The portable OGS is based on an amateur telescope for astronomy, albeit extended with a custom opto-electronic module to enable processing of the downlink signal. The telescope has an aperture size of \emptyset 30 cm, and 10-50 Mbps rates are expected when it will be used for communications. The downlink budget to each OGS is summarized in Table 2.2 and analyzed in greater detail in [36].

Parameter	Portable OGS	JPL OCTL	Units
Channel data rate	9.9	43	Mbps
PPM order	128	16	
Average optical power	-7.0	-7.0	dBW
Transmit optical loss	-1.5	-1.5	dB
Transmit gain	65.0	65.0	dBi
Pointing loss	-3	-3	dB
Path loss (1000 km)	-258.2	-258.2	dB
Atmospheric loss	-1.0	-1.0	dB
Receive gain	114.7	126.1	dB
Receive optics loss	-2.0	-3.0	dB
Receive implementation loss	-3.0	-3.0	dB
Signal power at detector	-92.9	-82.6	dBW
Needed power for BER = 10^{-4}	-93.2	-84.2	dBW
Margin at 1000 km	0.23	1.62	dB
Margin at 600 km	3.04	4.30	dB

Table 2.2: Simulated link budget to the portable OGS and to OCTL at JPL [36].

2.2.2 Pointing Requirement

NODE is designed with a single FSM-based fine pointing stage, which has to be versatile enough to reject the whole possible range of the spacecraft body pointing error. To reach its mission goal, the beamwidth of the NODE transmitter was chosen based on the downlink budget analysis and the availability of COTS collimators [50,53]. As a result, a beam collimator with a full width at half maximum⁴ (FWHM) divergence angle of 1.3 mrad was selected.

Since the downlink plan budgets a maximum of 3 dB for pointing losses, the beam has to be steered within its FWHM angle, so that at least the half-maximum power hits the receiver. This sets the pointing accuracy requirement of the fine pointing stage to ± 0.65 mrad. The minimum range within which the system has to operate was chosen in the early NODE design phase based on the expected

⁴Also referred to as the half-power beamwidth in traditional RF communications.

worst-case host satellite pointing capability. To make the design compatible with standard CubeSat pointing capabilities a minimum pointing range of \pm 3 deg was derived [53].

Table 2.3: Summary of parameters and requirements related to the pointing stage.

Divergence angle (FWHM)	1.3 mrad	
Pointing requirement (-3 dB)	\pm 0.65 mrad	
Minimum fine pointing range	\pm 3 deg / \pm 52.4 mrad	

2.3 Associated Research

In this section, we summarize previous research that was done in STAR Lab and is related to the NODE pointing system. Relevant prior takeaways that influenced the development of this thesis are also highlighted.

Pointing, Acquisition, and Tracking Analysis

T. Nguyen and K. Riesing built on top of the initial work of R. Kingsbury, and started the design from which the current fine pointing system is derived [50, 52, 53]. [52] thoroughly researched the beacon detection approach, and selected the hardware candidates for the beacon detector and the focusing lens. It also investigated potential frame processing algorithms for hardware implementation, which inspired some parts of the development process in this thesis, especially in the area of reliable beacon acquisition and tracking.

Characterization of the FSM that was selected for NODE was also researched in [50, 53]. By identifying various small sources of error in the open-loop steering of the mirror, including thermal deformation, zero position shift, sensitivity, and repeatability, the research inspired the potential of rejecting these errors by inclusion of a calibration laser in the newest design, which is a core research area of this thesis.

Beacon Link Budget

The work in [51, 52] also focused on the design of a beacon link budget based on the selected NODE hardware and parameters of the OCTL beacon laser. The resulting simulation was further adapted by R. Morgan, and provides good analysis of the expected power on the beacon detector, which helped during the design of the acquisition and tracking algorithms in this thesis [54].

Optomechanical Alignment Analysis

Another area of research from which this work benefited is an optomechanical alignment analysis of the current NODE optical design performed by M. Lee [55]. As part of the analysis, a simulation of the selected NODE optics was implemented in the Zemax environment, which helped understand various optical properties of the system, such as the focused laser spot sizes, point spread functions, and ray geometries.

CHAPTER 3

Approach

To point precisely at the receiver, NODE relies on a fine laser pointing system based on a beacon detector and an FSM, which augments the ADCS of the spacecraft bus and corrects for its pointing error. In Section 3.1, the NODE optics and the pointing system structure is described in detail, with some remarks on the selected flight hardware. Afterwards, the system is analyzed from a control engineering standpoint. In Section 3.3, the FSM dynamics are further analyzed, and an approach on the design of a closed-loop controller is presented. Section 3.4 focuses on the beacon acquisition and laser tracking algorithms, while Section 3.5 describes the derivation of a calibration algorithm devised to improve the control precision and robustness. Finally, Section 3.6 gives a high-level summary of the designed embedded control chain as a whole.

3.1 Payload Optics Analysis

A diagram depicting the core architecture of the NODE optics is shown in Figure 3.1. From a communications point of view, the architecture follows a monostatic design, as it only has a single aperture, through which the transmitted laser as well as the received beacon signal travels.

The beacon signal (light blue in Figure 3.1) is detected on-board the satellite on a camera through a focusing lens assembly. The downlink signal (red) is amplified in a fiber, collimated, and then reflected from the FSM and a dichroic¹ mirror outwards from the satellite. The fine pointing control is done by steering the FSM based on the angle of incidence of the beacon beam.

One disadvantage of the MEMS FSMs is that they lack any feedback sensors. This

¹Dichroic mirrors are characterized by having different reflectance/transmission properties for different wavelengths of light.



Figure 3.1: Optical diagram of NODE.

fact, combined with the possible misalignments in the system due to thermal and other effects can result in poor knowledge of where exactly the downlink signal is being pointed. For this reason, an internal calibration laser (black on diagram) was also included in the system design, albeit with a different wavelength, such that it is not reflected outwards from the satellite but back into the on-board camera. Sampling this signal on the camera then provides a direct optical feedback of where the FSM is pointing.

As outlined in Section 2.2, NODE leverages different wavelengths for different

purposes. All in all, the signals can be summarized as follows:

- **Beacon signal:** 976 nm laser beam from the ground station provides onboard knowledge of the ground station's location.
- **Downlink signal:** 1550 nm modulated downlink beam is used to transmit data to the optical ground receiver.
- Internal calibration/feedback signal²: 635 nm internal calibration laser is used as optical feedback of the FSM pointing angle.

3.1.1 Optical Hardware

In this section, a summary of the most important components used mainly as part of the fine pointing system is presented. As is common with CubeSat hardware, NODE too relies on COTS parts where feasible, which holds true for all the optical components. For the most part, the hardware was selected after numerous design iterations and trade-off studies, which, if relevant, are referred to in each case together with brief reasoning on the final component selection.

Internal Laser Sources

NODE internally generates two optical signals: the downlink signal and the calibration signal. The 1550 nm transmitter design is not covered in this thesis as it is not essentially relevant to the pointing system. Its design is based on previous research done by R. Kingsbury which is presented in great detail in [50].

The calibration laser itself does not need to be modulated as it is merely used as an optical feedback of the internal pointing angle, and thus a simple fibercoupled laser diode that can be switched on and off is sufficient. Its most important property of interest is the output power. Since the beacon camera is meant to detect very low power light from the uplink beacon due to its significant free-space path loss, the calibration laser should ideally be as low power as possible because the beam experiences negligible losses internally with comparison to the beacon signal (tens of dB vs. hundreds) [52]. The diode that was ultimately selected is a 1 mW fiber-coupled 635 nm laser diode manufactured by QPhotonics.

Beacon Detector

One of the most important pieces of hardware for beacon detection and tracking is the on-board camera. K. Riesing and T. Nguyen examined several focal plane

²Throughout this text this is referred to as either the calibration or the feedback signal/laser.

arrays (FPAs) in [51,53] and assessed which would best suit NODE. The beacon wavelength, being not too far in the infrared spectrum, allows for utilization of silicon detectors. These are significantly more affordable than sensors that operate wholly in the infrared, like InGaAs-based or similar. The main factors considered in the selection of the FPA were readout noise, dark current, quantum efficiency in near-IR, the pixel pitch and former space heritage.

After multiple design iterations, the 5-megapixel Aptina MT9P031 FPA was selected due to its small pixel size of 2.2 μ m and previous space heritage. The small pixel pitch allows for using shorter focal length lenses (hence saving space) while retaining good angular resolution for beacon tracking. The sensor has a quantum efficiency of 3% at 976 nm, which is sufficient for detection of the OCTL beacon. A compact COTS industrially packaged camera which incorporates the Aptina FPA and control electronics in a housing was selected from the German manufacturer Matrix Vision. The whole package is only 40 mm wide and weighs about 80 grams (see Figure 3.2).



Figure 3.2: On the left, the Matrix Vision mvBlueFox-IGC [56]. On the right, the Schneider Optics Xenoplan 1.4/23 Compact lens assembly [57].

Focusing Lens

Under ideal conditions, the lens system focuses the inbound beacon beam into a point on the detector whose location determines the angle of the beam's incidence. T. Nguyen created a list of COTS lens assemblies for NODE that are potentially suitable for flight and are vacuum-compatible in [52]. The primary property of interest of the lens is the focal length which determines the detector's field of view

(FOV). Apart from the FOV, low aberrations and a compact size were the driving factors in the selection process.

To correct for lens aberrations and ensure beacon detectability across the FOV, a system with multiple elements is preferred, as it performs better in maintaining a high brightest pixel flux fraction at different field angles [52]. Larger lens aperture also improves detectability by collecting more photons and thus increasing the receive chain gain. Ultimately, the selection came down to a compact lens assembly by Schneider Optics from the Xenoplan series (Figure 3.2). The Xenoplan 1.4/23 is a compact 6-segment lens assembly with a focal length of 22.5 mm and a clear aperture of approximately \emptyset 16 mm. The manufacturer also offers a ruggedized version of the lens which offers stable imaging performance even in shock and vibration dominant environments, which is of great benefit due to the harsh satellite launch conditions.

