

SYSTEMS DEVELOPMENT OF A TWO-AXIS STABILISED PLATFORM TO FACILITATE ASTRONOMICAL OBSERVATIONS



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Soli Deo Gloria

DECLARATION

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SUMMARY

INTRODUCTION

Inertially Stabilised Platforms (ISPs) aim to control the line-of-sight between a sensor and a target. They are required to perform two distinct operations: first, to keep track of the target as the sensor host and the target move in inertial space and, second, to attenuate rotational disturbances incurred to the sensor by host vehicle motion. This project aimed to develop a two-axis ISP for use in astronomical applications. Due to the high magnifications associated with astronomical observations, target objects are quickly lost from the field of view (FOV) of a stand-alone telescope due to the Earth's rotation. It was hypothesised that by mounting a telescope on a stabilised platform with an automatic target tracker it would be possible to overcome this problem as well as extend the allowable operating conditions of the telescope to include mountings on moving vehicles.

This project, therefore, represents the initial development of all systems of an ISP designed for the Meade ETX90 3.5" compound telescope. Due to budget constraints, it was decided early in the project to evaluate the hypothesis with a low-cost approximated system which made use of a mechanical assembly designed to mount a camera and inertially and geometrically model the specified telescope. This allowed the ISP development and testing to be performed at a lower cost than with the telescope itself. Figure 0-1 below shows the final ISP developed in this project during a Moon tracking test.



Figure 0-1: A Moon tracking test using the ISP developed

PROJECT DEVELOPMENT PROCESS

In order to achieve the above aim, a relevant review of the literature surrounding the various components of an ISP was performed to inform the design, implementation and testing cycle which comprised most of the project. A set of ideal system specifications were then developed to guide design decisions made and to evaluate the performance of the final system implemented. These specifications were developed for the initial project aim of stabilising the ETX90 telescope itself and, accordingly, served as design goals to be approximated by the low-cost system developed in this project.

During the project, the electro-mechanical structure of the ISP was designed and implemented. From a mechanical perspective, all parts of the physical structure, including the telescope modelling assembly, the yaw gimbal, and the mounting stand were designed and manufactured. The associated electrical systems required to facilitate control of this structure were also specified and configured. These systems included the relative angle sensors used to measure the orientations of the yaw gimbal and telescope modeller, the inertial measurement unit (IMU) used to measure the inertial rotational rates of the telescope modeller, the camera sensor used to acquire the image of the FOV of the telescope modeller, the motors and drive electronics used to actuate the gimbals, and the control hardware required to run the firmware and software written to achieve the stabilisation and tracking functions of the ISP.

These control hardware systems included a Raspberry Pi Model 3 B computer, an STM₃₂F0 microcontroller, and a laptop running a User Interface (UI) program written in LabVIEW. The Raspberry Pi was used to run an image processing script, written in Python 2.7, which was capable of detecting and locating the centre of the Moon in the camera FOV. The STM₃₂F0 microcontroller ran firmware, written in C, which was tasked with managing the various control and communications tasks required by the system. Finally, the UI helped to facilitate intuitive operator control of the system and performed datalogging of the system runtime data.

In addition, a complete simulation model for the system was written in the simulation language, Simul_C_EM, and used to design the various controllers for the ISP control system which were implemented on the STM₃₂F0. For each gimbal, compensated PI controllers were designed to allow manual orientation control of the telescope, compensated P controllers were designed to achieve target tracking, and compensated PI controllers were designed to reject rotational disturbances and so achieve the inertial stabilisation of the telescope modeller.

CONCLUSION AND RECOMMENDATIONS

Testing of the system showed a good correlation between the hardware and simulated results which indicates an accurate simulation model that can be used to test future design developments. Overall, most specifications developed for the initial system were met or

approached by the performance of the implemented model, with the notable exception of the tracking error of the system which overshot the specification by 50 %. This was due to the need to reduce the image resolution to 640x480 pixels in order for the Raspberry Pi to be able to process the images and provide target position data at a rate suitable for the tracking controller commands. Otherwise, the system showed good base motion disturbance attenuation properties of the order -31 dB and -34 dB for the yaw and pitch channels respectively, whilst line-of-sight (LOS) jitter was limited to a maximum of 2.5 mrad in response to tested disturbances of up to 1 rad/s at approximately 1 – 2 Hz. Figure 0-2 below is indicative of the type of attenuation performance achieved by the ISP for disturbances about axes parallel the control axes.

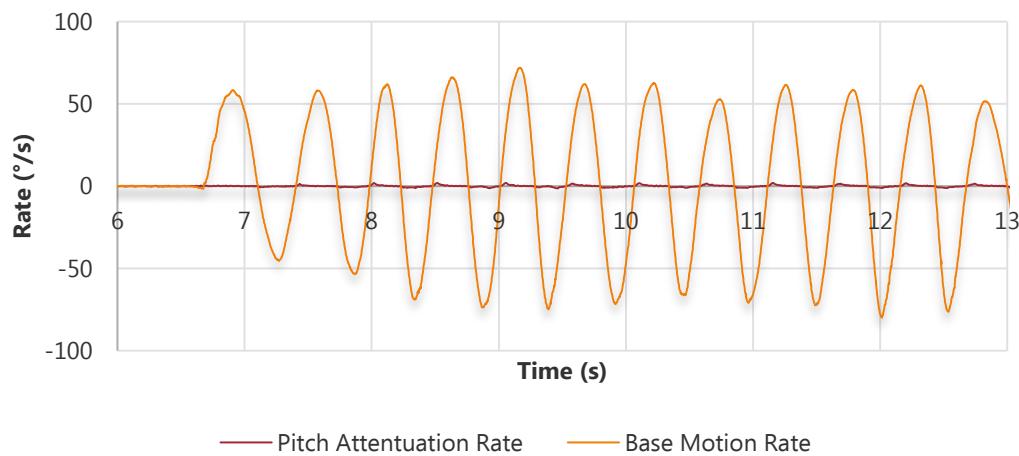


Figure 0-2: Typical disturbance attenuation of the pitch channel

Overall it was concluded that the project successfully achieved its aims and that future development should be continued with the ISP to include the ETX90 telescope. Suggested improvements that should be made include the change of computation hardware on which image processing is performed to improve the tracking performance of the system, the upgrading of the yaw motor such that a greater torque may be applied to the yaw gimbal and so attenuate stronger disturbance signals, and an investigation into the use of modern control methods which may help to improve the performance of the stabilisation control system.

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GLOSSARY AND ACRONYMS

ADC	:	Analogue-to-Digital Converter.
CPU	:	Central Processing Unit, circuitry which carries out computer program instructions.
CNC	:	Computer Numerical Control, computer-based automation of a manufacturing process.
EMF	:	Electromotive Force, voltage about a closed loop in a circuit.
GPIO	:	General Purpose Input/Output, a reconfigurable pin on an integrated circuit chip whose function can be set to various input or output modes.
GUI	:	Graphical User Interface.
HSV	:	Hue Saturated Value, a colour model closely aligned with the human perception of colour.
I ₂ C/I ² C	:	Inter-Integrated Circuit communications protocol.
MCU	:	Microcontroller.
NVIC	:	Nested Vector Interrupt Controller, a peripheral which manages the priority and handling of interrupts on many ARM Cortex microcontrollers.
PLA	:	Polylactic Acid, a type of thermoplastic commonly used in 3D printing.
RGB	:	Red Green Blue, a colour model used in digital images.
RS-232	:	An electrical standard for serial communication.
RMS	:	Root Mean Square average.
SAAO	:	South African Astronomical Observatory.
SPI	:	Serial Peripheral Interface communications protocol.
UCT	:	University of Cape Town.
USART	:	Universal Synchronous/Asynchronous Receiver Transmitter, serial communications hardware.
VI	:	Virtual Instrument, a computer program written in LabVIEW.

I

INTRODUCTION

This section aims to introduce the project undertaken by describing the subject of and motivation for the project in the context of the fields in which it lies. The rationale and motivation for the project are here given where inertial stabilisation is introduced and the specific application of inertial stabilisation technology applied in this project is described. The section concludes by stating the scope and limitations of the project and by detailing the objectives and plan of development of this report.

1.1 PROJECT RATIONALE AND MOTIVATION

Many examples of modern electronic and optical systems require inertial stabilisation for them to achieve their maximum performance. ISPs are systems capable of isolating a sensor from its host by attenuating rotational disturbances which may be coupled from the host to the sensor and result in a reduction in the sensor's performance. Examples of systems whose performance may be improved by using an ISP include missile seeker heads, communications systems, inertial navigation systems, surveillance systems, astronomical telescopes and handheld cameras.

In the case of telescopes and cameras, high-quality observations and pictures may only be achieved through stabilisation of the line-of-sight LOS of the centre of their FOV. One method by which this may be accomplished is by using a well-stabilised platform onto which they may be mounted. A most basic stabilised platform aims to prevent a sensor from rotating in inertial space. However, it is often insufficient to simply keep a sensor steady in inertial space: Most sensors requiring stabilisation are intended to point toward a given target or object of interest. Hence, inertial stability is required in conjunction with active control of the direction in which the sensor points to keep the sensor following the target if it is capable of motion.

Looking at a celestial object at high magnification through a telescope illustrates the problem clearly; even the smallest rotation of the telescope will cause, at the very least, blurring of the image observed, but is likely to cause a loss of the target altogether from the telescope FOV. Likewise, a high-resolution camera requires the sensor be as still as possible for maximum image clarity to be achieved. This problem is clearly aggravated when the observation instrument is mounted on a moving host. Even a telescope affixed to the Earth is subject to this problem; at high magnification, celestial objects will quickly move out of the field of view of the telescope due solely to the Earth's rotation.

Modern telescopes with motor drives generally account for the Earth's rotation using one of two different mounting methods: An alt-azimuth (or sometimes called azimuth-elevation) mounted telescope uses two orthogonal gimbals driven by motors to rotate the telescope in order to keep track of the target as it moves across the sky. An equatorially mounted telescope has only one axis of rotation to be controlled at a constant speed equal to the Earth's rotational speed, but that axis must be aligned with the Earth's rotational axis. Thereafter an inner elevation axis can be rotated to a fixed position with the desired celestial body in the FOV. In both methods, the gimbals are driven in a manner governed by a predefined algorithm which accounts for the initial setup conditions of the telescope and geophysical constraints such as time, date, and location in order to track the desired celestial body. ISPs in conjunction with automatic target trackers which are able to locate the target in the FOV of the imaging sensor may also feasibly be employed to meet the tracking and stabilisation challenges of telescopic observations.

The inclusion of automatic target tracking and gimbal stabilisation into the control system of the telescope would provide the same tracking capabilities as the aforementioned methods whilst adding robustness to the system: If the telescope was accidentally (or intentionally) moved after observations had begun, the target tracker would, within design constraints, keep the target in the centre of the FOV of the sensor. This has several positive implications, for example, it would increase the ease of use of the telescopic system for the amateur astronomer, or it would allow for the telescope to be mounted on a moving base such as the deck of a ship or a moving motor vehicle.

1.2 PROBLEM IDENTIFICATION

If a telescope is mounted in an alt-azimuth configuration at least two-axes of rotational control are required to track a celestial body as it moves across the night sky. Simultaneously, disturbances to the telescope may cause undesired rotation about any of the three axes of inertial space. Therefore, a mounting platform where the inertial rotation about multiple axes is controlled is required to stabilise and isolate the telescope from rotational disturbances. In the absence of a target tracking system, three-axes are the minimum about which control is required to successfully stabilise the telescope. This may be reduced to two axes if rotation of the image about the telescope LOS is allowed and a target tracker is used to keep the telescope pointing toward the target in response to disturbances about the LOS axis.

The thesis of this project is, therefore, that a multi-axis closed-loop stabilisation controller working in conjunction with an automatic target tracker can be implemented to keep an optical telescope sensor pointed at a celestial target in both static and dynamic host environments using image processing and control system design techniques.

1.3 PROJECT SCOPE AND LIMITATION

This project, therefore, had the following initial aim:

To develop an ISP-mounted telescope system, (a) capable of the automatic tracking of a celestial object through the use of an optical target tracker, and (b) whose jitter attenuation properties would facilitate the acquisition of clear images, even if mounted on a moving host.

