RS03153 / ESA RFP/3-17058/21/NL/GLC/zk

ACTIVE ALIGNMENT SYSTEM FOR QUANTUM COMMUNICATIONS

EXECUTIVE SUMMARY REPORT
9th March 2023

1) INTRODUCTION

This project was conceived to investigate and verify an approach for an Active Alignment System for use in small satellite applications based on tracking an uplink laser beacon with a fine steering mirror (FSM) on the satellite. The system performance was to be evaluated in a vacuum to increase the Technology Readiness Level (TRL) of the technology.

The application area for this technology is quantum encryption which typically involves generating an encryption key from the polarisation properties of a string of photons. The quantum key is then shared between users to allow secure communication. However, the sharing of quantum keys is challenging because the photons that make up the key must be propagated through free space or optical fibres, which are limited to short and medium distances on the earth's surface. There is therefore significant interest in the use of satellite links for the sharing of quantum keys over long distances. One possible arrangement would involve generating quantum keys on board a small satellite and propagating the keys to users in separate locations in a downlink optical beam. There is interest in developing technology compatible with small satellites, both due to the desire to quickly demonstrate the technology and due to the future potential for quantum-key generating small satellite constellations.

The optical signals used to generate quantum keys are typically power limited, making it necessary to minimise transmission loss between the satellite and the ground as much as possible. A very narrow beam is required to achieve a sufficient signal to noise ratio which places a strict requirement on the beam pointing precision, beyond that which can be achieved with on-board attitude control systems. This required pointing precision establishes the need for an active alignment system for the downlink optical beam. The solution implemented in this project uses an FSM in active alignment control to track an uplink beam, in order to steer the downlink quantum beam.

RAL Space is involved in two missions to demonstrate quantum key distribution from small (12U) satellites. The first is the SPEQTRE mission which is a collaboration with Speqtral, a company based in Singapore with expertise in developing small footprint entangled photon sources. The second is the In Orbit Demonstration (IoD) project of the QComms Hub, which is a quantum communications mission being developed as

Work Package 5 of the UK's National Quantum Technology Programme,. For both missions, RAL Space is developing the optical alignment system for fine pointing of the quantum beam, which includes a module similar to the active alignment system described in this project. The requirements for the active alignment system described here were developed based on the optical design of the alignment system developed for SPEQTRE and QComms Hub IoD. The performance requirements were derived from the optical disturbance which is expected at the satellites in these missions, and the required pointing accuracy to enable quantum key sharing. We show that the active alignment system was able to operate in these conditions and was able to supress external disturbances to within the proposed performance requirements.

2) ACTIVE ALIGNMENT SYSTEM DEVELOPMENT

Figure 1 shows the system architecture of the active alignment system, showing how an incoming beam (shown in red) is stabilised. The beam is reflected from an FSM, received on a detector array and the beam spot position is established and used to determine an input to the mirror drive control. Operating this system in closed loop control allows the spot to be iteratively centred at a setpoint on the detector, correcting for external disturbances.

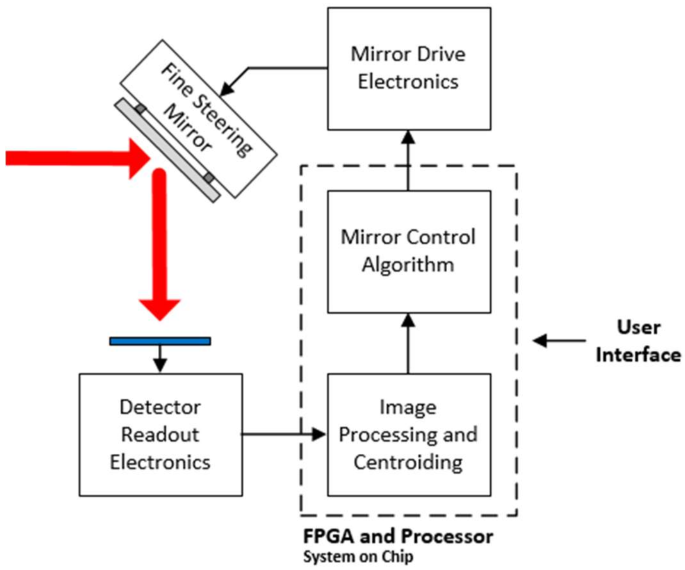

Figure 1: Active alignment system block diagram with the incoming beam indicated in red.