Knowing the detector and lens properties, two important parameters of the beacon tracking system can be calculated: the total angular FOV of the system and the FOV of one pixel on the sensor. As can be seen in Figure 3.3, using the similarity of triangles, the half-angle angular FOV of the setup can be defined as:

$$\frac{AFOV}{2} = \tan^{-1}\left(\frac{h}{2f}\right) \tag{3.1}$$

where *h* is either the detector's height or width and *f* is the focal length of the lens. Substituting in the hardware properties, the sensor's half-angle FOV is calculated to be 5.43 degrees vertically and 7.22 degrees horizontally. Similarly, substituting $\frac{h}{2}$ with the pixel size, the pixel angular FOV is found to be 0.0056 degrees, or approximately 98 μ rad. A more comprehensive FOV analysis is presented in Section 3.1.2 - Signal Analysis.

Dichroic Mirror

The dichroic mirror is located between the focusing lens and the satellite's main aperture. It is an important component from an optics standpoint as it determines the routing of the optical signals depending on their wavelength. Its intended purpose can be summarized in three points:

- 1. Reflect as much of the downlink 1550 nm signal as possible outwards through the main satellite aperture, i.e. act as a **mirror**.
- 2. Partially pass and partially reflect the 635 nm feedback signal, such that it can be detected on the camera, i.e. act as a **beamsplitter**.
- 3. Ideally, do not reflect any of the 976 nm signal so beacon detectability is not worsened, i.e. act as a **window**.



Figure 3.3: Angular FOV of a lens and detector system.

The dichroic mirror is placed at 45 degrees relative to the aperture's optical axis. A regular mirror is added on its side in order to reflect the partially passed feedback signal back and then to the camera through the focusing lens.

Due to the very specific requirements, finding an affordable COTS component of such properties is not easy. Eventually a trade-off was made and a COTS dichroic mirror manufactured by Thorlabs was selected, instead of ordering a custom solution. The Thorlabs DMLP1800R is a rectangular longpass dichroic mirror with a cutoff wavelength of 1800 nm. The primary property of interest is the mirror's reflection band between 1500 - 1750 nm which is guaranteed to be above 90% by the manufacturer. The bands for 635 nm and 976 nm are outside the mirror's intended operating range and are determined mainly by the manufacturing process. The reflectance characteristics of DMLP1800R can be seen in Figure 3.4 below, with the bands of interest highlighted in red.

It can be seen that the DMLP1800R mostly fulfills the needed criteria. The 1550 nm signal is almost perfectly reflected, with 99% reflection at this wavelength. The dichroic mirror reflects 85% of 635 nm light, therefore, assuming no loss, 15% is transmitted through, and 85% of that is then reflected towards the camera after reflection from the side mirror. Consequently, taking into account potential losses on both the dichroic and the regular mirror, about 10% of power from the calibration laser diode reaches the focusing lens, which is sufficient as the signal is generated internally and experiences negligible free-space path loss. The only drawback of DMLP1800R is the higher 53% reflectance at 976 nm, which had to be taken into account during the beacon link budget analysis.



Figure 3.4: Reflectance characteristics of the DMLP1800R, with bands of interest highlighted in red. The data is for unpolarized light with a 45 degree angle of incidence [58].

Bandpass Filter

To minimize noise on the beacon detector and thus add margin to the beacon link budget in terms of SNR, a bandpass filter is added to the satellite's main aperture to block background light from the Earth. The filter also helps protect the lens assembly from potentially damaging UV radiation from the Sun. A double-bandpass design was selected to attenuate all wavelengths apart from the downlink 1550 nm and the 976 nm beacon signal from the OGS. In this case, a ready-available COTS solution is unavailable, instead, a custom filter was ordered from the supplier Omega Optical. The characteristics of the received filter are shown in the graph in Figure 3.5.

The transmission at the center wavelengths of 1550 and 976 nm is above 85% with passband bandwidths of about 80 nm and 40 nm respectively. Out of these bands the transmission is on average below 0.02% which corresponds to about -37 dB of attenuation. The benefits of this in terms of SNR were addressed in the beacon link budget developed by T. Nguyen and R. Morgan (Section 2.3).

FSM

The FSM is integral to the fine pointing system: it steers the downlink beam towards the OGS based on the beacon's angle of incidence. Technological advancements in the industry that led to the development of ultra-compact microelectromechanical (MEMS) FSMs were one of the key enablers that made the NODE design feasible given the highly space and weight constrained environment.



Figure 3.5: Transmission characteristics of the custom Omega Optical double-bandpass filter.

The fine pointing system utilizes a MEMS FSM manufactured by Mirrorcle Technologies. The company offers a variety of 2-axis FSMs based on mirror size and steering range that are built in an extremely compact chip-scale package. For NODE, the most compact version that is pre-soldered on a small printed circuit board was selected, with a mirror diameter of \emptyset 3.6 mm and a mechanical steering range of \pm 3 degrees (the reasoning for the chosen range is given in Section 3.1.2 - Signal Analysis). The entire package, called TINY20.3, is only 20 x 13 mm in size (see Figure 3.6). The FSM dynamics are further discussed in Section 3.3 - FSM Dynamics & Control.

Collimator

The collimator is turning the fiber-propagated optical signal into a collimated freespace beam. Its properties determine the beam divergence angle, which in turn determines the pointing requirements. As described in Section 2.2.2, the beamwidth was chosen based on the link budget, as well as the availability of COTS components. A collimator from Thorlabs with a FWHM divergence angle of 1.3 mrad was eventually chosen. The CFS5-1550-APC is factory-calibrated for 1550 nm light, has a diameter of \emptyset 1 mm and is about 2 mm in length (see Figure 3.6).

Coupler

To ensure that the downlink signal and the calibration signal share the same exact beam path to the FSM, they need to be coupled into one fiber and fed into the same collimator. For this reason, a wavelength division multiplexer (WDM) is




Figure 3.6: On the left, the Mirrorcle Technologies FSM in a TINY20.3 TinyPCB package [59]. On the right, the Thorlabs CFS5-1550-APC Pigtailed Aspheric Collimator [60].

used. A WDM by Thorlabs (WD202A) was selected for NODE as the best COTS alternative. The WDM is intended to combine 1550 and 980 nm signals, but the vendor confirmed that the 980 nm channel can be used with a 635 nm signal with slightly higher insertion loss as the only drawback.

3.1.2 Signal Analysis

To further analyze the influence of the optical components on each signal, a summary of the signal paths with some relevant nuances that were identified is presented, together with a comprehensive depiction of the system's FOV (Figure 3.8) and the expected signal point spread functions (PSFs) on the FPA (Figure 3.7).

Beacon to Camera Path

The beacon signal is generated in the vicinity of the optical ground station to provide the most accurate knowledge of the receiver's location. The collimated 976 nm beam experiences significant power losses due to its divergence, atmospheric conditions and the beacon detection optics. The link parameters are analyzed in depth by T. Nguyen and R. Morgan in [52,54]. The expected SNR on the detector ranges from 14 to approximately 17 dB, which facilitates reliable detection. Since the beacon beam will be well collimated, the spot size on the detector is expected to be very small. An optomechanical simulation model developed by M. Lee revealed that the expected beacon spot size on the detector is around \emptyset 10 microns which translates to ca. 5 pixels across [55]. As there are no obstructions to the beacon beam, under favorable conditions, its spot is detectable across the entire camera full-angle FOV of 14.44 x 10.86 degrees (double the calculated half-angle FOV in Equation 3.1).

Calibration Path

The calibration laser diode produces a 1 mW fiber-coupled signal that is fed into a WDM for coupling with the downlink signal and then transmitted into free space from the collimator. It has to be taken into consideration that the selected collimator is tuned for the wavelength of the transmission signal and will perform sub-optimally for the wavelength of the calibration laser. This is mainly due to chromatic aberration of the collimation lens, which makes its effective focal length depend on the input wavelength. Consequently, the calibration beam will not be perfectly collimated and the spot size will be bigger on the FPA. Similarly as for the beacon path, the simulation model revealed that this size should be approximately \emptyset 120 microns, or ca. 55 pixels across [55]. The model did not, however, account for a focusing lens corrected for chromatic aberrations (such as the Schneider Optics lens), and such this value is expected to be smaller in the real system. The PSFs of both the calibration and the beacon signal calculated in the simulation are shown in Figure 3.7 below.



Figure 3.7: PSF of the beacon (left) and the calibration (right) signal on the FPA, obtained from an optomechanical simulation of the system [55]. The X/Y scaling is \pm 50 microns in each case. The beacon PSF is much sharper due to good collimation and focusing but also includes background noise from the Earth as seen by the ripples over the plane. The calibration PSF is more spread due to imperfect collimation but contains negligible background noise as it is being generated internally.

The FSM can be mechanically tilted by ± 3 degrees in both axes which allows for ± 6 degree steering of the internally generated beam, as the optical tilt angle is twice the mechanical angle by definition. This is well within the expected host satellite pointing error. Moreover, in the maximum of the steering range, the beam of the calibration laser is too displaced after multiple reflections (FSM, flat side mirror, dichroic mirror) and does not hit the focusing lens aperture due to geometrical constraints. This limits the visibility of the feedback signal to about ± 5 degrees on the FPA.

Transmission Path

NODE is designed so that the transmission signal experiences minimal loss on the internal optics. Both the WDM and the collimator are factory-calibrated for its wavelength, the loss on the FSM and the dichroic mirror is very low as well as on the bandpass filter. The well-collimated beam can be steered within the full field of regard of the FSM and it exits the aperture with a FWHM divergence of 1.3 mrad per the collimator parameters.

A more comprehensive depiction of the pointing system's FOV with regards to each signal is shown in Figure 3.8 below. As it can be seen, there exists a region in which the beacon is detectable but is not addressable by the transmission beam (due to FSM throw) and by the calibration laser (due to geometrical constraints). However, these regions are well beyond the expected host coarse pointing capability and thus can be neglected. The FSM throw was chosen as a trade-off so that certain extra margin is kept but also the pointing angular resolution is not decreased due to a very wide steering range.



Figure 3.8: Analysis of the pointing system's FOV.

3.2 Pointing Control Concept

From a control theory standpoint, the pointing system is not meant to settle on a static value, but rather follow a varying setpoint given by the beacon's angle of incidence (off-boresight angle), which will drift as the host satellite's body pointing is disturbed. Consequently, the information that determines the desired pointing vector is the centroid of the beacon spot image on the FPA.