Interviews with Dr Vanessa McBride of UCT and SAAO revealed that scientific telescopes are required to keep the image stable to the order of 1 arcsecond (approximately 5 μ rad). Whilst modern precision ISPs are capable of reducing jitter to a similar order of magnitude [1], it swiftly became clear that this level of precision was not achievable within the budget and resource constraints of this Masters project. Coupled with a budget revision and reduction early in the life of the project a revised primary aim was determined:

To implement a low-cost ISP, (a) capable of suitably approximating the initial aim of telescopic stabilisation and automatic tracking control using a low-cost camera instead of a telescope, and (b) designed for future project expansion with the incorporation of a telescope to work with the design target tracker and control system.

This revised aim was centred on determining the feasibility of the initial aim in a low-cost fashion. It was expected that the low-cost approximation would indicate positive implications in terms of increased robustness and ease of use of personal telescopes for amateur astronomy where observation specifications are less stringent and tolerances are wider.

1.4 PROJECT METHODOLOGY

To achieve the objectives above, extensive system design, modelling and simulation were performed before successful implementation could be achieved on a physical system. The system implementation then included the design and manufacture of the electro-mechanical assembly of the ISP, the control system, the specification of actuators and their associated electronic interfaces, and the development of the optical image processing target tracker.

Due to the cross-disciplinary nature of the project and the requirement for several interfacing systems to be developed, a structured systems engineering approach was followed in order to better define, track and verify the tasks undertaken.

The following outcomes were desired from the project: MSc (Eng.) dissertation, Master's journal paper, a fully-functioning ISP with high precision observation capabilities, and a complete simulation model with an analytical comparison and resolution of discrepancies between simulation and hardware results.

1.5 PLAN OF DEVELOPMENT

This dissertation attempts to detail the process by which a functional ISP well suited for adaption to astronomical applications has been designed, simulated, and implemented.

Accordingly, in **Chapter 2**, this report first surveys the diverse bodies of knowledge required for consideration in the design on an ISP.

Continuing from the literature review, **Chapter 3** details the initial, quantitative system specifications developed for the ISP and it associated systems.

Chapters 4 to 7 then detail the design and implementation of all systems associated with the ISP, control system, and target tracker before **Chapter 8** shows a discussion of the achieved test performance of the implemented system and how the simulation model was verified to ensure its correlation with the physical assembly.

Finally, this document concludes with the presentation of conclusions and recommendations for future development in **Chapter 9**.

2 LITERATURE STUDY

2.1 INTRODUCTION

This section aims to introduce and explore the factors of importance which have a bearing on the successful achievement of the aims and goals set in Chapter 1. The section begins by first exploring the fundamental systems and technologies associated with ISPs in general. An overview of the field is given before the general sub-systems of ISPs are described in detail. The section then moves to describe several key sources of performance limitation in general stabilisation systems after which a detailed evaluation of gyroscopic sensors which are critical to the implementation of a stabilised platform is given. A cursory discussion of target tracking techniques and available telescope technologies is then given before the section concludes with a detailed representation of the dynamics model of a typical two-axis gimbal system.

2.2 OVERVIEW OF INERTIALLY STABILISED PLATFORMS

A wide range of modern hardware requires inertial stabilisation to facilitate optimal operation. Some of these systems include cameras, communication systems, missile guidance systems, gun turret control systems and astronomical telescopes [1]. In these applications, there is a need to control the LOS between a sensor and a target in order to reduce jitter on the sensor which can cause unwanted effects and reduce system performance [2], [3]. Inertially stabilised platforms are frequently employed to help achieve the pointing and stabilisation requirements of such systems. An ISP is a mechanism that is used to control the orientation of a sensor payload. This is frequently achieved using a gimballed structure which facilitates the orientation control of a sensor. Figure 2-1 below shows some examples of modern stabilised platforms.



Figure 2-1: The DJI Ronin 3-Axis Brushless Gimbal Stabilizer [4], the Cinema Pro Gimbal [5], and the Paradigm SRP TALON Gyro-Stabilized Gun Platform [6]

The DJI Ronin is a three-axis handheld camera stabiliser, the Cinema Pro is a five-axis aircraft mounted optical stabiliser whilst the TALON is a two-axis stabilised platform designed for military use in precision shooting applications from moving vehicles.

Although varied in application, the goal of every ISP is to control the LOS of one object relative to another in an inertial reference frame [1], [7]. The most basic ISP attempts only to prevent inertial rotation of the sensor payload within the inertial frame, however, in practice, most ISPs are required to control the relative motion between two objects; the payload and the target. To achieve this, most ISPs are required to stabilise and point a payload about at least two axes in inertial space so that dynamic target tracking may be achieved in three-dimensional space. Many designs stabilise the payload about three or more axes in inertial space and have been shown to provide better host vehicle base motion isolation properties than two-axis platforms [1].

The role of an ISP is, therefore, to accurately control the LOS of a sensor in an environment where both intentional and disturbance motion of both the target or the ISP may occur, therefore changing the LOS orientation between the two objects. Two important aspects of LOS control are to first ensure that the ISP keeps pointing toward a selected target when either target or host base motion may occur, and second, to ensure that the sensor is held steady in inertial space whilst pointing toward the target when disturbance motion of the host may be present. The first objective may be achieved through the use of a tracking or position control system and is measured by the metric *tracking error*. The second objective may be achieved through the use of a rate controller and is measured by the metric *jitter* [7].

An application of ISPs is in optical imaging systems; these make use of ISPs to improve the performance of the imaging system. Advances in optical imaging performance have required the use of stabilisation for the best use of the available imaging technology to be realised. Known respectively as digital image stabilisation and optical image stabilisation, both digital image manipulation techniques and physical sensor stabilisation methods have been implemented to provide increased imaging performance. In both systems, the LOS is from the centre of the FOV of the camera or sensor to the target object being focused on by the imaging system. In many instances, the target of the sensor is dynamic and there is a need to track the target as it moves whilst maintaining the clarity and sharpness of the image. High-

performance examples of imaging systems can be expected to reduce jitter to less than $10 \mu\text{rad}$ even in highly dynamic environments [7].

In conjunction with a *target tracker*, an ISP may be used to achieve the above challenge. The target tracker is a general term used to describe any hardware or software system able to achieve target detection and positioning within the sensor FOV. Regarding optical imaging, two fundamental objectives for the ISP exist: First, to obtain high-quality images of the target, and second, to determine the location of the target with respect to a defined reference frame. The quality of the image may be affected by several factors which can be broadly grouped into three categories; target motion, host vehicle motion and operating environment.

A target with dynamic motion may easily move outside of the FOV whilst the host vehicle motion may also cause a loss of tracking. Environmental factors such as atmospheric conditions affecting the operating environment of the ISP may also cause challenges in target tracking. An ISP must be robustly designed in conjunction with its target tracker such that these influences do not affect the operation of the system beyond its prescribed limits during operation.

2.3 ISP OPERATING PRINCIPLES

An ISP typically consists of three fundamental sub-systems: A sensor payload requiring stabilisation, an electromechanical assembly which constrains the motion of the sensor payload, and a control system used to drive the electromechanical assembly. These systems are discussed in detail in the sections to follow.

2.3.1 SENSOR PAYLOAD

The sensor payload of an ISP is the dominant system that drives the overall size and specifications of the ISP. A vast array of different systems may require stabilisation. Any system which may experience a reduction in performance as a result of torque disturbances may potentially be stabilised. The payload to be stabilised determines the type of electro-mechanical assembly chosen.

2.3.2 ELECTRO-MECHANICAL ASSEMBLIES

ISP assemblies are complex electro-mechanical systems comprising of several different mechanical parts and electrical subsystems. The class of stabilised platform in which a design falls is determined by the configuration of the electromechanical assembly. The two main categories under which ISP designs fall are known as *mass stabilised* (or *platform stabilised*) and *mirror stabilised* (or *steering stabilised*) systems. These will be discussed in detail in the sections to follow, however, there are several components common to both mass and mirror stabilised systems which will first be discussed.

ISP COMPONENTS

Gyroscopes (gyros) are inertial angular rate sensors which are used to measure the ISP LOS rates. They are usually mounted directly on the sensor payload and so provide feedback of the inertial rotational rate of the sensor payload [7]. The stability of a system is a measure of its actual inertial rotational rate relative to the desired rotational rate and therefore these sensors play a significant role in the development of an ISP. The error introduced to the system by the gyro is directly coupled into the overall system and accordingly, they have been shown to be the main overall performance limiting components in small-sized stabilised platforms [1]. The appropriate selection of gyro for a system is then a critical design decision in the development of an ISP. Section 2.6 is devoted to a more complete discussion of inertial rate sensing and the technologies available for implementation on an ISP.

The friction and stiffness of the **bearings and suspension system** of an ISP's electro-mechanical assembly are two key factors associated with the implementation of a stabilised platform. Friction introduces unwanted disturbances into the system which must be overcome for successful stabilisation to be achieved, whilst a system with low stiff may suffer a reduction in performance through a variety of resonance effects. Friction and stiffness do however require a trade-off to be made in the design of the rotating joints and mounts of an ISP: Stiffer mechanisms generally introduce more friction into the system yet are better in terms of the structural resonance properties of the mechanism [1]. Ball bearings are used to suspend gimbals and rotating elements in most ISPs as they offer a good compromise between structural stiffness and rotational friction. Other alternatives include gas-lubricated bearings and magnetic suspension systems in applications where minimising friction is of specific importance, however, these mechanisms offer lower stiffness than traditional bearings.

Gimbal actuators of an ISP may take several forms. DC electric motors are the most common actuators although hydraulic actuators are also sometimes used as they are able to provide high torques at low speed when pole counts are high [1], [2]. Other types of actuators sometimes used in ISP designs include hydraulic and pneumatic drive systems. Gimbal actuators may either be coupled directly onto the gimbals as direct torquers or couple through gear or belt drivetrains. Actuators should have fast response times and be able to provide sufficient torque to overcome disturbances and achieve required tracking specifications without excessive hysteresis, cogging, or backlash.

ISP rotational rate requirements seldom exceed speeds of 100 °/s, therefore, gearing can be considered to reduce the mass and size of the actuators. However, when drivetrains are used, reaction torques inside the gearboxes contribute to the total torque disturbances and add friction, noise and torsional resonances [1]. Due to these effects, directly coupled actuators are the preferred method of control in stabilisation systems.

The final set of components common to all ISPs to be discussed before describing the main classes of ISPs are known as **auxiliary equipment** systems. This term groups the supplementary components required to facilitate the operation of an ISP. Positioning the target in an inertial frame requires a knowledge of where the ISP is pointing. This is achieved

using relative motion sensors affixed to the gimbals which can provide position feedback to the control and data-logging systems. Cable management systems also fall under this term.

MASS STABILISATION

Turning now to the main types of electro-mechanical configurations for stabilisation systems, the first main class, mass stabilised systems, will now be discussed. This method involves the stabilisation of the entire sensor payload through the rotation of a gimbal assembly to control the sensor LOS. When the host vehicle rotates, the gimbals facilitate sensor payload rotation in the opposite direction to the host vehicle motion in order to maintain a steady LOS direction. Consequently, the motion of the gimbals directly controls the LOS of the sensor. In a mass stabilised configuration, the number of orthogonal gimbals required in the electro-mechanical assembly is equal to the number of axes in which inertial control is required. Figure 2-2 below shows a possible configuration of a mass stabilised system.

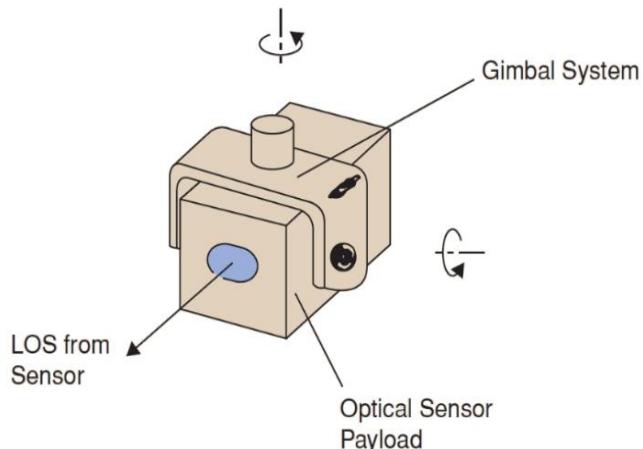


Figure 2-2: Mass stabilised sensor [7]

As with all ISPs, the goal of a mass-stabilised system is to hold the sensor payload steady in inertial space. The LOS of an ideal, frictionless, mass-stabilised ISP is held in its initial inertial position as a direct consequence of Newton's 2nd Law [1], [7]. When applied to rotation, Newton's 2nd law states that if an unbalanced torque (T) is applied to a body in equilibrium, the body, of moment of inertia (I), will accelerate with an angular acceleration (α), such that:

$$\sum T = I\alpha.$$

Stabilisation is, therefore, an attempt to keep the net torque on a sensor payload to zero. An ideal system is one balanced such that the resultant internal moment about each axis is zero. In addition, if friction between the gimbals and other internal disturbance torques are negligible, the system will remain stable, at rest, even in the presence of external disturbances [8]. In a real system, however, internal disturbances will be incurred from various sources

including imbalance, assembly flexure, cable flexure, kinematic and geometric coupling, and friction. Further discussion of disturbance sources is found in Section 2.4. The primary challenge in the development of such a system is therefore to design a system which incurs minimal disturbance effects onto the sensor [2], [7].