The active alignment system hardware was developed using commercial off-the-shelf (COTS) components and custom components that meet the volume, mass and power requirements for operation in a small satellite. Table 1 shows a summary of the components that were chosen.

Table 1: Components used in the active alignment system setup.

Component	Part
Detector	CMOSIS CMV4000
Detector readout electronics	Custom in-house electronics based on SmartFusion2 system on a chip and Microchip ARM Cortex M3 microprocessor
Control FSM	Demcon FSM 20mm
Mirror drive electronics	Custom in-house electronics

Following assembly of the component parts, we implemented the feedback control algorithm on the microprocessor. The algorithm captures a detector image, performs spot detection, calculates the required current, then sends the current command to the FSM.

In practice, it was found that a single spot detection algorithm on the full detector window, of 2048x2048 pixels, cannot execute fast enough to successfully centre the spot with external disturbances. Instead, a large detector window must be used to initially find the spot, followed by progressively smaller detector windows, where only a subset of the detector is sampled, allowing the readout and spot detection to operate at high speed. After surveying the options for spot detection algorithms, we opted to use a brightest group algorithm for the coarse spot detection and a centroid algorithm for the fine spot detection.

The closed loop control was implemented using a proportional-integral-derivative (PID) controller which is a simple feedback algorithm commonly used for closed-loop control. We surveyed the potential control options and concluded that PID control is a suitable choice as it is known to be effective on simple second-order systems, is easy to program, has low processing overheads, and is easy to tune.

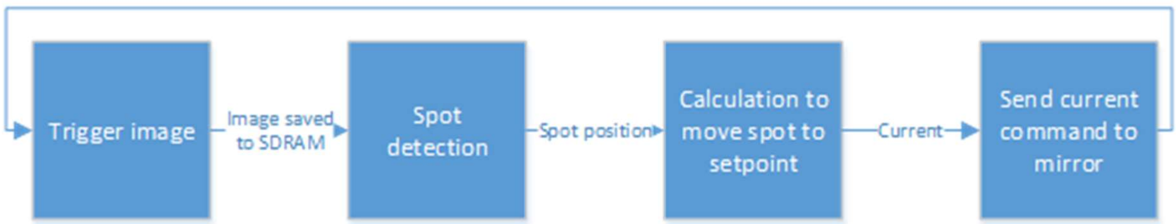

Figure 2: Combined active alignment system algorithm block diagram.

The combined active alignment system algorithm is summarised in Figure 2, showing the closed loop control system and the steps to transition between large, medium and small windows with coarse and fine spot detection. If the spot is lost from the medium or small window, or the FSM reaches the end of its range, the algorithm returns to the large window.

3) TEST SETUP

The system requirements as defined in the project proposal (v2, 18 June 2021) are shown in Table 2. These requirements lay out how the performance of the system was to be verified: with the laser spot characteristics and the external disturbances that are expected on a small satellite. It also specifies that the system performance tests should be repeated in vacuum conditions.

Table 2: Active alignment system requirements.

	Requirement	Verification method
1	The detector shall capture a spot of diameter between 3 and 5 pixels measured at the full-width half-maximum.	Test
2	The spot position shall be calculated in less than 20 ms using representative flight hardware.	Test
3	The control system shall stabilise optical perturbations of 3 arc seconds at frequencies of up to 5 Hz to within 0.5 pixels rms.	Test
4	The control system shall operate at a spot signal-to-noise ratio of 10 or higher.	Test
5	The active alignment system shall meet the dynamic performance requirements (3 & 4) within a vacuum environment.	Test