Similarly as in Figure 3.3 and Equation 3.1, we know that for a beacon signal with an angle of incidence θ_B at the satellite aperture, the following holds:

$$\tan \theta_B = \frac{|\vec{d_B}|}{f} \tag{3.2}$$

where f is the lens focal length and $\vec{d_B}$ is a focal-plane vector from the point where the FPA intersects with the lens optical axis (ideally its center) to the point onto which the signal rays are focused - the centroid of the beacon spot. The control goal is to align the transmission signal (coupled with the feedback signal) with θ_B . The pointing is thus optimal when the angle of the internal coupled signal, θ_C , equals θ_B at the satellite's aperture.

Likewise, for θ_C , the following holds:

$$\tan \theta_C = \tan \left(2\theta_{FSM}\right) = \frac{|\vec{d_C}|}{f} \tag{3.3}$$

where θ_{FSM} is the FSM mechanical tilt from its nominal pointing angle and $\vec{d_C}$ is a focal plane vector pointing to the centroid of the calibration laser spot.

If we analyze the ray geometry between the aperture and the lens, as is depicted on the left-hand side in Figure 3.9, we find that under optimal pointing, the beacon and the calibration rays are inverted in front of the focusing lens. This is due to the backwards reflection of the calibration beam from the side mirror. As a consequence, the vectors $\vec{d_B}$ and $\vec{d_C}$ mirror each other around a center of symmetry on the focal plane as long as θ_B equals θ_C . This is visualized on the right-hand side in Figure 3.9.

Because of this, the control goal can be written as:

$$\vec{d_C} \stackrel{!}{=} -\vec{d_B} \tag{3.4}$$

At this point, it is useful to switch to the coordinate frame of the camera's FPA as that is where the centroids will be sampled. The output from the camera is an image with origin in the top-left corner and is of 5 megapixels, 2592 pixels in width and 1944 pixels in height. This coordinate frame is also visualized on the right-hand FPA diagram in Figure 3.9.



Figure 3.9: Depiction of the ray geometry around the dichroic mirror, with the beacon beam in blue and the coupled transmission/calibration beam in red. If the beams are aligned at the aperture, they will have opposite angles of incidence at the focusing lens due to reflection of the feedback signal from the side mirror. As a result, the spot of the calibration laser has to mirror the location of the beacon signal around a center of symmetry on the FPA to achieve correct pointing, as is shown on the right-hand side.

We can now redefine $\vec{d_B}$ and $\vec{d_C}$ in these new coordinates as points on the image, P_B and P_C , in pixels and with origin in the top-left corner:

$$P_B = P_{CENTER} + \frac{\vec{d_B}}{\mu}$$
(3.5)

$$P_C = P_{CENTER} + \frac{\vec{d_C}}{\mu}$$
(3.6)

where P_{CENTER} is the location of the center of symmetry in pixels and μ is the pixel pitch. By inserting Equations 3.5 and 3.6 into Equation 3.4, we get:

$$\mu(P_C - P_{CENTER}) \stackrel{!}{=} -\mu(P_B - P_{CENTER})$$
(3.7)

which can be reduced and forms the final version of the equation that determines the desired value for the centroid of the feedback signal:

$$P_C \stackrel{!}{=} 2P_{CENTER} - P_B \tag{3.8}$$

3.2.1 Center of Symmetry Problem

In an ideal case, the point defining the center of symmetry between the beacon and feedback centroids, P_{CENTER} , would be in the center of the FPA. This would be the case if the lens was perfectly parallel with the FPA and its optical axis went exactly through its center. In reality, however, this is not necessarily the case, as there may exist a microscopic mechanical misalignment between the lens and the FPA, which would cause the optical axis of the lens to intersect with a different point on the FPA, and thus shift P_{CENTER} . Consequently, if this would be neglected, it would result in a fixed pointing bias, as the calculated P_C setpoints would not be compensated for the offset.

Another potentially severe issue is misalignment between the dichroic mirror and the regular flat mirror on its side. If the angle between these two mirrors is not exactly 45 degrees, or they are not both perfectly perpendicular to the baseplate (vertically), the calibration signal will always have an undesired offset on the FPA that will *skew the FSM pointing feedback*. Since the fine pointing system aims for the highest possible accuracy, and the pixels have FOV in the order of μ rad, microscopic misalignment could significantly worsen the pointing performance in this case as well. To compensate for this offset, the exact angle of misalignment would have to be subtracted from the P_C setpoints. Fortunately, this can also be achieved artificially by simply moving P_{CENTER} by a certain static offset, which is analogous to the lens misalignment problem.

Ultimately, if an appropriate P_{CENTER} is found experimentally with high precision, the control system is capable of compensating for both of the potential mechanical misalignment problems discussed. As the NODE mechanical structure will be built with certain machining tolerances, these misalignments should not be neglected, and finding the correct P_{CENTER} is a crucial step in assuring optimal performance of the pointing system.

An alternative optical design trade-off study that utilizes a retro-reflector and is also able to overcome these problems is discussed in Appendix A - Alternative Feedback Design with a Retro-Reflector.

3.3 FSM Dynamics & Control

The FSM from Mirrorcle Technologies is a gimbal-less scanning two axis (tip-tilt) MEMS mirror. It is mechanically steered by a set of electro-static actuators that dissipate less then a few milliwatts of power, and thus is one of the lowest SWaP COTS beam steering solutions available. The actuators are operated in a mode called the Bias-Differential Quad-channel (BDQ) mode, where each axis is linked to a pair of channels and rotated by differential voltage applied on the pair with a certain bias. This methodology is implemented either by custom amplification electronics, or a driver optionally provided by the manufacturer.

3.3.1 Feedback Mapping

In order to take advantage of the optical FSM pointing feedback and establish a control loop, a mapping, or transformation, between the measured feedback signal centroid position, P_C , and the FSM control voltage, V_{BDQ} , is needed.

If such mapping is known, a desired centroid location of the feedback laser, P_C^* , can simply be transformed:

$$(P_{C,X}^*, P_{C,Y}^*) \longrightarrow (V_{BDQ,X}, V_{BDQ,Y})$$
(3.9)

which immediately enables open-loop steering within the FPA reference frame, as P_C^* can be calculated from Equation 3.8 as long as P_B , the beacon centroid, is being tracked.

Likewise, if P_C is being tracked simultaneously, then a certain control error:

$$\Delta P_C = P_C^* - P_C \tag{3.10}$$

can be transformed:

$$(\Delta P_{C,X}, \Delta P_{C,Y}) \longrightarrow (\Delta V_{BDQ,X}, \Delta V_{BDQ,Y})$$
(3.11)

and fed into a controller to establish closed-loop FSM pointing.

Ultimately, a mapping that relates the FPA coordinate frame (where P_C is defined), to a coordinate frame defining the corresponding inputs, V_{BDQ} , is sought. Since this relationship is very sensitive to the geometrical alignment between the FSM and the FPA, a transformation with more degrees of freedom is desired to minimize the mapping error, as there may exist, for instance, certain rotation between the systems that causes unexpected X/Y axis coupling. Moreover, to enable open-loop control by mapping the points directly (as in Equation 3.9), a translational degree of freedom is also required as the two frames do not share the

same origin: the FPA system has origin in the image edge, whereas the FSM nominal zero tilt corresponds to the FPA center (ideally) and it can be steered in both positive and negative directions (see the system FOV analysis in Figure 3.8).

To fulfill these criteria, a mapping in the form of an affine transformation (also called an affine map) is chosen. Affine transformation is the most general form of a linear transformation, consisting of two functions: a linear map and a translation. In 2D space, the linear map is determined by a 2-by-2 matrix A and the translation by a 2-by-1 vector t. The affine transformation maps a point P to a new point, Q:

$$\begin{bmatrix} Q_X \\ Q_Y \end{bmatrix} = \begin{bmatrix} a_{xx} & a_{xy} \\ a_{yx} & a_{yy} \end{bmatrix} \begin{bmatrix} P_X \\ P_Y \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \end{bmatrix}$$
(3.12)

With six degrees of freedom, the affine transformation can cover a superposition of multiple generic operations. For example, the parameters of the linear map A can represent frame scaling, rotation, shearing and reflection, while frame translation is determined exclusively by the vector t. An example is visualized in Figure 3.10.



Figure 3.10: Illustration of a potential affine transformation between the FPA coordinate frame and the FSM input coordinate system, as described by Equation 3.13.

In our case, we are looking for an affine map between P_C^* and V_{BDQ} :

$$\begin{bmatrix} V_{BDQ,X} \\ V_{BDQ,Y} \end{bmatrix} = \begin{bmatrix} a_{xx} & a_{xy} \\ a_{yx} & a_{yy} \end{bmatrix} \begin{bmatrix} P_{C,X}^* \\ P_{C,Y}^* \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \end{bmatrix}$$
(3.13)

This formula corresponds to the mapping needed for open-loop control as shown

in Equation 3.9. For closed-loop FSM control (Equation 3.11), the translation vector t is cancelled out because differences (i.e. control errors) are used, which simplifies the formula to:

$$\begin{bmatrix} \Delta V_{BDQ,X} \\ \Delta V_{BDQ,Y} \end{bmatrix} = \begin{bmatrix} a_{xx} & a_{xy} \\ a_{yx} & a_{yy} \end{bmatrix} \begin{bmatrix} \Delta P_{C,X} \\ \Delta P_{C,Y} \end{bmatrix}$$
(3.14)

The matrix A is in this case sometimes referred to as the *sensitivity matrix*.

An approach for the actual determination of the transformation parameters is outlined and derived in Section 3.5 - Calibration Algorithm.

3.3.2 Pointing Modes

With a conceptual feedback mapping in place, a simple open-loop pointing chain can be set up, as is depicted in the block diagram in Figure 3.11 below.



Figure 3.11: A high-level block diagram of open-loop FSM pointing.

In this case, the camera is used solely as a beacon detector, tracking only the beacon centroid P_B . The beacon centroid is used to calculate P_C^* , the desired value of P_C (even though the calibration laser is turned off or not sampled) to follow the pointing concept. This value is then transformed into the FSM-space, and a control voltage is obtained and applied to the FSM after each sample.