Kinematic disturbances are disturbances coupled into the ISP due to the dynamic relationships between the assembly inertia characteristics and the angular motion of the gimbal assembly, whilst geometric coupling disturbances are those induced on the system by the geometry of the gimbal assembly; applying a rotation to one axis may cause unwanted rotation about a second axis purely due to the geometry of the system [2]. Kinematic disturbances in mass stabilised systems may be reduced significantly by suspending the gimbals from their principal axes. This is an important insight to be made use of in the design of an ISP. The process of determining the kinematic relationships between the gimbals is detailed in Section 2.9.

Gimbals require actuation due to the fact that it is almost never sufficient to simply stabilise the sensor; the LOS between a sensor and a target is required to be controlled which requires the gimbals to be driven such that the sensor follows the target [1], [8]. Gimbals are usually actuated using DC motors which have high torque and precision capabilities to move the gimbal assembly accurately. As previously stated, motor drives may be mounted directly onto the gimbal axes to control gimbal rotation, or they may make use of gear or belt linkages with the motor often then being mounted on the base of the assembly. A further disadvantage of geared or belt linked systems is that drivetrains inherently couple the base motion of the host vehicle to the gimbal assembly and hence to the sensor payload. Due to this, even an ideal, frictionless system must actively control the sensor LOS to account for the rotation of the host vehicle [2], [7].

Directly coupled DC motors represent the closest approximation of an ideal direct torquer, yet no type of electro-mechanical actuator is capable of achieving this due to viscous damping within the system [2]; back EMF causes viscous damping in electric motors whilst hydraulic drives are damped by flow feedback within their assemblies. These viscous damping terms induce further torque disturbances on the ISP system which must be accounted for. A common method for reducing these torques is to make use of current or pressure feedback minor loops [2]. A current feedback minor loop for a DC motor is shown in Figure 2-3 below.

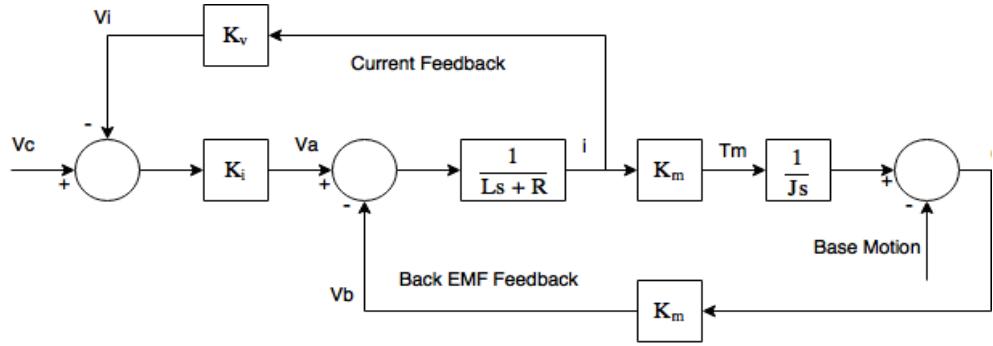


Figure 2-3: Current feedback minor loop

Figure 2-3 above shows a simplified block diagram model of a DC motor being controlled by a command voltage V_c . Current feedback is facilitated by the scaling block K_v and the minor loop controller gain K_i . These closed-loops have high gains and bandwidths and therefore are effective at reducing the effects of viscous damping at low frequencies and hence disturbance torques due to viscous damping are also reduced.

Overall, the LOS rates of a mass stabilised system are governed by the interaction of gimbal assembly and sensor payload inertial rates and these are constrained by system geometry [2]. These inertial rates are governed by the relationship between the inertial characteristics of the gimbal assembly and the total resultant torque (including disturbance and applied actuator torques) applied to each of the ISP axes.

MIRROR STABILISATION

The second main class of ISPs, mirror stabilised systems, involve the control of optical elements such as mirrors and prisms to ensure correct LOS orientation with respect to a sensor which is fixed to the host vehicle. Figure 2-4 below shows a possible configuration for a steering stabilisation system.

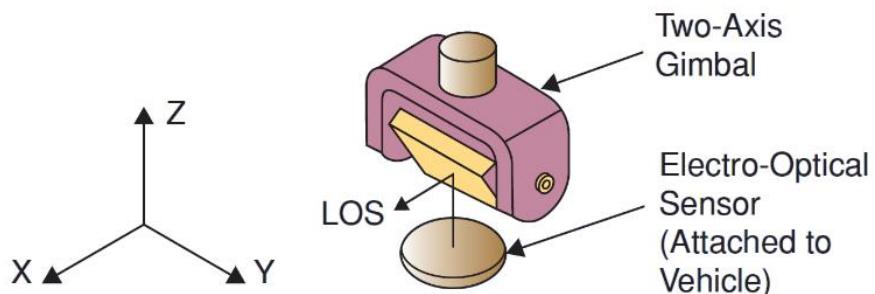


Figure 2-4: Mirror stabilisation mechanism [1]

Steering stabilisation techniques may be effectively employed systems where the sensor payload is large, under geometric design constraints, or where its mass distribution is unsuitable for mass stabilisation [1]. Since gimballed optical elements are used to move the LOS rather than the entire sensor system, mirror stabilised systems may be much smaller than mass stabilised systems. This makes mirror stabilisation systems more suited to applications where physical size is a design constraint. For example, they have been successfully employed

in applications where their small size aids the aerodynamic properties of a larger system, in military application where a small target is advantageous, and where space is highly constrained such as within handheld cameras [1], [7].

In systems that use mirror stabilisation, the motion of the steering sensor may not produce equal motion of the image on the sensor. The specific relationship is dependent on the design implemented. A behaviour called optical doubling may occur simply from the rotating of a plane mirror perpendicular to the LOS. In this case, the reflected LOS is turned through double the angle of the mirror rotation [2], [7], [9], [10]. Figure 2-5 below highlights the effect of mirror rotation on the LOS.

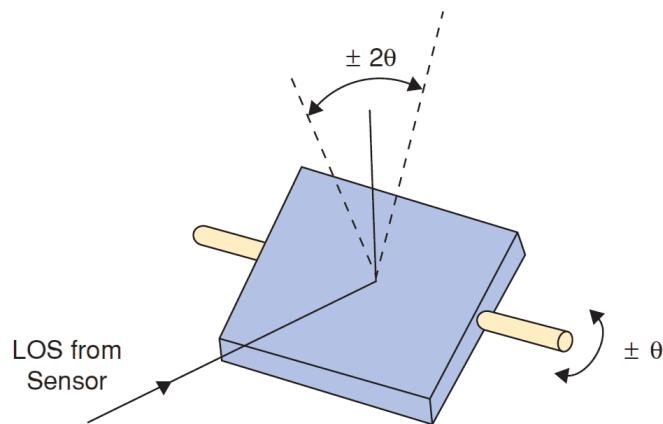


Figure 2-5: Optical doubling effect [7]

This sort of behaviour must be taken into account during system design and LOS kinematics generally become complex and extensive [1]. One of the challenges involved with mirror stabilisation is measuring the LOS rotation due to the optical doubling effects. If alignment is correct, a 2:1 drive linkage coupling the gyro to the mirror is often used.

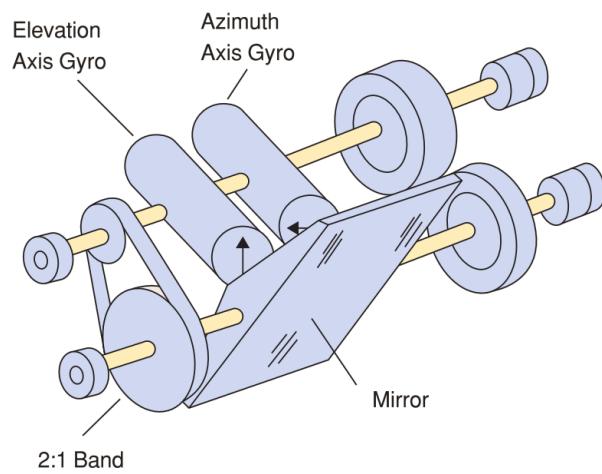


Figure 2-6: 2:1 drive linkage [7]

Figure 2-6 above shows how the mirror mounted such that it rotates about s parallel axis to the relevant measurement axis and due to the 2:1 linkage causes the same magnitude rotation on the LOS as the measured rotation angle.

Mirror stabilisation designs generally allow a smaller mechanical design and can be designed such that they exhibit the similar characteristics to direct drive mass-stabilised systems with no inherent base motion coupling [7]. However, it is generally agreed that mass stabilisation designs allow more precise control of LOS rates compared to other designs. Mass stabilisation provides better stabilisation when dealing with small operating angles as well as having better geometric and torque coupling characteristics than mirror systems [2].

ALTERNATIVE STABILISATION TECHNIQUES

In addition to mass and mirror stabilisation, three other stabilisation techniques are worth noting; momentum wheels, feedforward control systems, and redundant gimbal systems. A **momentum wheel** is simply a spinning mass which is used to hold an object steady inherently due to the spinning motion of the mass to which it is attached. This direct stabilisation technique does not make use of feedback gyros in an active closed-loop servo system, but rather causes the entire object attached to the spinning mass to become effectively self-stabilised. Momentum wheels have been extensively used in applications such as stabilising missiles, torpedoes, and ships [1].

A **feedforward control system** involves the gyroscope being fixed to the base or host vehicle. The gyro becomes referred to as a strapdown gyro. This approach is most commonly found in applications where LOS to be stabilised does not coincide with the necessary motion required to suppress disturbances, or there is no physical space to mount a gyro [1]. This method is often employed in handheld cameras and in other mirror stabilisation systems.

This method involves estimating the LOS motion based on the data from the strapdown gyro and a measurement of the relative motion between the base motion and the mechanism facilitating LOS motion such as a gimbal [11]. The servo loop is now closed on the estimated LOS signal, not on the gyro signal [1]. Therefore, the gyro is not driven to zero by the control system and must accurately provide measurements continually throughout operation and care must be taken to adequately handle gyro noise, offsets and drift in the implemented ISP. Typically, gyros used in feedforward schemes require greater sensitivity and accuracy than those used in gyro feedback loops. Major error sources also now include the dynamics of the relative motion sensors required for this approach [1] and the sampling frequency of the control hardware if it is digitally implemented [11].

Some feedforward techniques have also been shown to reduce the uncertainty of classical control methods at dealing with non-linearities in ISP systems such as friction and cable restraints. They have also been shown to improve base motion rejection, a key performance metric in evaluating ISP behaviour [1], [3], [12].

ISP designs with **redundant gimbals** make use of more than one gimbal per control axis. They allow more degrees-of-freedom of control than are technically required for a given application [13]. They are often used in situations with high aerodynamic disturbances where large torques may be applied to a control axis. The outer gimbal plays the role of attenuating the majority of the external disturbance applied to the sensor payload which the inner gimbal on the axes can then more accurately perform tracking and stabilising operations [1], [8].

Redundant gimbals may also be used to prevent gimbal lock, a behaviour where a loss in a degree-of-freedom of control of the gimbals is experienced in response to certain input commands whilst the gimbals are in lock-specific orientations. The presence of a redundant gimbal makes it possible to design systems always capable of maintaining tracking and stabilisation capabilities through driving other gimbals such that they are kept away from gimbal lock orientations [13].

2.3.3 CONTROL SYSTEMS

The third main subsystem of an ISP is the control system. Used here in a broad sense to describe the control algorithms as well as the hardware and software through which they are implemented and any user interface software facilitating supervisory control of the ISP.