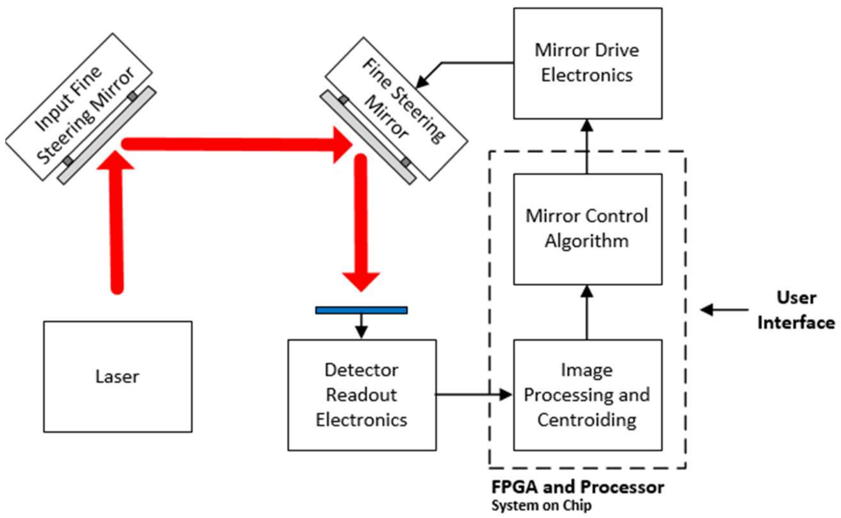

Figure 3: Active alignment system with setup for input disturbance.

To simulate the conditions described in Table 2, an input laser beam simulating the uplink laser was reflected from an additional FSM (referred to as the input FSM), to actuate the beam with representative disturbances before entering the active alignment system, as shown in Figure 3. We designed and aligned an optical system to generate the required laser spot and disturbance characteristics. Subsequently the opticak system was adapted to allow the active alignment components to be operated within a small vacuum chamber. Figure 4 shows the active alignment system and optics mounted with vacuum compatible components inside the vacuum chamber.

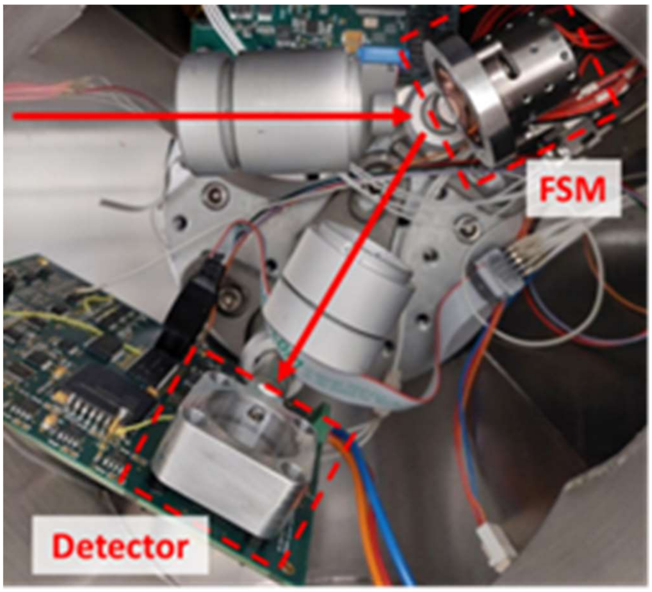

Figure 4: Active alignment system inside the vacuum chamber mounted using vacuum compatible optomechanical components.

4) OUTCOMES

We investigated the performance of the active alignment system against a sine wave disturbance applied using the input FSM. The stated requirement was to reduce a 5 Hz 3 arcsecond disturbance to a root mean square error (RMSE) of less than 0.5 pixels on the detector. The RMSE in the spot position when the control system is turned off is approximately 2.3 pixels for a disturbance of 3 arcseconds, we therefore measure how much this can be reduced with the aim of supressing RMSE below 0.5 pixels.