Correspondingly, if the camera samples both the beacon and the feedback signal simultaneously, a closed-loop pointing control chain can be established. In this case, the control error is transformed using Equation 3.14, which gives the needed control error in FSM-space as a voltage. A simple discrete integral controller is then utilized to drive the FSM voltage, as the expected pointing disturbance is inherently slow and continuous. The integral term assures minimization of the steady-state error and compensation of potential nonlinearities in the system.

There are benefits and downsides for both of the control modes. The open-loop chain is very simple to implement if the feedback mapping is calculated. In this regime, only the beacon spot is sampled, so only a small fraction of the FPA needs to be read out continuously, which can be achieved with the camera windowing



Figure 3.12: A high-level block diagram of closed-loop FSM pointing control. An integral controller is utilized to correct for steady-state error calculated using the feedback signal.

functionality. This has the potential to considerably increase the sampling rate, as there is no need to sample the calibration spot, which is also bigger in size due to the optical properties of the system. The number of pixels to be sampled is therefore certainly less than half of what would be needed for closed-loop control, which leads to more than double the sampling rate. Moreover, if the calibration laser is turned off, there is no chance the two signals can interfere with each other on the FPA. On the other hand, the pointing accuracy of the open-loop mode inherently depends on the accuracy of the a priori calculated affine map. Any uncertainty in the map, or in a certain region on it, will directly cause a steady-state error that cannot be compensated. It is also unable to deal with any misalignment introduced throughout the control process, such as mechanical shifts caused by thermal expansion, which could make the affine map gradually obsolete. Hence, the open-loop chain lacks a certain robustness and is not very favorable.

The closed-loop mode is obviously more challenging to implement as the detector needs to sample two different signals simultaneously. Consequently, sampling rate is decreased and problems with interference can also arise, which potentially further increases implementation difficulty. The major benefit, however, is that the controller ensures rejection of steady-state errors. Even if the affine map has local uncertainties, e.g. due to neglected nonlinearities, the integral controller will make up for the introduced pointing errors. In addition, should temperature variations during fine pointing disrupt the optical alignment, the sensitivity matrix can be potentially updated continuously with new measurements from the calibration laser, and thus "learn" for gradual alignment changes in an adaptive fashion.

The pros and cons of the control modes are summarized in Table 3.1. Ultimately, both pointing regimes are to be implemented, with the closed-loop mode being

Open-Loop FSM Control	Closed-Loop FSM Control
+ simple implementation	+ error always converges to zero
+ higher sampling rate	+ can adapt to thermal shifts
+ no signal interference	 more complex implementation
– errors in steady state exist	 potential signal interference
– cannot adapt to thermal shifts	– lower sampling rate

Table 3.1: Summary of pros and cons between open-loop and closed-loop FSM control.

favored for its higher accuracy and robustness.

3.3.3 Dynamic Model

In order to tune the closed-loop controller optimally, the dynamics of the process chain need to be modeled. Modeling of the FSM itself is significantly simplified because the manufacturer provides each unit with a unique datasheet, where the FSM frequency characteristics measured during its factory calibration are documented. This allows for a quick determination of the FSM transfer function without the need to perform any system identification process.

For us, the two main parameters of interest are the FSM resonant frequency, w_0 , and its quality factor Q, which is analogous to the damping ratio. Based on these two parameters, the dynamics of the FSM can be modeled as a damped mechanical oscillator using a second order transfer function simply as:

$$\frac{\theta_{FSM}(s)}{V_{BDQ}(s)} = \frac{w_0^2}{s^2 + \frac{w_0}{Q}s + w_0^2}$$
(3.15)

Notably, because of a highly resonant step response, the manufacturer recommends usage of an analog low-pass filter (LPF) at the FSM input. The custom datasheet also provides the recommended cut-off frequency given the unique frequency characteristics. This LPF is to be included in the amplification electronics used to drive the FSM voltage. The driver provided by Mirrorcle Technologies already incorporates a 6-th order Bessel LPF for every of the four BDQ output voltages. For the dynamic model, the LPF is modeled in the MATLAB environment using the besself function in the Signal Processing Toolbox, from which the filter's transfer function is obtained based on its order and cut-off frequency.

To make sure the values are correct and the model is representative, we analyze its step response with and without the inclusion of the LPF, as shown in Figure 3.13. Comparing the modeled response with the real response measured by Mirrorcle Technologies, we find an identical match and thus assume a sufficient representation of the FSM dynamics for our needs.



Figure 3.13: Step response of the dynamic FSM model with and without a LPF on its input.

The last dynamic element from the chain is the camera, which samples the beam steered with the FSM. Since the camera is based on CMOS silicon photodiodes, the pixels have response times on the order of nanoseconds. While the camera itself dictates the sampling rate due to the large number of elements and the necessary exposure time, the dynamic response of each pixel is almost negligible when compared to the rather slow dynamics of the FSM. Consequently, we do not focus on modeling the dynamic response of the FPA, but instead, as a next step, model some of its other properties that more severely influence the control chain, such as readout noise and potential lag between frame capture and final centroid determination.

3.3.4 Controller Tuning

Following the determination of the dynamic system model, we continue by investigating it inside a control loop simulated within the MATLAB Simulink environment, so that a controller with suitable performance can be obtained. A typical recursive backward-Euler discrete integral controller is utilized:

$$I(z) = K_I T_s \frac{z}{z - 1}$$
(3.16)

where K_I is the tunable integral constant and T_s is the control loop sampling time.

The control loop simulation is further augmented by a quantizer to represent the digital-to-analog converter (DAC) resolution available in the mirror driver and by elements in the sampling chain. These include the readout noise, the FPA sampling rate and an artificial sample delay which is expected due to the camera USB interface and algorithm execution under a non-real-time operating system³. While the transfer functions were determined primarily in an analytical way, these blocks are tuned mostly after experimental measurement trials with the actual beacon camera, which are further discussed in Chapter 4. The complete controller tuning simulation scheme is depicted in Figure 3.14.



Figure 3.14: Simulation scheme used to tune the discrete integral controller.

The controller is tuned by analysis of its reference tracking capability using the Control Design Toolbox within Simulink. It has to be taken into consideration, however, that this simulation scheme does not account for inaccuracies that may exist in the feedback mapping, i.e. the feedback signal is directly used in the loop with unity gain. Moreover, slow frame rate and the non-real time nature of the system that leads to the transport delay between frame capture and eventual centroid calculation makes the system very sensitive to instabilities. A more conservative approach in the controller tuning is therefore taken, so that a stable, albeit slower response is maintained.

³The control loop and associated image processing algorithms are running as a process under the Linux operating system.

3.4 Detector Sampling

Before a controller can be implemented on the payload hardware, a technique to obtain and track centroids from the FPA exposures has to be developed. In this section, the approach on the sampling of the detector is presented, including centroid determination, its tracking, and beacon acquisition logic. Furthermore, an approach that enables simultaneous tracking of the two centroids, P_B and P_C , without significant mutual interference, is presented.

3.4.1 Frame Processing

The initial processing step is primarily focused on the determination of the centroids of the laser signals within the FPA, or a certain region of it. Given that the camera outputs a matrix of 10-bit values, an image processing algorithm that transforms this intensity map into 2D positional information is necessary. To make this procedure as flexible and reliable as possible, it was split into three independent phases: thresholding, grouping, and centroiding.

Phase 1: Thresholding

In the first phase, thresholding of the frame is performed, which discards all pixels below a certain determined intensity of significance. This leads to two benefits: it dramatically reduces the number of active pixels considered for further processing, and it also helps reject background noise that might add uncertainty to the centroid calculation.

To work reliably under a variety of SNRs, a unique threshold is calculated based on the properties of each frame that is captured. Since by design, a vast majority of each frame is the background, the mean intensity is utilized in the threshold calculation. This gives a good starting value, which is analogous to the average background noise intensity, albeit slightly biased upwards if there is a laser spot present. This value is then further offset by a small intensity offset to reject peaks in the noise distribution and used as the final intensity threshold.

This approach leads to the following threshold formula:

$$h_{threshold} = \frac{1}{WH} \left(\sum_{i=1}^{W} \sum_{j=1}^{H} h_{ij} \right) + h_{offset}$$
(3.17)

where h is a specific intensity and W and H is the frame width and height in pixels respectively.

Phase 2: Grouping

In the second phase, neighboring pixels that remained after the thresholding process are grouped together. As the shapes of the laser spots are continuous by nature, this step separates them from any potential leftover disturbances in the frame. A group size check is also performed, and groups that contain a negligible or extreme amount of pixels are discarded. This further helps to isolate the wanted signal and also serves as a technique to discard potentially radiation-damaged pixels that are stuck in a saturated state, also referred to as *hot pixels*. Finally, the groups are sorted by their maximum intensities in a descending order.

Phase 3: Centroiding

In the last phase, the actual centroid of each group is calculated using a standard center-of-mass formula:

$$P_k = \frac{1}{N_k} \sum_{i=1}^{N_k} h_{k,i} \, p_{k,i} \tag{3.18}$$

where P_k is the centroid of the *k*-th group, N_k is the number of pixels in that group, $h_{k,i}$ are the individual pixel intensities and $p_{k,i}$ are the pixel X/Y indices within the FPA. The final result from the initial frame processing algorithm is thus a list of pixel centroids sorted by brightness, serving as a prioritized "candidate list" for the sought signal in further processing.

3.4.2 Sampling Scheme

With a technique to process the raw data obtained from the FPA, we focus on the high-level sampling approach. In particular, the beacon acquisition and the subsequent centroid tracking logic is investigated.

Acquisition

Before the centroid tracking process can begin, the initial beacon signal has to be acquired. For this reason, a beacon acquisition procedure is designed and ran during which the calibration laser is disabled. The core of this procedure is continuous sampling of the whole FPA, while sweeping the exposure time and performing fast sanity checks on the frame histograms. If the sanity checks pass, the frame processing algorithm is executed and if a good signal candidate is found, acquisition is declared successful.