The objective of the control system is to control the motion of the electro-mechanical assembly such that the desired LOS rate is maintained whilst accounting for disturbances to the ISP. This system has three primary aims:

- i. To stabilise the LOS so that precise sensor data may be realised with low jitter,
- ii. To maintain tracking of the target and,
- iii. To measure the LOS orientation and so position the target in the inertial frame of the ISP mechanism.

The stability and effectiveness of a control system is a function of the system dynamics of each component comprising the total system. Therefore, to achieve the above objectives according to the overall system specifications, the control system must be designed as part of the total iterative design process. Classical control systems using Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers are the most commonly implemented type of controllers on ISPs ([1], [7], [14]–[17]) yet it has been demonstrated that improved track command following and disturbance rejection is possible using a variety of more complex control techniques. These are diverse and include fuzzy PID [18], adaptive control, sliding mode control [19], feedforward compensation [1], H_∞ [8], internal model control [16], [20], and variable feedback designs. Typical systems using classical controllers are capable of disturbance attenuation ratios from the disturbance source to the output rate of between -10 and -30 dB whilst advanced control methods have been shown to be capable of improving this figure to approximately -40 dB at low frequencies up to 2 Hz [16], [20], [21].

The main motivation for the implementation of each of these advanced control methods has been to better deal with non-linearities in the ISP systems and to increase controller robustness to parameter variation and uncertainty in the models. Sources of non-linearities in ISPs include components that may saturate at their operational limits (such as actuator amplifiers, actuators themselves, and inertial measurement sensors), structure compliance and resonances, and disturbance torques from friction, cable restraint, and mass imbalance. Classical control methods are theoretically only valid for linear systems and for non-linear

systems at the point at which they are developed. Accordingly, they are generally sufficient for systems with small variations from the operating point but become increasingly inaccurate with distance from the operating point and with increasing frequency [17], [22].

Typically, an ISP control system consists of two loops per gimbal axis configured in a cascade control structure. The outer loop is a low-frequency tracking or position loop used to keep the sensor pointing toward the target, and the inner loop a high-frequency rate or stabilisation loop used to control LOS rate and account for high-frequency disturbances [1], [7]. The track loop has the objective of removing low-frequency parallactic motion between the payload and the target, and any possible drift in the rate loop [1]. Parallactic motion is present whenever either object has a velocity component orthogonal to the LOS. Figure 2-7 below shows a typical cascade control structure with an outer tracking loop driving an inner stabilisation loop.

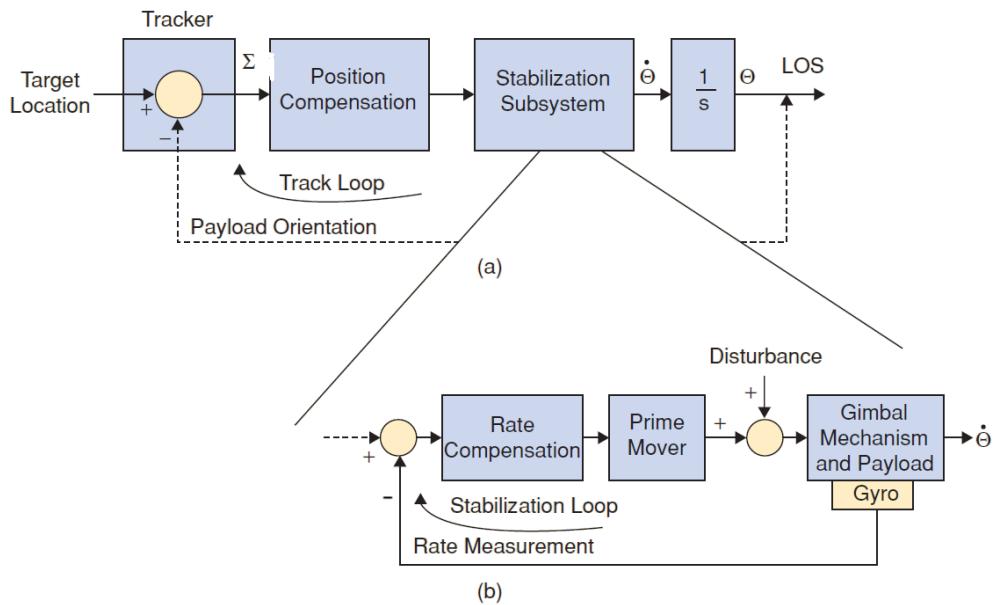


Figure 2-7: Cascade control structure [7]

Stabilisation loops are high bandwidth, closed-loop servo systems which receive their input commands from the tracking loop enclosing it. They are usually chosen to have a PI or PID controller. This is due to the fact that at low frequencies, disturbances are not suppressed adequately by Proportional (P) controllers and constant errors may result. PID controllers show the best low-frequency disturbance rejection (of the classical control methods) due to their error-accumulation integral actuation, yet have the longest settling time in response to an input command, especially when mechanical resonances are considered. These loops operate on rate inputs and therefore feedback is usually provided using a gyro fixed to the relevant gimbal. Typically, the gyros used in mass stabilisation systems are electromechanical systems that output an analogue or digital electrical signal in response to inertial rotation about the gyro's sensitive axes [1].

The closed-loop bandwidth of the stabilisation control system is the most important factor predicting the disturbance torque rejection performance of the ISP [1]. Bandwidth is

a measure of the control system's ability to cause the feedback signal (or LOS output rate) to follow the command input. It is fundamentally limited by the non-linearities caused by components such as drive systems and sensors as well as structural compliance of the ISP. Rate-command following error is attenuated at frequencies lower than the loop bandwidth by a factor approximately proportional to the loop bandwidth. Also, torque disturbance rejection ratio is roughly proportional to the squared inverse of the closed-loop bandwidth for frequencies lower than the bandwidth frequency [1], [11].

Tracking loops are low bandwidth position loops that receive input commands from the target tracker, therefore these components must be designed concurrently with each system affecting the design of the other. As the target tracker is a sampled device operating at a fixed rate, phase lag will be introduced into the control system which must be accounted for in the design process.

2.4 SOURCES OF TORQUE DISTURBANCES

As previously stated, an ideal mass stabilised system is a design such that the LOS of the sensor remains inertially stable in the presence of disturbances. However, in a practical system, there are many sources of disturbance. If the disturbance torque can be nulled such that the net applied torque is only that which is required to rotate the LOS in such a manner as to track the target, the LOS of the sensor will be stabilised. Torque disturbance rejection is, therefore, the most important performance metric for an ISP [7].

Some key sources of torque disturbance are discussed below [1], [2], [7]:

Torque disturbances that must be considered in ISP design include Coulomb friction from surface interactions between parts of the electro-mechanical assembly. This type of friction may be reduced through the careful design of the assembly and the use of bearings to facilitate smooth inter-gimbal rotation. Spring torques may arise from flexure in the various cables used to provide power to, and communication with the actuators and sensors. Rotating imbalance from non-symmetric gimbal design will cause jitter in the LOS of the sensor. Kinematic coupling from base motion which translates into gimbal rotations will also cause undesired torque disturbances on the LOS.

It is the role of the control system to null these disturbances by applying the required torque to the gimbals such that the resultant torque is that which facilitates target tracking. This is accomplished by the actuators driving the different gimbals of the assembly, however, due to the geometric and kinematic constraints of the assembly itself, inter-gimbal torque coupling will inevitably occur to some extent: the product of inertia terms in one gimbal will cause disturbances in another. This is detailed further in Section 2.9.

Misalignments between the LOS axis, gyroscope axis and the axis of applied torque also cause disturbance torques in other axes and are the cause of unwanted LOS motion [1].

Further disturbance torques result from the structural dynamics of the assembly itself and environmental disturbances [1], [2]. The structural dynamics of the system play a

fundamental role in limiting the bandwidth and hence the performance of the control system, therefore careful mechanical design is required to achieve high bandwidth stabilisation capabilities through the reduction of the structural compliance of the electro-mechanical assembly [1].

The impact of the structural dynamics on the performance of an ISP is further detailed below. In order to accurately specify the torque requirements of the system, all the above disturbances must be considered as well as external loading and noise [2].

2.5 ISP STRUCTURAL DYNAMICS

Structural resonances set up by the electromechanical assembly and the load are fundamental to limiting the bandwidth of the ISP [1], [2], [7]. All the components of an ISP influence the structural dynamics of the system. Their properties interact in multiple ways producing an almost unlimited number of modes of response due to their many different mass distributions, material properties, damping properties, geometric configurations that change with time, and variations in forcing functions.

The structural modes of the assembly respond to all frequencies of the forcing function whether it results from an external disturbance, actuator motion or other cause. However, at the resonant frequencies of the components, the effects of these forcing functions are significant. The amplitude and frequency of the forcing function and the damping properties of the structure affect the amplitude of the frequency response. The amplitude of the response of metallic structures with low damping and high stiffness may be 15 to 25 times greater than the amplitude of the forcing function at the resonant frequencies [1]. The asymmetric geometries of many parts in the gimbal structure also mean that multiple modes of different types (bending and torsional etc.) may be excited simultaneously, further aggravating resonance effects. Kinematic and geometric coupling may also introduce cross axis modes that further aggravate issues [2].

The analysis of gimbal designs may be performed using finite element methods (FEM) or physical vibration testing to determine the transfer functions and responses between different points in the structure in response to different forcing functions. Important aspects of these analyses are that the forcing functions used correspond well to forcing functions found in the expected operating environment of the ISP and that tests are done that analyse the response in the three-dimensional operating environment expected. The results of these analyses may be used to inform controller designs and dramatically improve the dynamic stabilisation properties of ISPs [23].

According to Hilkert [1], structural dynamics of ISP systems affect the performance through three primary interactions. These are detailed in Sections 2.5.1 to 2.5.3 below.

2.5.1 PART BENDING

Bending modes set up in the components by base motion vibrations and actuator torques cause LOS displacement. This displacement is generally not sensed by feedback gyros measuring the LOS rates due to the high-frequency nature of these disturbances and therefore the stabilisation control system is not effective at removing these effects. These effects may also be amplified by some sensor payloads themselves such as optical imaging systems with high magnification or systems which employ optical elements such as mirrors. Increasing the stiffness of the mechanism is the first step in reducing the effects of part bending, especially where actuator torques are the cause of bending modes being excited. When base motion is the primary cause, vibration isolation systems may be used to attenuate vibrations.

2.5.2 TORSIONAL RESPONSES

Independently of the operating environment, the assembly structure may interact with the control system causing torsional modes between the actuators and gyro to be excited. These are critical interactions that limit the bandwidth of the control system and hence directly affect the performance of the ISP. These interactions affect the transfer function between the actuator and the feedback gyro [2]. This often results in additional actuator travel capabilities being required.

Again, stiffening the structure is the first method of reducing these effects. However, it has been noted that current (or pressure) feedback minor loops tend to minimise this effect [2]. As these types of loops reduce the effects of disturbances originating internally with the plant model, they are effective at stabilising the system against torsional responses arising between the actuator and feedback sensor. In addition, filters such as notch filters may be used to reduce the controller gain near resonance frequencies.

2.5.3 GIMBAL MOUNTING STRUCTURE COMPLIANCE

Compliance in the ISP mounting structure between the gimbal assembly and the host vehicle may also affect the structural dynamics of the system. The effects of these dynamics are seen in both the stabilisation [2] and tracking loops but are most notable in the positioning system or tracking loops if relative motion sensors are used to provide feedback signals to these systems.

Actuator torques driving the gimbals react against the support structure and cause deflections that are measured by the relative motion sensors causing errors to propagate into the positioning or tracking systems. In addition, this motion may couple further motion into the gimbal system through the geometric constraints of the design. This problem is more pronounced in systems that use passive damping systems as vibration isolators to assist with part bending interactions. This makes the structural design of the ISP more complex as trade-

offs start to appear where a design that improves the dynamic response of one type of interaction may compound the problems of another type of interaction.

In addition to the methods described for the previous two structural interactions, adding mass to the support structure may improve the response of the ISP in terms of this interaction.

For all types of interaction, any attempt to reduce the effects of structural resonance by stiffening the structure or providing vibration isolation systems modifies transfer functions within the system. These must be noted and remodelled in simulations for an accurate design to be achieved.