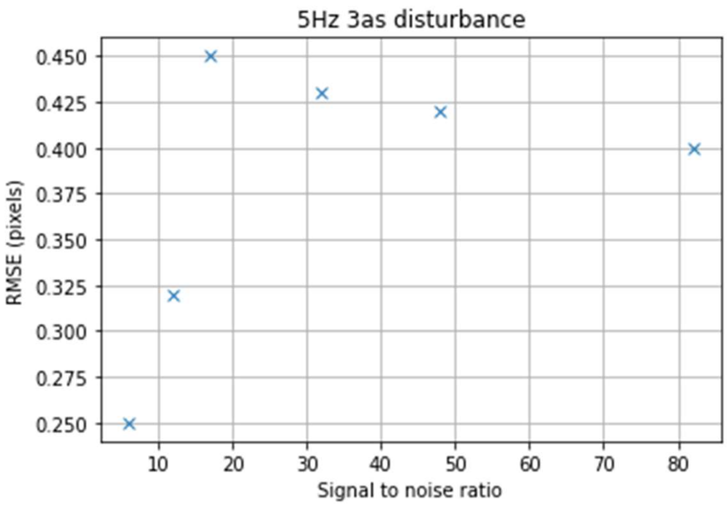

Figure 5: Root-mean-square error in spot position when controlling for a 5 Hz 3 arcsecond sine wave disturbance for a range of detector signal to noise ratio. The control loop frequency was 166 Hz.

Figure 5 shows an investigation of the active alignment performance as a function of the detector signal to noise ratio (SNR), achieved by varying the operating environment and the detector gains. Some variations are observed in the RMSE that can be achieved but we find no strong correlation between SNR and the performance.

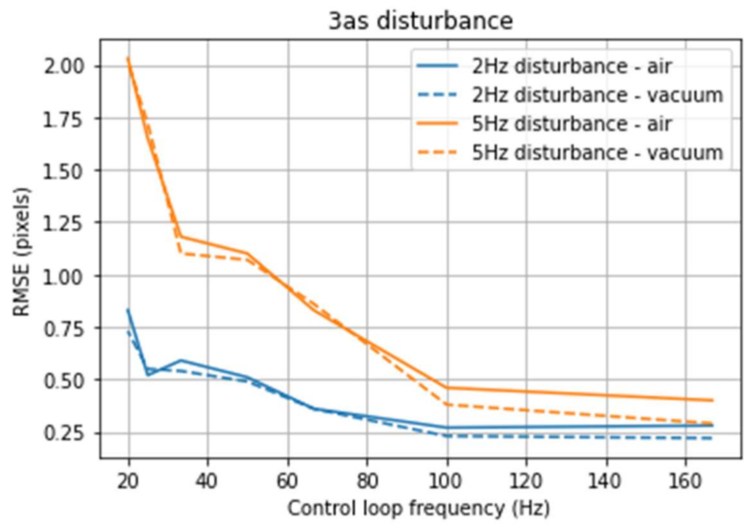

Figure 6: Root-mean-square error in spot position when controlling for a sine wave disturbance with intensity 3 arcseconds and frequency 2Hz (blue) and 5Hz (orange) as a function of control loop frequency. Solid lines show measurements taken in air and dashed lines show measurements taken in vacuum.

Figure 6 shows the RMSE in the spot position as a function of the control loop frequency and shows that the alignment system performance is strongly dependent on the control frequency. We find we can achieve control of a 5 Hz sine wave to less than

0.5 pixels when operating at greater than 140 Hz. The same requirement is met with a 40 Hz control loop frequency for the 2 Hz disturbance. Very similar results are seen in air and in vacuum. It should be noted that it was necessary to tune the control loop gains at each control loop frequency, due to the variation in the FSM response dependent on operation frequency.