The exposure sweep is continuously performed in a rapid manner, so that there is a high chance of getting proper acquisition parameters for a wide range of beacon powers⁴ quickly, where the detector is neither too saturated nor reading zero. After each image is obtained, its histogram is calculated and two fast sanity checks are performed:

- 1. The highest intensity recorded in the histogram is verified. If this value is above a certain acquisition intensity threshold, the check passes.
- 2. The distance between the histogram maximum and the highest intensity is verified. This value serves as a good indication of whether a signal with sufficient SNR is present in the frame, such that it can be processed successfully. If the distance is above a certain threshold, the check passes.

If any of the checks fails, the frame is discarded and a new sample is immediately requested with adjusted exposure. If both of the checks pass, the frame processing algorithm is ran, which returns the potential signal candidates. If no centroids are found⁵, the frame is discarded and the acquisition procedure continues until a signal is found. Ultimately, if a good centroid is obtained from the processing algorithm, the beacon acquisition concludes successfully.

Straight after the beacon is acquired, the exposure time is fine-tuned for its power, and a window (i.e. region on interest) around the spot is determined for further sampling. In the next step, using the acquired P_B , the desired value of P_C is calculated following Equation 3.8, and initial pointing is set using the open-loop control mode. The feedback laser is then turned on and can be acquired on the detector in the given location. After both signals are acquired, the acquisition phase ends and the tracking phase can begin.

Tracking Logic

With the initial locations known, the centroids are tracked following a doublewindow sampling methodology. The core idea of this technique is that the camera is reconfigured after each frame to sample either a window around the beacon spot, or a window around the calibration laser spot, with exposure time unique to each window. The signals are sampled in an alternating fashion, such that a snapshot of the beacon is followed by a snapshot of the calibration signal, followed by a snapshot of the beacon again, and so on. This is visualized from the perspective of the FPA in Figure 3.15. Consequently, the request and update chain on the detector can be illustrated as shown below.

Acquisition \longrightarrow Request $P_B \longrightarrow \underset{\text{Request } P_C}{\text{Update } P_B} \longrightarrow \underset{\text{Request } P_B}{\text{Update } P_B} \longrightarrow \underset{\text{Request } P_C}{\text{Update } P_B} \longrightarrow \underset{\text{Request } P_C}{\text{Update } P_B}$

⁴The received beacon power will vary greatly due to change in distance during an overpass. Weather conditions may also severely affect the power during an overpass.

⁵This might also be the case when the frame is overexposed.



Figure 3.15: Illustration of the double-window sampling technique. The beacon and the feedback signals are sampled independently in an alternating fashion. Each signal is sampled with a different exposure window within the FPA that is adapted based on the location and power of the signal. The windows are switched after each sample so that both signals are sampled with a static rate.

After each sample update, the parameters for the respective window are recalculated iteratively, in order to adapt to the signal location and power changes. This technique is very advantageous, as it increases the sampling rate significantly due to the small window size that needs to be sampled in each step. Moreover, any potential disturbances outside of the small windows are immediately avoided and do not disturb the frame processing procedures.

To further maximize the tracking reliability, the properties of a signal are saved from its former sample and then compared with the properties of each candidate from the next sample. Properties such as spot size, its location and intensity, are evaluated against each signal candidate that the frame processing algorithm returns. The candidate with the closest match is then selected as the sought signal. This allows for uninterrupted tracking of a signal, even in the case if another erroneous signal with higher intensity appears in the sampled FPA window.

Signal Loss

There is a substantial likelihood that a signal loss scenario might occur during an overpass. This is especially due to potential cloud coverage that might lead to unexpected beacon fading and drop the SNR below a detection threshold. Because of this possibility, a procedure that restarts the acquisition process depending on a specified duration of the signal loss is implemented. This procedure is then executed if the saved parameters of the last valid sample are considered to be too outdated for confident continuation in the described tracking technique.

3.4.3 Minimizing Interference

It is anticipated that the beacon and the calibration signals might interfere with each other on the FPA. This will happen when the beacon signal will be in close vicinity of the center of symmetry around which the calibration signal mirrors it, i.e. P_B will be converging to P_{CENTER} . If this distance becomes low enough that the spot of the calibration beam will start overlapping with the spot of the beacon beam, the frame processing algorithm may fail to isolate them.

This is especially dangerous for samples of the beacon signal, as the calibration laser spot is bigger and might entirely cover it. Moreover, the beacon power, and thus the exposure time of its sampling window, may vary rapidly. On the other hand, the power output of the calibration laser is designed to be constant, so it might happen that their window exposure times will differ significantly. If the spots are close, this might lead to an extreme situation, where the beacon sampling window will also contain the calibration signal, but sampled with such high exposure time that it will saturate the window completely.

To minimize this interference as much as possible, a feedback switching mechanism is implemented. The central idea is that the calibration laser is switched off during the beacon readout phase and then switched back on before a snapshot of itself is requested. Consequently, in the beacon readout phase, only the beacon signal is hitting the FPA, while during the feedback readout, both signals are present. This solves the biggest potential issue that was described earlier. However, when the feedback signal is sampled, it might still suffer from slight interference from the beacon signal, depending on its power. For this reason, the power of the calibration laser is fine-tuned in hardware such that it can be reliably sampled using the lowest possible exposure time of the detector, which is orders of magnitude lower than the exposure needed for the beacon, even at the highest satellite elevation angle. Ultimately, even if the spots theoretically "cover" each other in the feedback readout phase, due to the extremely low exposure used in its sampling window, the interference from the beacon photons will be almost negligible.

A high-level visual summary of the sampling scheme together with all the other pointing control elements is presented in the concluding Section 3.6 - Summary.

3.5 Calibration Algorithm

The earlier outlined optical feedback mapping is one of the most sensitive and crucial elements of the entire pointing control chain, as it facilitates utilization of the calibration laser for both open-loop and closed-loop FSM control. In an ideal case, where the optics are perfectly aligned, it is possible to analytically calculate both the sensitivity matrix A and the translation vector t using the FSM voltage vs. mechanical angle characteristics and the lens and detector parameters. However, as hypothesized in Section 3.2.1, perfect alignment is not expected and so potential misalignment should be accounted for to achieve optimal pointing precision. For the affine map in particular, misalignment introduces uncertainty in the vector t, but also in the linear map, for instance in the form of axis rotation. Because of such sensitivity to the system geometry, and especially the fact that this geometry might be disturbed during and after the satellite launch due to shock and vibration, a more robust and accurate approach to obtain the affine map is desired.

The proposed solution is to develop a calibration algorithm that will estimate the transformation parameters based on an automated measurement, which can be ran at any point on orbit. This measurement can collect a certain amount of corresponding points in the two systems (i.e. landmarks in a sense) and then numerically estimate the transformation using the collected pairs. As it would be optimal to run the calibration directly before the transmission and fine pointing begins, the algorithm runtime is also considered as a relevant attribute besides the estimation accuracy.

3.5.1 Parameter Estimation

With six degrees of freedom, a minimum of three source points (in the FPA system) and three corresponding target points (in the FSM system) are necessary for full determination of the affine map. This would give a balanced set of equations that can be solved directly:

1

$$\begin{cases}
AP_1 + t = Q_1 \\
AP_2 + t = Q_2 \\
AP_3 + t = Q_3
\end{cases}$$
(3.19)

However, this is not a very redundant solution, as a single errant correspondence profoundly affects the entire transformation. It is also very sensitive to the camera readout noise, which is inherently random and can add undesired uncertainty to the map. A more favorable approach is to collect a higher amount of points and then estimate the parameters more optimally by minimizing the total transformation error. Consequently, using an arbitrary number of source and target points, we get an overdetermined equation system:

$$\begin{cases}
AP_{1} + t = Q_{1} \\
AP_{2} + t = Q_{2} \\
\vdots \\
AP_{N} + t = Q_{N}
\end{cases}$$
(3.20)

To derive an optimal transformation from the set in a least-error sense, a minimization of the following error criterion is sought:

$$f(A,t) = \sum_{i=1}^{N} \|AP_i + t - Q_i\|^2$$
(3.21)

which is a standard least squares fitting problem. The purpose is to find a solution over all possible 2-by-2 matrices A and all possible 2D-vectors t such that the gradient of f vanishes.

With the following denotations:

$$\bar{P} = \frac{1}{N} \sum_{i=1}^{N} P_i$$
 (3.22)

$$\tilde{P}_i = P_i - \bar{P} \tag{3.23}$$

where \overline{P} is the center of mass of a set of points, and \tilde{P}_i denotes the thereafter centered points, it can be shown with an intrinsic proof (derived in [61]) that the gradient of f vanishes for the following A and t:

$$A = \left(\sum_{i=1}^{N} \tilde{Q}_{i} \tilde{P}_{i}^{t}\right) \left(\sum_{i=1}^{N} \tilde{P}_{i} \tilde{P}_{i}^{t}\right)^{-1}$$
(3.24)

$$t = \bar{Q} - A\bar{P} \tag{3.25}$$

The calculation is valid for any number of corresponding point pairs equal or higher than 3, which are not contained within any sub-space of the transformed system, for instance on a straight line. This gives the calibration algorithm good flexibility, as the number of points to be collected can be chosen at will depending on the desired accuracy and algorithm runtime.

3.5.2 Data Collection

To obtain the necessary data for the calculation, an automated measurement is performed, which gradually changes V_{BDQ} while tracking the resulting P_C on the

detector. To facilitate this measurement, the FSM is steered in a spiral pattern, as visualized in Figure 3.16. This approach has several advantages. Firstly, it is very easy to implement in a parameterized way, such that the number of points and their density can be tweaked easily using the frequency of the sines and cosines. Secondly, by standard definition, the density of the points is decreasing outwards from the center, and thus the lowest local uncertainty should correspond to the center of the steering range. This follows the assumption that statistically the pointing disturbance is expected to have a normal distribution around zero. Lastly, the measurement can be performed in a single continuous motion without unnecessary revisits or big voltage steps, and so is quite time and space efficient.



Figure 3.16: An example of two different spiral measurement patterns used to collect data for the affine map determination.