2.6 DISCUSSION OF INERTIAL RATE SENSING

This section builds on the content introduced in Section 2.3.2, where it was stated that gyros are the most important feedback sensor used on ISPs. They are used to measure LOS rotational rates and provide the feedback signals for the stabilisation loops fundamental to the operation of the system. Any noise or error resulting from the gyro is directly introduced into the closed-loop stabilisation system and is translated into the tracking system as well. As errors in the gyro measurements are directly coupled into the control system, they are a major source of performance limitation in the system and an appropriate choice of gyro for an application is therefore essential to the successful implementation of a stabilised platform. Various gyro technologies are presented and evaluated in detail in the following sub-sections.

2.6.1 INTRODUCTION TO GYROSCOPIC SENSORS

Initially, the term gyroscope was reserved for a spinning mass device used for the sensing angular position of a body relative to the spin axis of the spinning mass. Through the use of more complex electro-mechanical assemblies, these gyros were then developed into angular rate sensing devices. Electro-mechanical gyros dominated the markets for guidance, navigation and control since the 1920s [24]. The term gyroscope or gyro has now come to describe any inertial sensor capable of sensing angular position or angular rate.

Two important factors that influence gyroscope choice are scale-factor stability (in ppm), which is a measure of how closely a sensor's output response matches to a known input rate, and bias stability (in °/h), which is a measure of the error associated with the sensor under the influence of no inertial motion. These two specifications are typically measures of the largest error sources in gyroscopes [25] and are therefore important considerations in the choice of sensor for an ISP.

The best-performing gyros in terms of these two factors are electro-mechanical spinning gyros (also termed mechanical gyros) however, these have a high cost. Typical uses of mechanical gyros are in high-precision strategic missile guidance systems. Dynamically Tuned Gyros (DTG) are electro-mechanical gyros that offer rate sensing about two axes. Similar performance may be achieved by Ring-Laser Gyros (RLG). These offer high

performance, although inferior to mechanical gyros, although at a lower cost. DTGs and RLGs share many of the same applications and these include autonomous submarine navigation, cruise missile navigation and surveying. Interferometric Fibre-Optic Gyros (IFOG, or simply FOG) and Quartz resonator gyros also tend to be employed for similar applications. These also show inferior performance compared to RLGs and DTGs but are successfully used in applications such as torpedo guidance, mid-term missile guidance, and anti-skid control systems in vehicles. Figure 2-8 summarises the above information. [25]

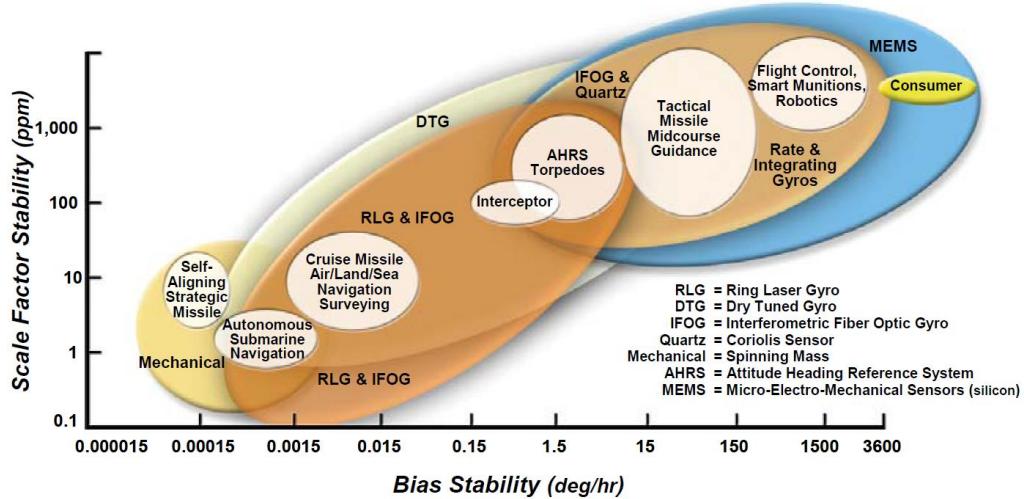


Figure 2-8: Types of gyro and their applications [25]

2.6.2 MECHANICAL GYROS

In its most simple form, a mechanical gyro consists of a spinning mass, typically a wheel, which has been mounted such that it is free to rotate about the two axes perpendicular to the spin axis. Figure 2-9 below shows a typical implementation of a mechanical gyro.

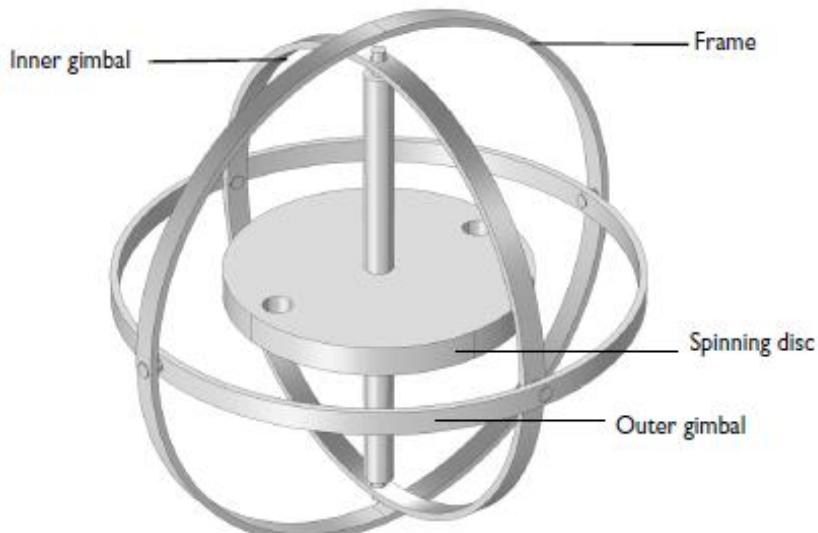


Figure 2-9: Mechanical gyroscope [26]

Mechanical gyros make use of the principle of the conservation of angular momentum to measure the angular rotation of the case to which the gyro assembly is attached. According to this principle, which states that the angular momentum of a body will remain unchanged unless acted upon by a torque, the spinning mass will maintain its inertial orientation in response to rotation of the body if it is free to rotate about its orthogonal axes. Hence the angles between the gimbals will change. This angular displacement is measured by the angle pick-offs. Rotational rates may be obtained by differentiating the angular rotation with respect to time, or through the use of more complex mechanical assemblies: These systems keep the spinning mass aligned with the case. As torque is equal to the rate of change of momentum, measuring the torque required to keep the spinning mass aligned with the case may give an indication of the angular rate applied to the body onto which the gyro is mounted. [27]

2.6.3 FIBRE-OPTIC AND RING LASER GYROS

FOGs and RLGs were first developed in the 1960s and both measure the Sagnac Effect to enable their operation. The Sagnac Effect is defined as follows.

Sagnac effect rotation rate sensors result from the counter-propagation of light beams in a waveguide that exhibits optical reciprocity between its clockwise and counter-clockwise paths. Rotation normal to the waveguide plane upsets this symmetry, which is then photo-electronically detected to provide an indication of rotation rate [24].

RLG gyros are manufactured from solid glass blocks with three tubes drilled at 60 degrees from each other, forming an equilateral triangle. These tubes are filled with a neon-helium gas. The arrangement is shown in Figure 2-10 below.

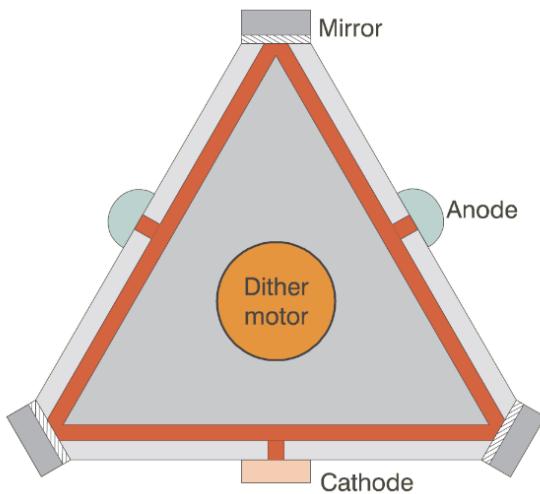


Figure 2-10: Ring Laser Gyro schematic [28]

A charge is set up between the cathode and anode causing a laser discharge in the tubes. Two counter-propagating lasers of the same frequency travel in opposite directions around the tubes. The topmost mirror is a partially transmitting mirror on the other side of which the laser beams are detected. In the presence of no rotation about the axis normal to the tube ring, the wavelength of both received lasers is the same. However, rotation about the normal axis effectively changes the path length seen by each laser to the detector: Clockwise rotation will cause the laser propagating clockwise to travel a slightly longer path to the detector, whilst the counter-clockwise propagating laser will travel a slightly short path to the detector. This change in path length results causes a slight difference between the wavelengths of the two lasers. This is measured by the detector and gives a precise indication of the rotational rate about the normal axis. [28]

RLGs display very repeatable linear performance in highly dynamic environments as well as under temperature variations. They have digital outputs, fast turn-on times, and no moving parts. These factors amongst others have led to RLGs dominating strapdown applications. [29]

FOG sensors use a fibre optic coil ranging in length between metres and kilometres as the waveguide, broadband light sources and photodetectors to accomplish inertial rate sensing. A schematic of an IFOG sensor is shown in Figure 2-11 below.

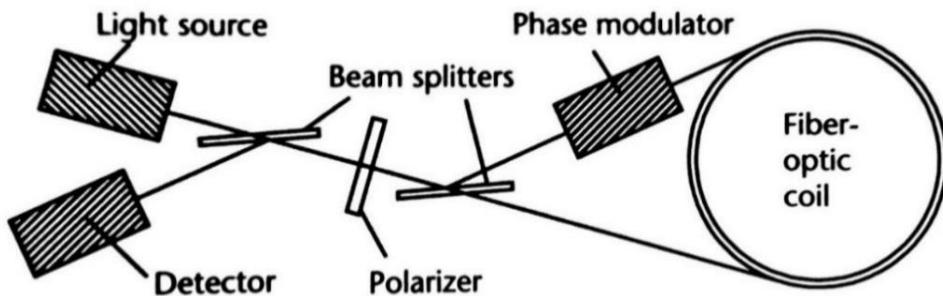


Figure 2-11: Schematic of an IFOG sensor [27]

IFOGs operate on a similar principle to RLGs but have a lower cost due to much wider manufacturing and assembly tolerances associated with fibre optics than with laser. Two light beams are sent through the coil in opposite directions using the broadband light source. Rotation about the coil axes changes the effective path lengths for each beam to travel. As with the RLG, this results in a slight change in wavelengths of the two waves giving them slightly different phases due to the Sagnac Effect. The beam splitters shown in Figure 7 above are used to merge the two light beams. This combined beam will have a different phase to the initial beam from the light source. This change in phase is dependent on the rotational rate and is used as a measure of rotational rate. The performance of Sagnac Effect gyros is dependent on the length of the light path, with longer paths being better than shorter paths [27].

FOGs and RLGs tend to be employed in many of the same applications (see Figure 2-8) however as technologies advance, it is becoming clear that RLGs offer superior scale-factor

stability to FOGs and therefore in applications requiring high scale factor stability, RLGs dominate applications [25]. However, apart from these environments, FOG sensors have become a suitable lower cost alternative to RLGs [28], [29]. In addition to lower cost, FOG sensors have the advantage of not requiring high voltages and of being lighter in weight than RLG sensors.

2.6.4 MEMS GYROS

Micro Electro-Mechanical System Gyros (MEMS) are a recent development in gyro technology. These devices are designed as electronically driven resonators. They take advantage of the Coriolis Effect to measure inertial rotation. The simplest designs are single masses electronically vibrated along an axis. According to the Coriolis Effect, a mass (m) moving with a linear velocity (v) experiences a force (F) in response to its reference frame rotating at an angular velocity (ω) such that [30]:

$$F = -2m(\omega \times v).$$

This force is orthogonal to the direction of v and ω and causes a displacement along this orthogonal axis which may be measured capacitively or piezoelectrically. Some MEMS gyros are designed to have a resonating tuning fork within the package. When inertial rotation is applied about the fork's axis, Coriolis forces are applied to the fork causing torsion about the sensitive axis [24]. This torsion, therefore, causes the displacement to be measured which can then be transformed into an indication of rotational rate.