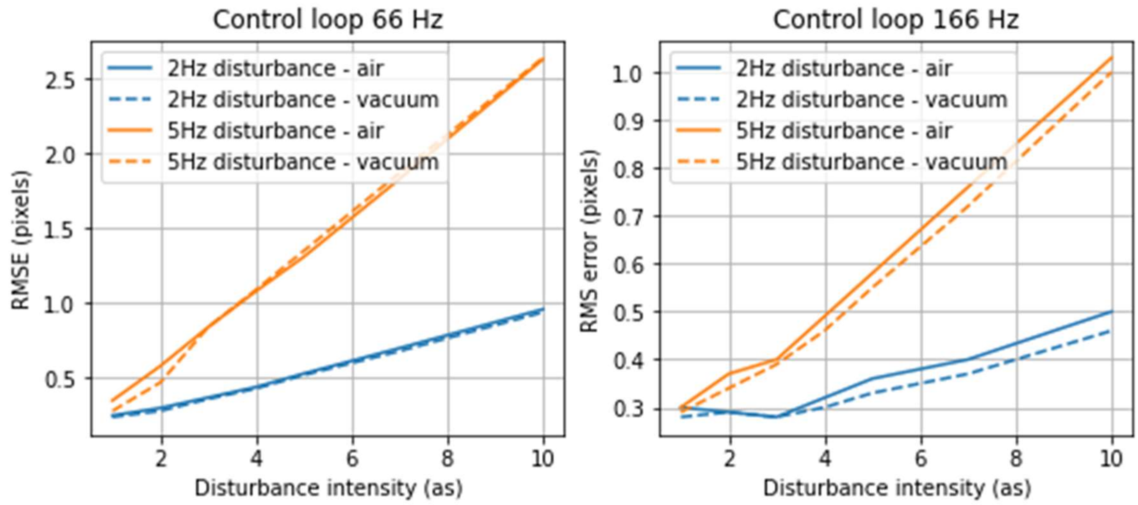

Figure 7: Root-mean-square error in spot position when controlling for a sine wave disturbance with varying intensity. Performance was investigated for disturbance frequency 2Hz (blue) and 5Hz (orange) shown for control loop frequency 66 Hz (left) and 166 Hz (right), achieved with detector window 50x50 pixels and 15x15 pixels respectively. Solid lines show measurements taken in air and dashed lines show measurements taken in vacuum.

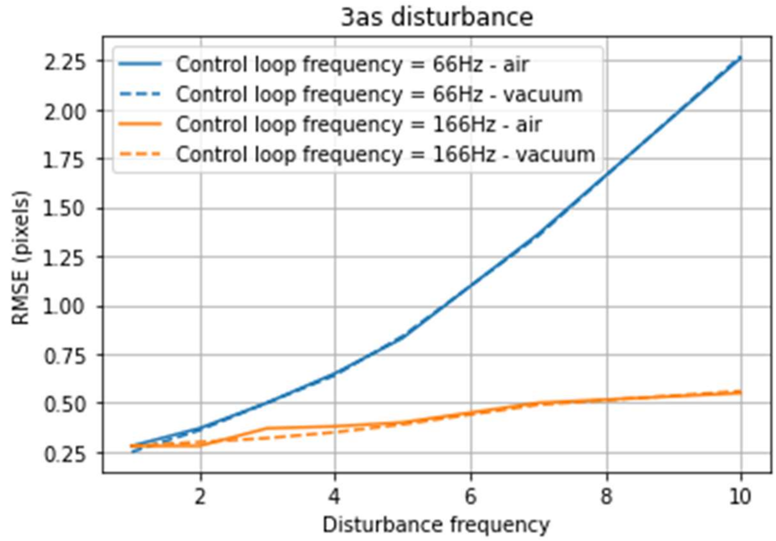

Figure 8: Root-mean-square error in spot position when controlling for a sine wave disturbance with varying frequency for control loop frequency 66Hz (blue) and 166Hz (orange). Solid lines show measurements taken in air and dashed lines show measurements taken in vacuum.

We also investigated the active alignment system performance against disturbances of different intensity (Figure 7) and frequency (Figure 8) and find the ability of the system to supress disturbances is strongly dependent on their frequency and intensity. When the control loop operates at 66 Hz, the RMSE can be supressed to less than 0.5 pixels only for disturbances less than 2 arcseconds at 5 Hz and less than 5 arcseconds at 2 Hz When the control loop operates at 166 Hz, the RMSE can be supressed to less than 0.5 pixels for disturbances less than 4 arcseconds at 5 Hz and less than 10 arcseconds at 2 Hz. The 66 Hz control loop can perform control to less than 0.5 pixels only for disturbances less than 2 arcseconds at 5 Hz and less than 5 arcseconds at 2 Hz. The 166 Hz control loop can perform control to less than 0.5 pixels for disturbances less than 4 arcseconds at 5 Hz and less than 10 arcseconds at 2 Hz. Very similar results are observed in air and in vacuum.