3.5.3 Implementation

The overall algorithm can be summarized in a few major steps. In the initial phase, the FSM-system points are generated based on the desired total count of correspondences, N. Let:

$$n = [0, 1, 2, \dots, N - 1]$$
(3.26)

$$a = \frac{V_{BDQ,max}}{N-1} n \tag{3.27}$$

$$\omega = \pi \frac{\sqrt{N}}{N} \tag{3.28}$$

where *n* is a vector of point indices, *a* is a growing vector of amplitudes scaled to the FSM maximum voltage, $V_{BDQ,max}$, and *w* is an angular frequency function of choice that defines the spiral point distribution. We then define the FSM-system points as:

$$V_{BDQ,X,i} = a_i \cos \omega n_i \tag{3.29}$$

$$V_{BDQ,Y,i} = a_i \sin \omega n_i \tag{3.30}$$

which together gives $V_{BDQ,i}$, the *i*-th point in the measurement pattern, as visualized in Figure 3.16.

Next, the FSM is steered continuously using each $V_{BDQ,i}$, and after each update, the resulting feedback laser centroid, $P_{C,i}$, is saved to memory. Ultimately, after all the *N* corresponding points are collected, the general transformation from a desired P_C^* to V_{BDQ} is calculated:

$$A = \left(\sum_{i=1}^{N} \tilde{V}_{BDQ,i} \, \tilde{P}_{C,i}^{t}\right) \left(\sum_{i=1}^{N} \tilde{P}_{C,i} \, \tilde{P}_{C,i}^{t}\right)^{-1}$$
(3.31)

$$t = \bar{V}_{BDQ} - A\bar{P}_C \tag{3.32}$$

After A and t is obtained the algorithm concludes and the feedback can be mapped accurately within the control chain. Experimental results of the performance of this algorithm are summarized in Chapter 4.2 - Calibration & Acquisition Testing.

3.6 Summary

In conclusion, we present a short top-level analysis of all the techniques that were designed to enable robust implementation of the whole fine pointing control chain, and look at how these sub-processes interact.

The initial process that is executed at the beginning of the pointing chain (i.e. before the satellite overpass) is the calibration algorithm. This is vital, as the controller performance depends on having an accurate optical feedback mapping, which in turn depends on the current system alignment. The algorithm is ran with the feedback laser turned on, and performs an automated measurement, in which the frame processing algorithms are utilized to find correspondences between input voltage and output feedback centroid configurations. The resulting mapping is then used each time the FSM is moved to achieve precise steering.

After the calibration concludes, the feedback laser is turned off and the system is ready to begin pointing control as soon as a beacon signal is acquired. For this reason, a robust beacon acquisition procedure is ran until a valid signal is obtained on the FPA. The procedure rapidly sweeps the FPA with different exposure times and performs fast sanity checks to determine if the frame can be potentially processed successfully. If a good signal candidate with correct properties is obtained from the frame processing algorithm, acquisition is declared successful.

With the initial beacon location on the FPA, the actual tracking and control scheme begins. The system is designed to allow both open-loop and closed-loop FSM pointing. In either case, the beacon spot is sampled with a small adaptive window on the FPA to increase the sampling rate, and robust tracking algorithms are utilized to provide reliable centroiding by evaluating the signal properties in between samples. In the open-loop mode, the FSM is steered immediately after each beacon sample using the affine map. In the closed-loop mode, the feedback laser is turned on and sampled after each sample of the beacon signal in an alternating fashion. The control error is then determined using the calibrated sensitivity matrix, and the FSM is driven by a discrete integral controller to reject pointing error.

In the case of a total signal loss, the tracking and control process is interrupted, and the system switches back to the beacon acquisition phase. The whole chain is visualized in a block diagram in Figure 3.17.



Figure 3.17: A high-level block diagram of all the major processes in the pointing control chain, showing both of the possible control modes and the associated branching logic.

CHAPTER 4

Experiment

To test and verify the fine pointing algorithms, a laboratory setup is assembled based on the optical design and selected payload electronics. The control chain is then implemented on the payload microcontroller (PMC), and each process in the chain is verified. The testbed itself is summarized in Section 4.1, followed by experimental results of the calibration and acquisition processes in Section 4.2. Next, Section 4.3 focuses on precise measurement of P_{CENTER} , which is necessary for optomechanical misalignment compensation. Lastly, Section 4.4 and 4.5 cover the approach and results from the pointing accuracy verification.

4.1 Testbed Assembly

The testbed is built based on the design and optical hardware described thoroughly in Section 3.1. The primary optical components are mounted on an optical breadboard and manually aligned. This includes the beacon camera, focusing lens, dichroic and regular mirror, FSM, and collimator (Figure 4.1). The optics are mounted such that they are spaced as closely as possible to the NODE mechanical structure design. The beacon camera is connected to the PMC using a standard USB interface. The FSM is wired to a mirror driver from Mirrorcle Technologies, which contains a DAC and a tunable LPF to facilitate the FSM operation. The driver itself is commanded over a serial peripheral interface (SPI) bus from the PMC, and the LPF cut-off frequency is set with a clock that is generated using a pulse width modulation (PWM) output on the PMC.

The calibration path is closed using two optical fibers which connect the collimator to a fiber-coupled 635 nm laser source through a WDM. The second WDM input port is left unconnected, since the transmission laser is not required for pointing experiments. The calibration laser source is connected to the PMC us-



Figure 4.1: Mounted optical components in the initial laboratory testbed. The components are mounted to be as close as possible to the designed NODE mechanical structure.

ing an analog modulation port, which allows the PMC to control its on/off state using a general purpose input/output (GPIO) pin. To imitate the beacon signal, another collimated 635 nm laser source is set up independently in the camera's FOV for initial testing. A functional diagram that depicts the interfacing between the components can be seen in Figure 4.3.

4.1.1 Initial Hardware Testing

The testbed was used to test a lot of preliminary embedded software, mainly focused on the FSM operation and the beacon camera configuration. The camera offers the capability to sample sub-regions of the FPA for faster readout (windowing), and also neighbor-pixel averaging (binning) to increase readout while sacrificing resolution. To test its performance, a frame rate measurement was ran under all the possible windowing and binning configurations. The results are depicted in Figure 4.2. It can be seen that the frame rate increases exponentially for smaller window sizes, which further motivated the double window sampling approach that was designed. A significant rate boost can also be seen with higher binning modes, which motivated the usage of binning in the beacon acquisition algorithm, during which high resolution is not necessary.

Another measurement investigated the effect of camera configuration changes



Figure 4.2: Measured sampling rate of the beacon camera as a function of the sampled window size (i.e. width). The measurement was performed for all the available camera binning modes using a one millisecond exposure time.

between samples on the overall sampling rate. This included the window location and exposure time as a continuously varying parameter. It was found that the camera trigger mode plays a crucial role in the case where configuration is changed rapidly. By default, the detector uses a continuous trigger, which struggles if the configuration is continuously updated. The alternative on-demand trigger has proven to be much more optimal for this case. A summary of some measurements can be seen in Table 4.1. While continuous trigger outperforms the on-demand trigger in static configuration cases, it becomes extremely slow for varying configurations. As the designed sampling technique is based on switching between windows and exposure times after each sample, the on-demand trigger is preferred.

Sampling configuration	Continuous trigger	On-demand trigger
Static 100 px window	330 Hz	265 Hz
Moving 100 px window	40 Hz	110 Hz
Varying exposure full-frame	4 Hz	16 Hz

Table 4.1: Sampling rates of the camera under varying sampling configurations.

Initial testing of the camera under different configurations also revealed that a 1 mW calibration laser source is too overpowered, as it saturates the beacon detector when using the lowest possible exposure time, even after all the optical losses. Consequently, it was decided to add a variable inline fiber attenuator between the laser source and the WDM. This prevents the detector saturation, and allows fine-tuning the power of the free-space signal, such that it can be reliably sampled using the lowest exposure setting to minimize the beacon-feedback interference, as discussed in Section 3.4.3.

Lastly, after initial trials, an external graphical user interface (GUI) was developed to facilitate monitoring and debugging of the embedded pointing algorithms. The GUI is running on an external computer connected to the PMC through a serial universal asynchronous receiver-transmitter (UART) interface. Flexible communication with the PMC is achieved using the Point-to-Point Protocol (PPP). A summarizing functional block diagram of the interfaces between each component on the testbed is shown in Figure 4.3 below.



Figure 4.3: Interfacing of components in the laboratory testbed. A variable fiber attenuator is added to lower the calibration laser power, together with a link to a GUI used for software debugging and monitoring on an external laptop.

4.2 Calibration & Acquisition Testing

As a first major experiment, the designed FSM calibration algorithm was implemented on the PMC and tested on the optical testbed. Multiple measurements were ran with different N – the number of collected corresponding points between the FSM and FPA systems – to verify how accurately, and how fast can the feedback mapping be estimated. The test procedure was as follows:

- 1. Run the calibration algorithm configured for collection of N point pairs.
- 2. Densely re-visit different points on the FPA using the estimated mapping.
- 3. Compare output centroids to input locations to evaluate mapping errors.

This procedure enabled the construction of a 2D calibration error map across the FPA region of interest, as is shown for different configurations in Figure 4.4. An RMS mapping error (RMSE) was calculated for each test run as the primary figure of merit. The time needed for the calibration algorithm to complete was also measured. The experiment results are summarized in Table 4.2.

Configuration	Runtime (s)	RMSE (px)	RMSE (μ -rad)
10 point pairs	6.6	2.5	244
50 point pairs	8.2	1.4	137
100 point pairs	10.9	1.0	98
500 point pairs	28.8	1.0	98
1000 point pairs	49.3	1.0	98

Table 4.2: Results obtained from the calibration algorithm experiments.

It can be seen that when more than roughly 100 points are used for the estimation, the accuracy of the map remains at 1 px RMSE, which is the best mapping accuracy achieved. The angular RMSE results are consistent with associated research done in [50,53], which investigated the FSM tip/tilt repeatability and other sources of potential open-loop pointing error. Given these results, it is hypothesized that with correct alignment, an overall pointing accuracy of roughly 100 μ rad should be achievable even in the open-loop pointing mode, which already fulfills the pointing requirement with a lot of margin. Ultimately, the 100 point configuration was chosen as the default calibration procedure. With a quick runtime of about 10 seconds, it can be easily run after the payload is woken from standby before the satellite overpasses the OGS.