These types of gyro are very low power consumption devices and may be implemented at a fraction of the cost of other types. Their low part count compared to optical and mechanical gyros help to reduce their cost as far few high precision parts require manufacturing per gyro. Manufactured from silicon or quartz, MEMS gyros have great durability and strength [29] and are small in size and weight. Their durability, therefore, makes them ideal for implementation in applications where high acceleration is expected or a hostile environment is present. A further advantage of these sensors is the fact that gyros can be manufactured such that three sensitive axes may be contained within a single package. Due to their superior size, weight and cost, MEMS sensors are expected to replace RLG and FOG gyros in many applications in the future. These factors have made them suitable for applications where size is a primary concern such as smartphones or hand-held cameras. Figure 2-12 below shows the type of applications where MEMS gyros find their use.

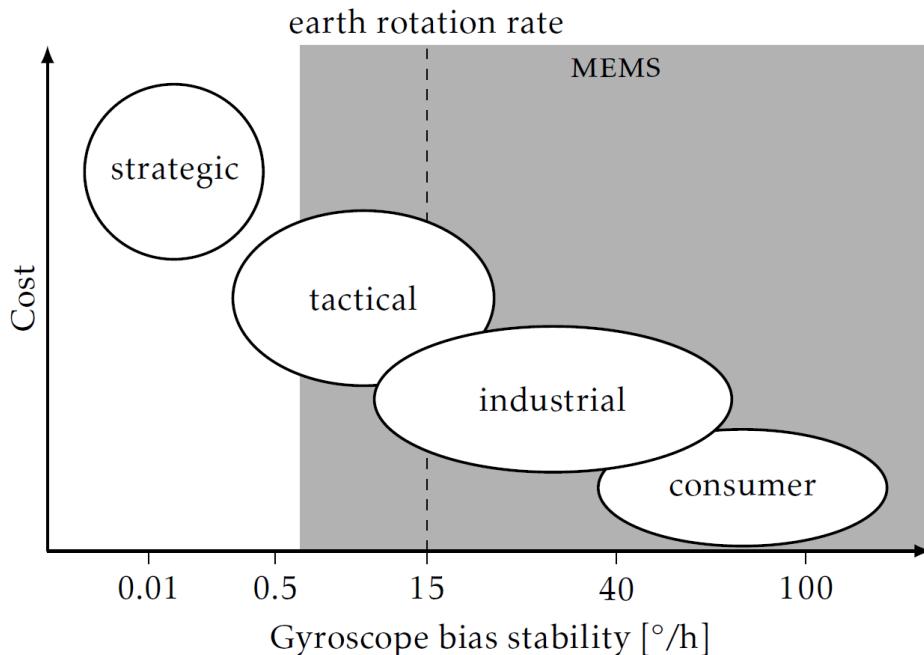


Figure 2-12: Applications of MEMS gyros [31]

Despite the many advantages of MEMS gyros, their small size does cause various challenges. As size decreases, noise and thermal sensitivity increase whilst sensitivity decreases [29], whilst they also display inferior performance to all the aforementioned gyros, with their accuracy and bias stability being far lower than other types of gyro [30]. In order, then, to usefully implement a MEMS gyro on an ISP a more detailed evaluation of their noise and error characteristics is required to ensure that the greatly reduced cost of this type of gyro justifies their inclusion over some of the costlier yet better performing gyro types. The subsection to follow describes some of these sources of error in detail.

SOURCES OF ERROR IN MEMS GYROS

The performance of MEMS gyros is limited by several error sources that affect the reliability of the signal. Most of these errors are most noticeable in the integrated position signal from the rate gyro. Woodman [30] summarises these errors as follows:

- i. **Constant Bias Error** – A MEMS gyro's output will show a non-zero reading in the presence of no inertial rotation. The long-term average of this reading is referred to as the gyro's Constant Bias.
- ii. **White Noise** – Thermo-mechanical noise affects the output of a MEMS gyro at a frequency much higher than the sampling frequency of the sensor. This noise is a random walk error meaning that the error itself is a sequence of steps whose direction and size are randomly determined. White noise error is also therefore known as Angle Random Walk (ARW). The mean value of angle random walk error is zero and has a finite variance of σ^2 . Angle random walk is evident as a function of time in the integrated position signal such that:

$$\sigma_\theta(t) = \sigma\sqrt{\delta t \cdot t}$$

It can be seen that the standard deviation of error position signals grows with the square root of time, where δt is the time between successive sensor samples. This noise (measured in $^{\circ}/\sqrt{hr}$) is specified at $t = 1$, therefore:

$$ARW = \sigma_\theta(1)$$

- iii. **Bias Stability (BS)** – The bias of a MEMS device changes with time due to flicker noise in the electronics. Bias stability is a measure of this phenomenon over a specified period of time. It has units of $^{\circ}/h$. The change in output due to this error also follows a random walk process within limits (the error associated with the integrated signal does not grow to infinity), therefore Bias Random Walk (BRW) can be defined as follows:

$$BRW = \frac{BS}{\sqrt{t}}$$

BRW has the same units as ARW, and t is the period over which BS is specified.

- iv. **Temperature** – associated errors are caused by environment changes and affect the constant bias of the device.
- v. **Calibration Errors** – errors associated with scale factors, misalignments, and nonlinearities in MEMS sensors. They cause bias errors that are seen when the device is rotating causing additional drift in the integrated position signal.

According to Woodman [30], the dominant sources of error in the output of a MEMS gyro are white noise and unaccounted bias errors. For a specific gyro, the noise characteristics can be determined through a process called the Allan Variance (AV) technique. Initially used to study the frequency stability of oscillators, it has been applied to inertial sensors to study the drift properties associated with their measurements [32]. Different variations of the Allan Variance may be employed depending on the type of analysis being performed and the expected noise profiles. Of these, the most suited to a general purpose analysis is the Overlapping Allan Variance [33].

Overlapping Allan Variance is a time-based averaging function which can be computed using the output angles of the gyroscope data in the following manner [30], [32], [34], [35]:

- i. For a set of N discrete sampled gyro output rates, sampled every sample period τ_0 , the output angle θ is calculated from:

$$\theta(t) = \int \Omega(t')dt'$$

For a discrete set of data where samples are taken at times $t = k\tau_0$, where k varies from 1 to N , the cumulative sum of the gyro rate output multiplied by the sample period τ_0 gives the angle output at each $k\tau_0$.

- ii. The Allan Variance may then be calculated as a function of averaging time, $\tau = m\tau_0$, where m is known as the averaging factor of the set of N samples, and K is the discrete set of samples from 1 to N :

$$AV(\tau) = \frac{1}{2\tau^2(N-2m)} \sum_{k=1}^{N-2m} (\theta_{K+2m} - 2\theta_{K+m} + \theta_K)^2$$

This equation calculates the AV for a given value of τ .

- iii. The Allan Deviation (AD), measured in ${}^\circ/s$, is given by:

$$AD(t) = \sqrt{AV(t)}$$

AD is plotted against τ and a logarithmic scale is typically used to display the data on the chart. Different error sources appear in distinct parts of the graph and can be easily identified. An example of a typical AV plot is shown in Figure 2-13.

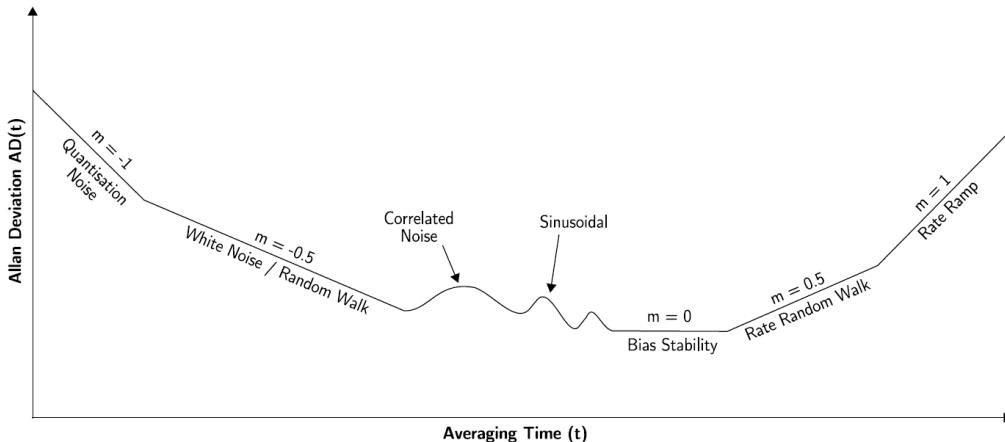


Figure 2-13: A typical Allan Variance plot [30]

The region of the plot with a gradient -0.5 determines the white noise component of the error signal. The measurement of this error is made by extending a straight line through this slope and reading its value at $t = 1$ [35]. The measurement of Bias Stability is found in the region of zero gradient and is made from the reading of the lowest point on the curve [30].

The AV noise analysis method was used in the evaluation of available gyros in Section 5.2.2 where the IMU chosen for implementation on this project is detailed.

2.7 OVERVIEW OF TARGET TRACKING

A system fundamental to the operation of an ISP is the *Target Tracker*. The role of the target tracker is to locate the target in the FOV of the sensor and to provide position commands to the tracking loops of the system. This section introduces some concepts required for the successful implementation of an optical image processing system with target tracking.

Two types of optical image processing are possible depending on the type of optical signal available: *Analogue image processing* may be performed on analogue image signals whilst *digital image processing* refers to the processing of digital images [36]. A digital image is a two-dimensional array of elements known as pixels which store the colour information of a point in an image. *Image processing* is a term used to describe a broad array of techniques by which the values of individual pixels are evaluated and modified in order to more easily obtain specific information stored in the image [37], [38].

A range of processing techniques are suited to recognising a target within an image. The three most common are summarised by Rezac [8] as:

- i. **Pattern Matching**, where a pre-defined pattern is searched for in an image. There are two main approaches to recognising a pattern, the discriminant approach which compares a group of characteristic measurements of the target pattern to the image, or the structural approach which breaks down the pattern into sub-patterns which comprise the overall pattern. By evaluating the image patterns against these sub-patterns using a set of rules which describe the target pattern, the target may be obtained within an image [39].
- ii. **Feature Tracking**, where a number of key, largely time-invariant points of interest which adequately describe the target are defined [40]. These points are then searched for in the image and the target is located once the position of these points is determined.
- iii. **Object Recognition**, where a specific, well-defined object is to be recognised in the image using machine learning techniques.

The different approaches to target identification have different advantages and disadvantages and are suited to different types of targets and operating conditions. Conditions which may affect the performance of a target tracker include the target motion dynamics, the rigidity of the target which cause distortions of the target's appearance in the FOV of the sensor, signal noise and image background noise (non-uniform background to the target), and environmental factors such as rain, cloud, smoke, and light conditions. All approaches to target recognition also cause delays in the tracking loops of the ISP systems as computational time is required to locate the target in each image frame. Pattern matching algorithms are generally more computationally intensive than the other approaches and therefore incur the largest delays or the highest implementation cost to make use of hardware capable of processing the complex algorithms quickly. Other challenges against which the system is required to be robust are system faults and loss of target scenarios which negatively affect the overall performance of the ISP. [7], [8]

Masten [7] defines the overall operation of the target tracker using the block diagram shown in Figure 2-14 below.

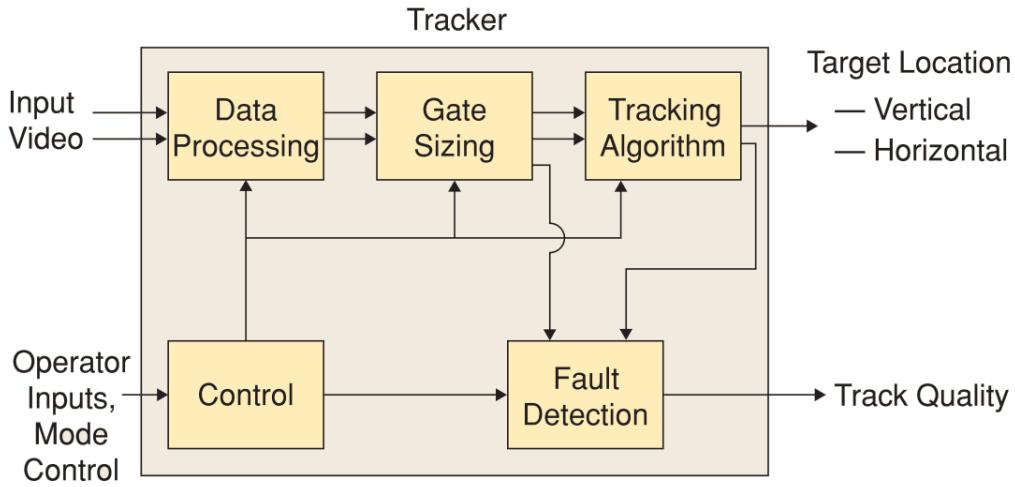


Figure 2-14: Target tracker operation

Figure 2-14 introduces several target tracker attributes not yet discussed: Most target trackers facilitate user interaction in order to provide high-level control of the system and to provide a means of initially determining the target to be tracked. Gate sizing refers to the mode by which a specific sub-section of the image is evaluated for the target position. As images are computationally expensive to process, the delays incurred to the system may be reduced by scanning only a region of the entire FOV available if there is a high degree of confidence that the target is located within the sub-section. However, as this technique reduces the angle-of-sight through which the system scans, it, therefore, results in an increase of the chance of a loss of target scenario in response to system faults or highly dynamic target motions. It must, therefore, be determined whether the gain of reduced delays in the control offset the loss of robustness due to reduced allowable target angular displacement in the design of a successful ISP.