The similarity between the measurements in air and in vacuum, seen in all tests, indicates that the vacuum conditions do not have a strong impact on the FSM performance when optimised for each case. To understand the impact of the vacuum in more detail we also monitored the temperature on the FSM housing and control board and found the thermal management of the FSM in vacuum performs well. Our measurements also suggested that variations in temperature will not immediately result in changes to the FSM dynamics, as is observed in the performance data above.

5) CONCLUSIONS

A range of different hardware and software solutions were considered to meet the project requirements and a solution was proposed and implemented. A suitable test setup was also developed which has been used to measure the performance of the system. The project requirements are shown in Table 3 with their compliance status, showing that the proposed solution is compliant with all requirements. As a result of these tests, we conclude the TRL level of the technology has been raised from 3 to 5.

Table 3: Active alignment system requirements and their compliance status.

	Requirement	Verification method	Status
1	The detector shall capture a spot of diameter between 3 and 5 pixels measured at the full-width half-maximum.	Test	Compliant
2	The spot position shall be calculated in less than 20 ms using representative flight hardware.	Test	Compliant
3	The control system shall stabilise optical perturbations of 3 arc seconds at frequencies of up to 5 Hz to within 0.5 pixels rms.	Test	Compliant
4	The control system shall operate at a spot signal-to-noise ratio of 10 or higher.	Test	Compliant
5	The active alignment system shall meet the dynamic performance requirements (3 & 4) within a vacuum environment.	Test	Compliant

The results in section 4 show that the active alignment system is able to meet the requirement to supress an input disturbance of 3 arcseconds (as) and frequency 5 Hz to below 0.5 pixels. The best system performance was recorded when operating at 6ms per loop which is in excess of the requirement to operate at 20ms. The results are in keeping with our expectation that typical PID can only control for disturbance frequencies approximately 10% of the control frequency.

The work in this project has highlighted the importance of control loop speed in the control performance. For the kind of small satellite platform that this project is concerned with, the magnitude and frequency of microvibrations and their impact on optical links is somewhat unknown. The ability to control for disturbances of a range of frequency and magnitude is a big advantage. Our results show that increasing both the magnitude and frequency of an input disturbance degrades the control performance, but that increasing the control loop speed can compensate for this.

This finding highlights a potential avenue for future work, exploring methods to increase the control loop speed further. Some methods to consider could include performing more of the spot processing algorithms on the FPGA to further speed up detector readout time. Alternatively, spot detection algorithms on the microprocessor could also be sped up using alternative readout methods such as burst mode.

The results show that SNR on the detector does not strongly impact the active alignment system performance. Above SNR=5, we find the spot position on the detector can be reliably determined and there is no performance advantage to increasing the SNR. This is an important finding for the application to optical communications, as throughput is often a limitation.

The results in section 4 suggest that very similar control performance is achieved when operating the active alignment system in vacuum as is achieved in air. The system can reduce the RMSE in the spot position to below 0.5 pixels when correcting for a 3arcsecond disturbance of up to 8 Hz or a 5 Hz disturbance of up to 10 arcseconds. We find the FSM temperature increases by approximately 0.07 ˚C/mA applied to the coils. The temperature variation of the FSM is unchanged in vacuum, suggesting the thermal management is working well. Varying temperature does not seem to impact the active alignment performance or make a significant difference to the control gains required to achieve optimum control loop performance.

One limitation of this system is that the PID gains must be tuned when operated at different control loop frequencies. This is likely to be due to approaching the resonant frequency in the FSM response. A further investigation of alternative FSM models could focus on identifying FSMs with a flatter response profile with operation speed. However, our results have highlighted the importance of high loop speed in the active alignment performance therefore operation will most likely be maintained at the maximum speed. This means the PID gains are likely to only need to be tuned once.

6) PROJECT DELIVERABLES

- Technical Data Package: **GSTP RS03153 Technical Data Package.zip**
- Executive Summary Report: **GSTP RS03153 Executive Summary (this document)**
- Final Report: **GSTP RS03153 Final Report**
- Contract Closure Documentation:
- Technical Achievement Summary: **GSTP RS03153 Technology Achievement Summary**
- Photographic Documentation: **GSTP RS03153 Photographic documentation.zip**

Signatures:

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