Figure 4.4: Comparison of calibration errors for affine maps estimated using different number of point pairs. The color represents re-visit errors for locations on the FPA when the FSM was commanded in open-loop using the affine map. The darker the color, the better the mapping is for a given pixel. RMS calibration errors are calculated for each case. It can be seen that a 100 pts estimation has already the same accuracy as a 1000 pts estimation.

Further experiments also focused on the beacon acquisition procedure. The exposure sweep, which is done to ensure good conditions for acquisition under any beacon power, was fine-tuned for the power range obtained from the beacon link budget simulation. The minimum and maximum expected beacon power (based on satellite elevation) was reproduced in the lab to find the rough exposure time range needed on the detector, with certain added margin. This range was then split between ten continuous samples, which results in acquisition times less then one second long (see full-frame rate in Table 4.1), and is versatile enough to make the frame processing chain perform correctly.

4.3 Center of Symmetry Determination

In this section, we describe an experimental procedure that was developed for precise determination of the point P_{CENTER} . As discussed in Section 3.2.1, precise knowledge of P_{CENTER} is critical to reject errors introduced by optomechanical misalignments in the system. If P_{CENTER} is calibrated well, pointing bias due to lens-FPA axis misalignment, as well as due to dichroic-to-side-mirror misalignment can be compensated by the controller software.

To experimentally determine the optimal P_{CENTER} , a setup that can independently measure the angle between θ_B and θ_C with high precision outside of the system is built. Afterwards, P_{CENTER} can be varied manually during a pointing test (with the control loop engaged), until θ_B and θ_C are equal, which means the optimal P_{CENTER} has been found.

To measure the angle between the two beams, we utilize a second detector onto which the rays are reflected from a beamsplitter, which is placed outside of the aperture. A retro-reflector is used on one side of the beamsplitter so that both signals share the same path onto the detector. This ensures that if the signals have the same angle of incidence at the NODE aperture, they will be focused to the same point on the external FPA, as is illustrated in Figure 4.5 below.



Figure 4.5: An external optical setup used to measure the angle between the beacon and the outgoing NODE signal. A retro-reflector prism is used to screen both of the signals on a single FPA without misalignment issues. This setup enables software calibration of the controller to remove pointing bias due to optomechanical misalignment inside the primary NODE setup.

To experimentally obtain the optimal P_{CENTER} , a simple procedure is followed:

- 1. The main NODE testbed pointing chain is ran with a default P_{CENTER} set to the center of the FPA.
- 2. The external setup is used to check the bias in the pointing, i.e. if there is an offset between the two centroids on the camera.
- 3. P_{CENTER} is adjusted continuously from the GUI while the pointing control loop is engaged. This will shift the feedback centroid on the external FPA.
- 4. Once the spots are exactly at the same point on the external FPA, the beams are aligned, and the optimal P_{CENTER} has been found.

A longer 125 mm focal length lens is used with the external camera to decrease its FOV, and thus improve angular resolution, so that the beams can be aligned with higher precision. The detector is the same as the one used in the primary NODE hardware. With this configuration, the beams can be aligned within approximately 1 μ rad, which is more than sufficient.

This procedure also generally serves as a good check of the alignment quality in the optomechanical structure. Since the pointing testbed assembled during this thesis is manually aligned, big P_{CENTER} offsets of up to several tens of pixels were observed, which is already on the order of a mrad of pointing bias. When the optics will be mounted on the actual structure of the engineering model of the payload, the bias is expected to be much smaller, mainly determined by the machining accuracy of the optomechanical mounts. The procedure is also a good means of testing how well can the system preserve alignment e.g. after vibration or thermal vacuum testing, which is planned in the near future.

4.4 Disturbance Simulation

To begin with the verification of the pointing control loop performance, a way of simulating the spacecraft body pointing error in the laboratory is needed. Since a varying body pointing error on orbit will be effectively seen as drift of the beacon centroid on the NODE FPA, we can accomplish the same by using a second external FSM, which will steer the beacon signal generated in the laboratory.

Thus, we augment the testbed with another FSM from Mirrorcle Technologies placed on the optical axis of the main focusing lens. The FSM is placed at 45 degrees relative to this axis, and a beacon laser source is added next to it, so that the FSM can steer its beam within the detector's FOV. This FSM is also connected to the PMC via a mirror driver. The PMC can steer it independently and in parallel to the main control loop, and this way generate a disturbance "for itself" to control. The mounted optics in the final testbed can be seen in Figure 4.6, and a diagram visualizing the interfaces between all the components in Figure 4.7.



Figure 4.6: Final version of the laboratory testbed, including the NODE pointing system, the P_{CENTER} measurement setup, and a setup for simulating the beacon drift.



Figure 4.7: A block diagram of interfaces between each component in the final testbed.

4.4.1 Representative Disturbance

In order to make the pointing control verification representative of on-orbit operation, an expected body pointing error dataset is generated for the external FSM to "play". This will ensure that the beacon drift on the FPA will be as close as possible to what is expected on orbit during the spacecraft ground-tracking slew maneuver, which the bus will be performing during each overpass.

The dataset generation is based on information available from the bus ADCS specification, which includes statistical information about the pointing accuracy, stability, and potential pointing offset due to payload misalignment with regards to the ADCS reference frame. A summary of these parameters is given in Table 4.3.

A MATLAB script is written to generate a body pointing error waveform follow-

Parameter	Specification
Pointing accuracy	\pm 0.15 deg (3 σ)
Pointing stability	\pm 0.0225 deg/s (3 σ)
Worst-case pointing bias	\pm 1 deg

Table 4.3: Parameters used for ADCS pointing error data generation.

ing these specifications. In the first step, random errors with a normal distribution are generated using the MATLAB randn function. One dataset is generated for both the X and Y axis, with the same amplitude and standard deviation, so that both axes are exercised equally. These sets are then scaled to make the standard deviation of the total error correspond to the ADCS pointing accuracy (i.e. 0.05 deg 1σ). A constant offset is also added to each axis, so that the total mean error equals the worst-case pointing offset of 1 deg. The samples are then spaced in time in a way that the magnitude RMS rate agrees with the pointing stability specification. Finally, the samples for each axis are splined together with a small sampling period, and exported to a file as a waveform that can be played by the PMC. The waveforms are generated for a duration of 10 minutes, which roughly corresponds to a satellite overpass duration when in LEO.

An example of a waveform resulting from the script is visualized and analyzed in Figure 4.8. It can be seen that the resulting error distribution precisely follows the assumptions given by the bus ADCS specification. The expected planar drift of the beacon signal over one OGS overpass as seen by the payload detector is also shown in a trace plot in Figure 4.8.



Figure 4.8: On the top, a magnitude plot of the ADCS body pointing error as a function of time. The bottom left plot shows the error distribution, which conforms with the ADCS specification. On the bottom right, a 2D trace of the waveform is shown, as is expected to be seen by the NODE beacon detector over one OGS overpass.
4.5 Pointing Control Verification

The last and the most important experiment focused on verification of the whole fine pointing chain, and analyzing its performance with regards to pointing precision. The testbed was configured for two end-to-end tests, one for each fine pointing mode, i.e. either running with open-loop or closed-loop FSM control. The tests included FSM calibration, beacon acquisition, beacon tracking, and pointing control for the duration of one overpass. The test procedure was as follows:

- 1. The FSM calibration algorithm is executed with the calibration laser on. (Manual step)
- 2. The laser is switched off and the system begins beacon acquisition. (Automatic step)
- The FSM in the disturbance generation setup starts playback of the body pointing error waveform to simulate body pointing drift. (Manual step)
- The beacon laser is turned on. (Manual step)
- 5. The system acquires the beacon and begins pointing control. (Automatic step)
- 6. After the body pointing simulation concludes, the pointing chain is stopped. (Manual step)

During the actual tracking and control phase, the PMC was configured to collect all samples of the beacon and the feedback signal for accuracy evaluation. This process is detailed for each mode in the following sections.

4.5.1 Open-Loop Test

In the open-loop FSM pointing mode, the feedback laser is not utilized in the chain after the calibration phase. As is summarized in Figure 3.17, the FSM steering is performed using the calibrated affine map immediately after a new sample of the beacon signal is obtained. However, for the sake of the pointing accuracy test, we keep the laser turned on, although it is not being used to drive the FSM. Instead, the samples are only kept in memory, and then saved into a file together with the beacon samples when the pointing chain finishes. Processing this file then enables evaluation of the pointing error after the test.



Figure 4.9: Time and scatter plots of fine pointing error obtained during the open-loop pointing test. The NODE pointing requirement is also visualized in the scatter plot as a red circle.



Figure 4.10: Statistical analysis of the error distribution. The orthogonal component histograms are fit to a Gaussian and the magnitude histogram is fit to a Rician distribution.

Figure 4.9 shows the magnitude of the pointing error during the test, both as a function of time, and also component wise as an aperture-plane scatter plot. It can be seen that the error has a constant offset (i.e. a steady state error is present), which is expected due to the nature of this control mode. The scatter plot illustrates that this error is, however, well within the required accuracy region.

The red circle on the scatter plot corresponds to the \pm 0.65 mrad pointing accuracy requirement, which was defined earlier in Chapter 2.

To obtain reasonable accuracy metrics from the measurements, the error histograms are fit to probability distribution functions (PDFs), from which the mean and the standard deviation are calculated. The data is fit in MATLAB using the fitdist function, which is visualized in Figure 4.10. The orthogonal components of the error vector are fit to a Gaussian distribution, while the magnitude histogram is fit to a Rician distribution. The Rician distribution is appropriate since the magnitude is a norm of bivariate normally distributed components which have non-zero mean. A summary of the calculated statistical parameters is given in Table 4.4.

	Mean (μ rad)	σ (μ rad)
θ_X	-193.5	22.0
θ_Y	36.9	17.7
$ \theta $	197.5	23.8

Table 4.4: Pointing accuracy metrics from the open-loop pointing test.

4.5.2 Closed-Loop Test

The second test followed the same procedure, but was configured to utilize the calibration signal to drive the FSM with the designed closed-loop integral controller. Both the beacon and the feedback signals were sampled with the double-window tracking technique, and the FSM was steered after each update of the feedback signal (following the concept in Figure 3.17). Using this configuration, the control loop was running at an update rate of roughly 30 Hz.