The target tracker development for this project is detailed in Section 7.3 where a feature tracking algorithm based on colour contrast was implemented.

2.8 TELESCOPIC CONSIDERATIONS

The initial aim of this project was to achieve automatic celestial body tracking from a telescope mounted on a moving vehicle. Accordingly, some consideration of telescope technologies is required for successful implementation of a telescope stabilising ISP. This section, therefore, details some of the important astronomical considerations of the project.

2.8.1 INTRODUCTION TO TELESCOPIC OBSERVATIONS

Telescopes are systems which facilitate detailed astronomical observations to be made. A wide variety of technologies are used in the design of telescopes. All telescopes use electromagnetic (EM) waves of varying frequencies to observe their targets via remote sensing. Objects radiate EM waves across the frequency spectrum in a way that is primarily

dependent on their temperature. Many frequencies of EM radiation are emitted concurrently, however, different elements emit or absorb various levels of energy in the different frequencies at various temperatures in a way that is distinctive of each element [41]. Figure 2-15 below shows the spectra of hydrogen gas under two different conditions: The absorption spectrum for cool, low-pressure conditions, and the emission spectrum for hot, low-pressure conditions.

Hydrogen Absorption Spectrum



Hydrogen Emission Spectrum



Figure 2-15: Blackbody spectrum of hydrogen [42]

Spectra such as the above can be used to identify the chemical composition of different bodies. Consequently, astronomers require images of celestial objects at various frequencies to be taken to provide different temperature indications of celestial objects and hence increase the information that may be inferred from their observations. Different telescopes have, therefore, been developed which see across the EM spectrum as shown in Figure 2-16.

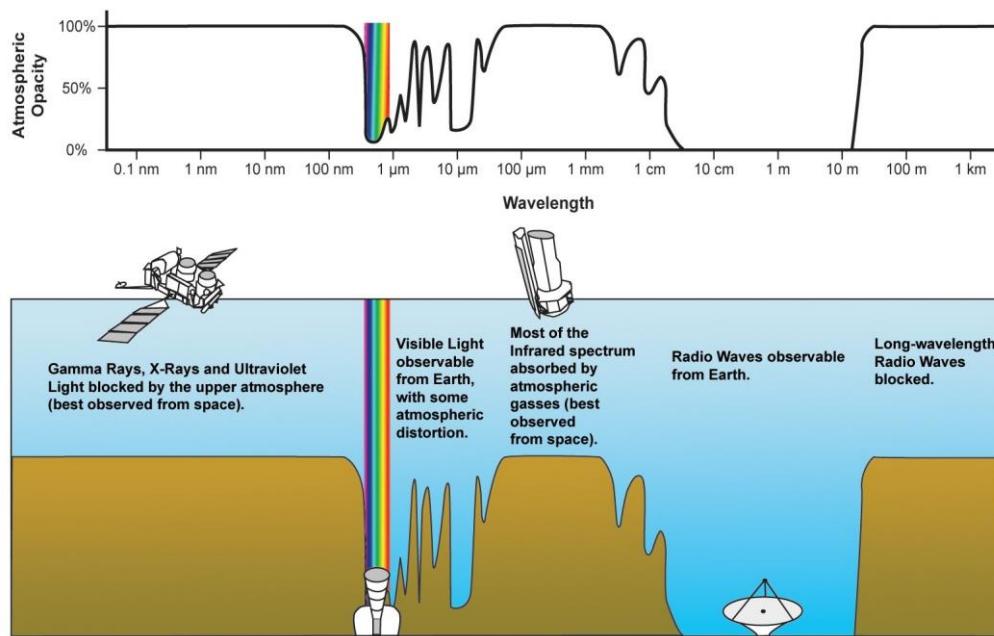


Figure 2-16: Telescopes across the EM spectrum [43]

The figure above also indicates the opacity of the Earth's atmosphere to most of the wavelengths of the EM spectrum. The atmosphere is transparent to only the visible light (and a narrow band of adjacent wavelengths) and radio wavelengths. Therefore, all telescopes which are designed to operate on frequencies outside of those are placed outside of the Earth's atmosphere. The flowing figure shows various frequency images of the Messier 101 galaxy. The images each reveal different information about the galaxy and help to contribute to a fuller understanding of Messier 101.

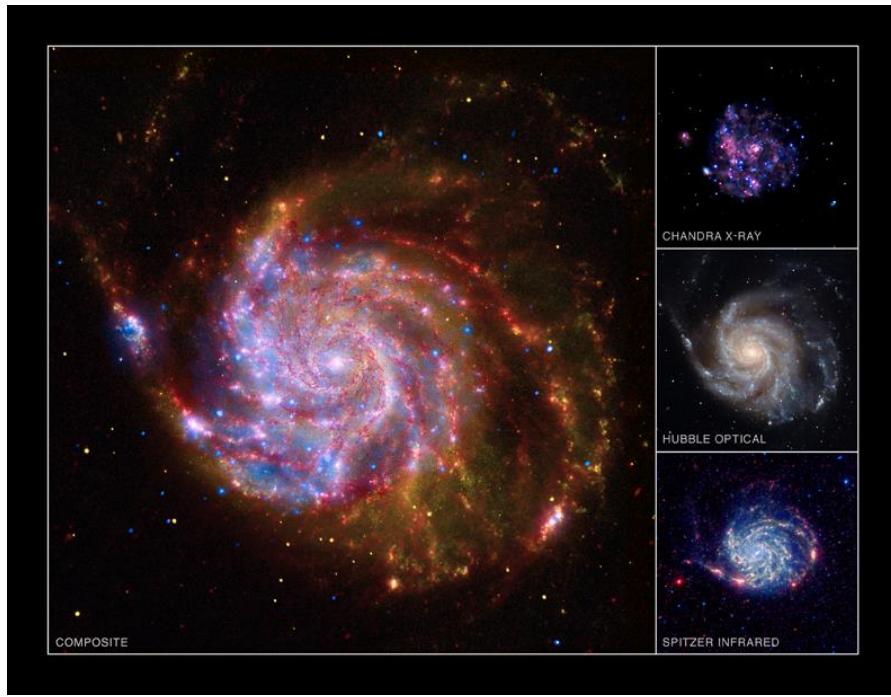


Figure 2-17: The Messier 101 galaxy observed with various frequency images [44]

This project aimed to achieve tracking and stabilisation using an optical telescope system. Section 2.8.2 describes the most common optical telescope designs and their mounting mechanisms.

2.8.2 OPTICAL TELESCOPE DESIGNS

Optical telescopes themselves are varied in design with several factors influencing their overall performance and cost. Optical telescopes make use of refractive or reflective or a combination of refractive and reflective elements to achieve magnification. Refractive elements all suffer from an effect known as chromatic aberration where the elements refract the varying wavelengths of light by differing amounts. This effect is shown in Figure 2-18 below where the method by which chromatic aberrations may be corrected by using a second lens is also shown.

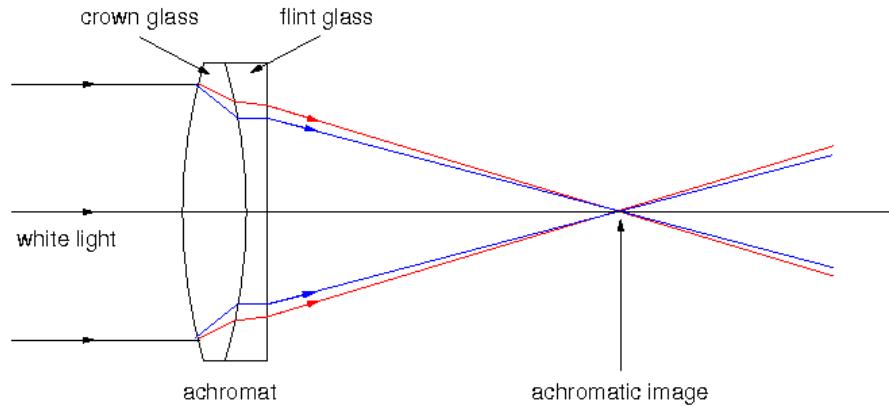


Figure 2-18: Achromatic lens [45]

The first lens, known as the crown glass, is a convex lens which causes a dispersion of the different wavelengths whilst the second, concave lens which corrects for the dispersion caused by the first lens. Chromatic aberrations become more noticeable in telescopes as the diameter of their apertures increase [46]. Larger diameter lenses become costly to produce, therefore refractive telescopes become increasingly costly with diameter and increasing achromatic correction required. In order to combat this, many telescopes make use of reflective rather than refractive elements which are achromatic [47] and less costly to produce. Refractive telescopes have few parts and are easier to maintain and use than reflective telescope whose parts may easily fall out alignment. The third main type of telescope is a compound telescope which makes use of both refractive and reflective elements. These telescopes are generally compact in size and easily portable. Figure 2-19 below shows the three main types of optical telescope. [46]

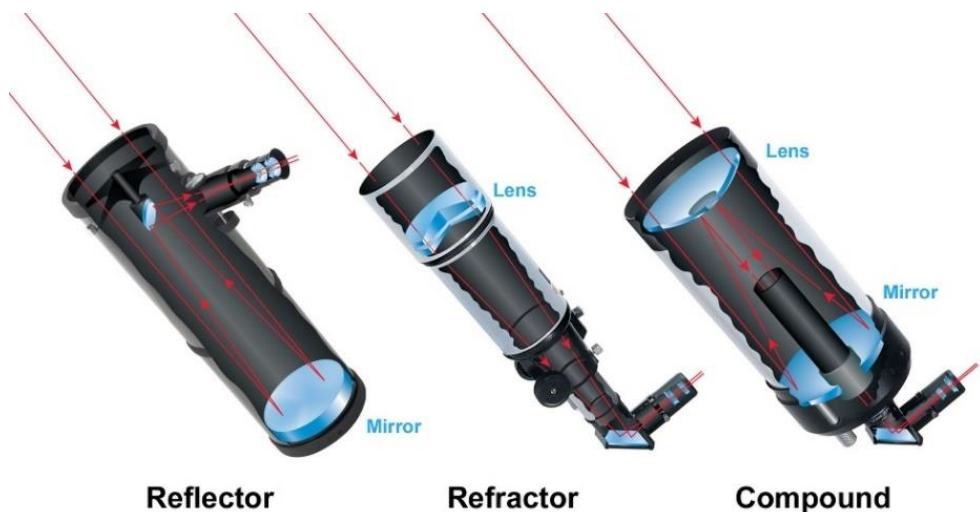


Figure 2-19: Optical telescope designs [46]

The performance of all three types of optical telescope is affected by three main factors: The **aperture** refers to the diameter of the primary optical element. This determines how much light is collected by the telescope and therefore the level of detail that can be seen using the telescope. The **focal length** of the telescope is a measure of the distance between the primary optical element and the focal point of the refracted/reflected image. It determines

the field of view of the telescope with shorter focal lengths producing wider fields of view, and it plays a role in determining the magnification of the telescope. Overall magnification is the ratio of the focal length of the telescope to the focal length of the eyepiece. [46], [48] The **mounting** of the telescope describes the mechanism used to support and orientate the telescope. Three types of mounting are common:

EQUATORIAL MOUNT

Equatorial mounting systems are designed such that the motion of star may be tracked by controlling the motion of the telescope about a single axis. Stars appear to move along circular trajectories in the sky about an axis running between the north and south celestial poles. The polar axis of an equatorially mounted telescope is aligned with this axis. Stars are then able to be tracked once located by movement of only the polar axis [49]. Figure 2-20 (a) below shows an equatorially mounted telescope.