The same body pointing disturbance dataset was used, so that a representative comparison between the two modes could be obtained. The measured fine pointing errors are summarized in Figure 4.11. We can observe that the controller is performing as is expected, since the error converges to zero for both axes. Similarly as in the previous case, we derive the pointing accuracy metrics by analysis of the error histograms. In this case, we fit the magnitude histogram using the Rayleigh distribution, as both of the components have nearly zero mean normal distributions. The obtained statistical values are summarized in Table 4.5.



Figure 4.11: Time and scatter plots of fine pointing error obtained during the closed-loop pointing test.



Figure 4.12: Statistical analysis of the error distribution. The orthogonal component histograms are fit to a Gaussian and the magnitude histogram is fit to a Rayleigh distribution.

4.5.3 Discussion

The performed hardware-in-the-loop pointing control tests were an important part of the fine pointing system verification process. We have shown that the fine pointing stage is able to successfully reject a representative body pointing disturbance

	Mean (μ rad)	σ (μ rad)
θ_X	0.09	15.6
θ_Y	-0.31	16.4
$ \theta $	20.0	10.5

Table 4.5: Pointing accuracy metrics from the closed-loop pointing test.

that is expected by the payload on orbit. The analysis shows that under laboratory conditions, both of the pointing modes can meet the pointing requirement with significant margin.

The results of the open-loop FSM pointing confirm that a steady state error is inevitable in this mode, as a certain constant bias can be seen in both axes. This is mainly determined by the uncertain regions in the calibrated feedback mapping, which mostly depend on the FSM repeatability and non-linearity. It can be seen that especially the X axis error had a high mean value of nearly 200 μ rad, which is around double the calibration algorithm RMSE. Thus, it is likely that the FSM was positioned around a higher uncertainty peak in the feedback map.

The closed-loop FSM control results show significant pointing precision improvements due to rejection of the steady state errors. Both orthogonal error components have a nearly zero mean and a standard deviation of roughly 16 μ rad. The total error has a mean magnitude of 20 μ rad and a standard deviation of approximately 10 μ rad. These errors were traced down primarily to two sources. The first one is the lag between the beacon and the feedback signal samples. With a control frequency of 30 Hz and a body pointing error rate of up to 0.0225 deg/s, this can lead to fine pointing errors of up to 13 μ rad, just due to the delays. The second one is the readout noise of the beacon detector, which leads to noise in signal centroiding. This noise was measured to be a roughly 0.05 px RMSE, which corresponds to 5 μ rad. Ultimately, if the system is calibrated well for misalignment and the ~50 μ rad 3 σ pointing accuracy is reached during operation on orbit, it would result in essentially negligible pointing losses (-0.005 dB) with the current downlink beam divergence. This would be a good motivation to decrease the beam divergence and aim for higher downlink rates in future iterations of NODE.

To improve the pointing accuracy even further, a few hardware and software upgrades are feasible. Some form of a non-linear feedback mapping with more degrees of freedom could be estimated for the case of open-loop pointing. This might help reduce the mapping uncertainty that exists due to small non-linearities in the system. The closed-loop control errors could be reduced for example by using a higher frame-rate detector, which would reduce the sample lag, and could also utilize frame averaging to mitigate centroiding noise.

CHAPTER 5

Conclusion

In this chapter, we conclude the thesis with a short summary of the addressed topics and the achieved results. Specific contributions are highlighted, and future work related to the pointing subsystem is discussed.

5.1 Thesis Summary

The rapid increase of small satellites on orbit is accompanied by higher downlink demand, which becomes problematic with traditional RF technology. Limited payload size, weight, power, and strict regulations lead to communications systems with low rates that are bottlenecks for many proposed data-intensive missions. The Nanosatellite Optical Downlink Experiment (NODE) developed at MIT is aiming to demonstrate the feasibility of using laser communications to achieve high downlink rates within a highly constrained platform of a 3U CubeSat.

In this thesis, we focus on the fine laser pointing system of NODE, which is required to improve the downlink beam pointing precision due to spacecraft body pointing errors. The primary objective of this work was to build a flight-like laboratory testbed of the system, develop pointing algorithms for its hardware, and verify its functionality and pointing precision in an end-to-end hardware-in-theloop test. A specific area of focus was the development of a technique to improve the pointing precision and robustness by utilizing an internal calibration laser.

Chapter 1 motivates the need of a scalable high rate communications solution for small satellites. Several recently proposed highly data-intensive missions are presented. The problem of significantly increasing downlink rates on small satellites using standard RF technology is investigated. Next, the benefits and challenges of laser communications are explored.

Chapter 2 provides more research background on the area of fine laser pointing and NODE itself. Two recent space laser communications demonstrations are investigated. Their pointing systems are analyzed in detail, and their key parameters are compared to the NODE design parameters. Afterwards, the NODE system-level architecture is presented, and its pointing accuracy requirement is derived to be ± 0.65 mrad.

Chapter 3 presents and analyzes the optics and the fine pointing mechanism used in NODE in detail. A beam steering solution based on a ground beacon detector and a fast steering mirror (FSM) is described. Since the miniature FSMs do not have feedback sensors, the benefit of utilizing an internal calibration laser is emphasized. An approach on the design of an open-loop as well as a closedloop FSM controller is presented. Next, algorithms for signal sampling on the detector are outlined, followed by a technique to automatically calibrate the FSM for precise pointing by estimating a mapping between its input and the detector's reference frame. Lastly, the whole designed control process chain is summarized.

Chapter 4 describes the laboratory testbed assembly and the carried out experiments. Results show that the designed FSM calibration algorithm enables on-demand open-loop pointing of the FSM with a root mean square error of 98 μ rad with regards the beacon detector's reference frame. The algorithm takes less then 10 seconds to finish and can be ran on orbit before an overpass if needed. A method that enables the measurement and software compensation of optomechanical misalignment in the system is also presented. Ultimately, an approach on verification of the whole pointing control chain is described. A representative spacecraft body pointing disturbance is simulated in the laboratory with the fine pointing control loop engaged. Both open-loop and closed-loop FSM control modes are analyzed for overall pointing accuracy. Experimental results show that both modes fulfill the pointing accuracy requirement with significant margin, and that in the closed-loop control mode, 1σ error as low as 16 μ rad can be achieved for each axis. The mean of the fine pointing error magnitude was measured to be 198 μ rad and 20 μ rad for the open-loop and closed-loop modes respectively. The main sources of error were traced down to uncertainty in the feedback map for open-loop control, and sample lag and centroiding noise for closed-loop control.

5.2 Contributions

Specific contributions of this work are highlighted below:

- Assembly and alignment of a laboratory testbed with flight hardware, which can be used for fine laser pointing experiments.
- Development of a novel detector sampling technique, which allows tracking of two laser signals independently without mutual interference.

- Development of a robust on-orbit FSM calibration algorithm that increases the optical feedback accuracy.
- Design of a laboratory setup and method to measure and compensate for optomechanical misalignment in the system.
- Implementation of all the algorithms in the fine pointing control chain on the payload microcontroller in C++.
- Experimental analysis of the designed FSM calibration algorithm with regards to re-visit precision of the feedback map.
- Verification of the pointing system in an end-to-end test, which simulated spacecraft body pointing disturbance over one OGS overpass.
- Statistical analysis of the achievable pointing accuracy in both open-loop and closed-loop FSM pointing modes under the expected disturbance.

5.3 Future Work

Further areas of work needed on the fine pointing system for the path to flight:

- The testbed utilizes a FSM driver by Mirrorcle Technologies, but a custom compact board is being fabricated for the NODE payload. The embedded software has to be updated to command the FSM through the new driver, which is interfaced to an FPGA that controls the laser transmitter.
- A more rigorous solution on adapting the beacon detector's exposure with regards to the received beacon power has to be implemented. A simple control loop that adapts the exposure based on the signal intensity could be designed, with appropriate logic for detection of beacon loss.
- While the pixel grouping algorithm can reject individual "hot pixels" (due to radiation damage), a more robust solution should be implemented to decrease risk. The beacon camera offers calibration functionality to detect defective pixels, which should be researched as a possible improvement.
- A solution to monitor and debug the fine pointing system as part of the payload telemetry/telecommand has to be implemented. Information from the pointing chain should be fused with other telemetry generated by the payload microcontroller for analysis on ground.

• The pointing precision and ability to compensate optomechanical misalignment should be tested in thermal vacuum (TVAC) conditions for better understanding of the expected performance on orbit.

Areas that may be beneficial for further study:

- Experimental analysis of the benefit of estimating a non-linear feedback mapping with more degrees of freedom between the calibration signal centroid and the FSM input.
- Analysis of the benefit of a more advanced controller design with regards to error rejection. An adaptive Linear-Quadratic-Integral (LQI) controller could be investigated as a replacement for the calibrated feedback mapping and the simple integral controller.
- Testing if a high frame-rate detector would lead to rejection of errors due to sample lag and centroiding noise by utilizing frame averaging.

APPENDIX A

Alternative Feedback Design with a Retro-Reflector

Because of the problems with the determination of P_{CENTER} due to potential optomechanical misalignments, another alternative design solution was simultaneously researched to tackle the issue with the optical pointing feedback. One plausible idea is to use a retro-reflector next to the dichroic mirror instead of a regular mirror. This would result in a case where the rays are not inverted at the detector, but would have the same angles of incidence as at the aperture. Consequently, for optimal pointing, the spots would not need to mirror each other on the detector, but would copy each other's position, as is visualized in Figure A.1.



Figure A.1: Ray geometry with a retro-reflector-based feedback.

This solves the potential misalignment issue completely, as the retro-reflector will not bias the feedback signal, unlike a misaligned mirror would. However, it also means that the spots will always be sampled at the same point on the FPA, which will load to slight interference of the feedback signal, as discussed in Section 3.4.3. Moreover, retro-reflector prisms are bigger in volume, therefore a significant redesign of the optomechanical payload structure would be necessary. Ultimately, it was decided to pursue the original design with a regular mirror, and come up with a solution to compensate potential misalignment in software, which was discussed in Section 4.3.

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