Figure 2-20: Equatorial mount [50] (left), Alt-az mount [51] (centre), and (c) Go-To mount [52] (right) telescopes

ALT-AZIMUTH MOUNT

The Alt-Azimuth (Alt-Az) mount is the simplest mounting mechanism. The telescope is suspended from a two-axis gimbal system as shown in Figure 2-20 (b) above. Alt-az mounted telescopes require motion of both gimbals to follow the trajectory of their targets as they move in their circular patterns.

Go-To MOUNT

The final type of telescope mount is known as the Go-To mount, shown in Figure 2-20 (c) above. Go-To mounts are an adaption of the first two mounting systems where the rotation axes are motorised and computer controlled to automatically keep track of celestial bodies as the Earth rotates. These telescopes require the operator to achieve initial alignment of the telescope with specific celestial bodies, as well the date, time, and location of where they are being used to successfully track their targets [46], [49]. These systems are costly but can greatly improve the ease of use of the telescope. However, as with all telescope mounts, if Go-To systems are moved whilst tracking a body, tracking of that object will be lost. Go-

To systems rely on careful alignment and a knowledge of their Earth location and time in order to control the rotation axes of a telescope according to a defined algorithm such that a celestial body is tracked. The available literature seems to suggest that no active feedback is present on Go-To systems by which a deviation from this pre-defined path may be detected in response to a loss of initial alignment.

2.9 MULTI-AXIS GIMBAL KINEMATICS

Most ISPs are required to stabilise and point a payload around at least two axes in inertial space. In a mass stabilised configuration, the number of orthogonal gimbals required in the electro-mechanical assembly is equal to the number of axes in which inertial control is required.

Most ISPs have multiple axes of control. Various non-intuitive kinematic coupling effects occur which are not evident when considering each gimbal individually. This section presents the equations of motion for a two-axis gimbal mechanism. Sources [8], [9], [15], [53]–[56] contributed to the development of this section but it was primarily based on [57].

2.9.1 AXES AND ANGLE DEFINITIONS

Consider an idealised two-axis gimbal mechanism as shown in Figure 2-21 below.

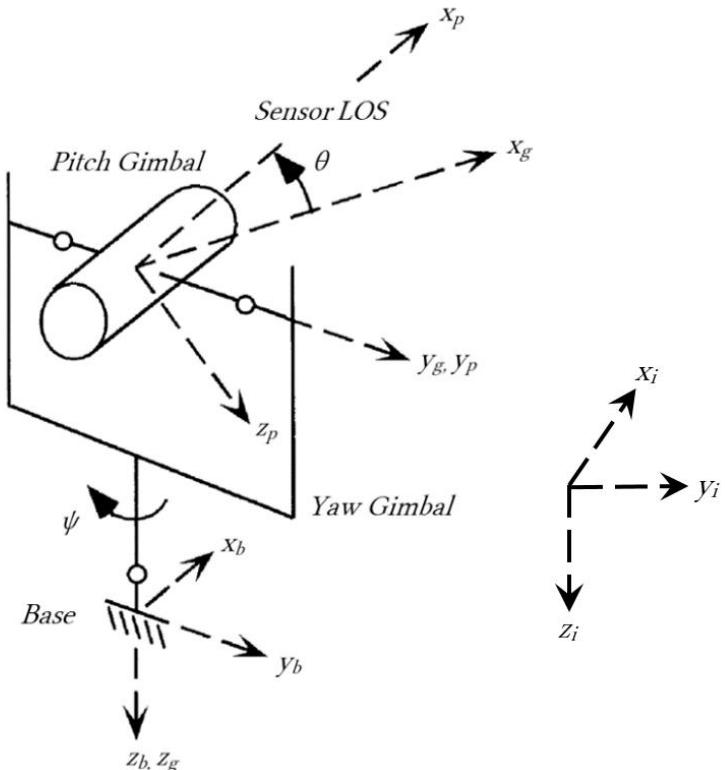


Figure 2-21: Double gimbal schematic. Adapted from [53]

The yaw gimbal facilitates rotation about the z_b, z_g axis whilst the pitch platform rotates about the y_g, y_p axis. The gimbals are modelled as rigid-bodies suspended on frictionless joints. The sensor payload is mounted on the pitch platform.

Three reference frames are defined using triads of orthogonal vectors, $\{x, y, z\}$ fixed to their hosts such that the frames rotate with the members to which they are affixed. These frames are defined as:

- i. The Inertial reference frame, I, given by $\{x_i, y_i, z_i\}$,
- ii. The Base fixed frame, B, given by $\{x_b, y_b, z_b\}$,
- iii. The Yaw-gimbal fixed frame, G, given by $\{x_g, y_g, z_g\}$, and
- iv. The Pitch-gimbal fixed frame, P, given by $\{x_p, y_p, z_p\}$.

The angular position of the gimbals relative to the inertial frame is given by the yaw angle, ψ_i , and the pitch angle, θ_i . These are defined by Figure 2-22 below.

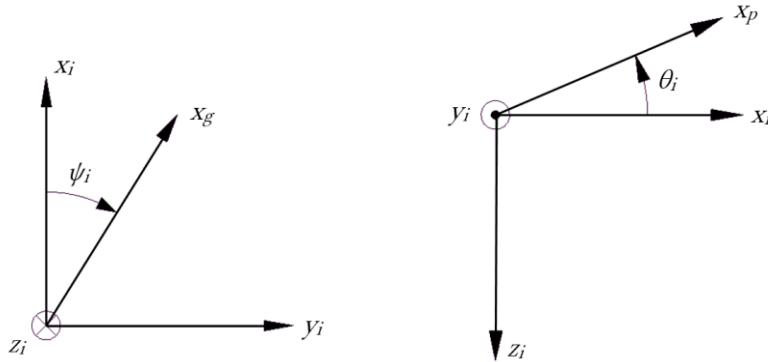


Figure 2-22: Inertial angle definitions

Where, ψ_i is equal to the anti-clockwise angle between the x_i and the x_g axes, and θ_i is equal to the anti-clockwise angle between the x_i and the x_p axes. The angular positions of the frames relative to each other are given by the yaw angle, ψ , and the pitch angle, θ . Figure 2-23 below defines the angles such that ψ is the angle between frames B and G whilst θ is the angle between frames G and P.

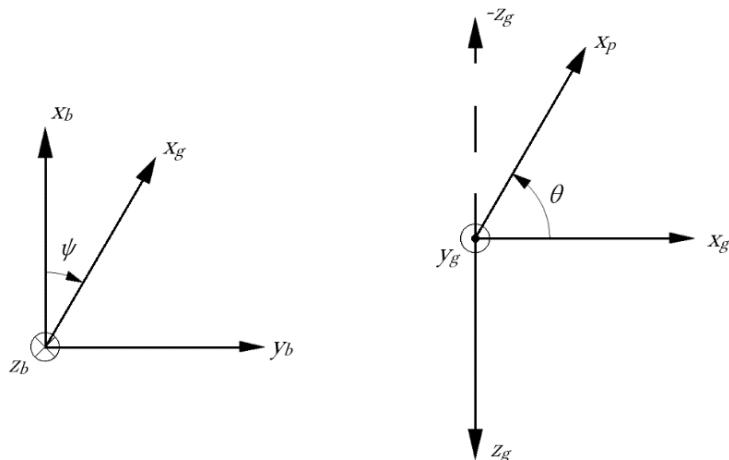


Figure 2-23: Relative angle definitions

Where ψ is equal to the anti-clockwise angle between the x_b and the x_g axes, and θ is equal to the anti-clockwise angle between the x_g and the x_p axes. The system is therefore defined to be “pointing forward” when $\psi = \theta = 0$ and x_g is co-planar with x_b and x_p is co-linear with x_g .

Following from the previous definitions of ψ and θ ,

$\dot{\psi}$ is therefore the angular rate between the base and the yaw gimbal, and

$\dot{\theta}$ is therefore the angular rate between the yaw gimbal and the pitch platform.

The definitions given above are used to represent a Euler sequence of the order yaw-pitch or $\psi\text{-}\theta$, from the base to the pitch platform.

Frame B is carried into frame G by a rotation ψ about the z_b, z_g axis such that a vector in frame B may be transformed into frame G using the rotation matrix, L_{GB} , where:

$$\overline{\overline{L}_{GB}} = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Frame G is carried into frame P by a rotation θ about the y_g, y_p axis such that a vector in frame G may be transformed into frame P using the rotation matrix, L_{PG} , where:

$$\overline{\overline{L}_{PG}} = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix}$$

2.9.2 KINEMATIC RELATIONSHIPS

The general equations of motion for the gimbals of the two-axis system are derived from the law of the conservation of angular momentum:

$$\sum \bar{M} = \dot{\bar{H}} \quad \text{where} \quad \bar{H} = \bar{I} \cdot \bar{\omega} \quad \text{eq. (2-1)}$$

Which states that the sum of the external moments, \bar{M} , about a fixed point or the centre of mass of a body is equal to the time derivative of the angular momentum, \bar{H} , of the body where \bar{H} is defined relative to a fixed co-ordinate system and $\bar{\omega}$ is the angular velocity of the body.

When the angular momentum vector is defined relative to a moving coordinate system, which has a rotational velocity of $\bar{\Omega}$ the conservation of momentum equation can be modified to include the changes in momentum due to the Coriolis Theorem [55], [56], giving:

$$\sum \bar{M} = \dot{\bar{H}} + \bar{\Omega} \times \bar{H} \quad \text{eq. (2-2)}$$

If the moving coordinate system is attached to the rotating body, $\bar{\Omega} = \bar{\omega}$ and the inertia tensor, \bar{I} , of the body is constant with respect to time, giving:

$$\sum \bar{M} = \bar{I} \cdot \dot{\bar{\omega}} + \bar{\omega} \times \bar{H} \quad \text{eq. (2-3)}$$

The two-axis gimbal system in discussion consists of two rigid bodies free to rotate relative to each other. Gimbal-fixed co-ordinate systems, $\{x_g, y_g, z_g\}$ and $\{x_p, y_p, z_p\}$ (frames G and P) are attached to the gimbals and rotate with them. Frame B, $\{x_b, y_b, z_b\}$, is attached to, and rotates with the base on which the gimbals are mounted. It follows then, that eq. (2-3) can be used to develop the general equations of motion for the two-axis gimbal system as defined in Section 2.9.1. The pitch platform will first be evaluated before evaluating the yaw-gimbal.

PITCH PLATFORM EQUATION OF MOTION

The pitch platform has a tensor of inertia, \bar{I}_p , and an angular rate, $\bar{\omega}_p$, such that:

$$\bar{I}_p = \begin{bmatrix} I_{xxp} & D_{xyp} & D_{xzp} \\ D_{xyp} & I_{ypy} & D_{yzp} \\ D_{xzp} & D_{yzp} & I_{zzp} \end{bmatrix}$$

And,

$$\bar{\omega}_p = \begin{bmatrix} \omega_{xp} \\ \omega_{yp} \\ \omega_{zp} \end{bmatrix}$$

Applying eq. (2-3), the net external torque on the pitch platform, \bar{T}_p , is given by:

$$\bar{T}_p = \bar{I}_p \cdot \dot{\bar{\omega}}_p + \bar{\omega}_p \times \bar{H}_p$$

Where,

$$\bar{H}_p = \bar{I}_p \cdot \bar{\omega}_p$$

$$\begin{aligned} \bar{H}_p &= \begin{bmatrix} H_{xp} \\ H_{yp} \\ H_{zp} \end{bmatrix} = \begin{bmatrix} I_{xxp} & D_{xyp} & D_{xzp} \\ D_{xyp} & I_{ypy} & D_{yzp} \\ D_{xzp} & D_{yzp} & I_{zzp} \end{bmatrix} \cdot \begin{bmatrix} \omega_{xp} \\ \omega_{yp} \\ \omega_{zp} \end{bmatrix} \\ &= \begin{bmatrix} I_{xxp}\omega_{xp} + D_{xyp}\omega_{yp} + D_{xzp}\omega_{zp} \\ D_{xyp}\omega_{xp} + I_{ypy}\omega_{yp} + D_{yzp}\omega_{zp} \\ D_{xzp}\omega_{xp} + D_{yzp}\omega_{yp} + I_{zzp}\omega_{zp} \end{bmatrix} \end{aligned}$$

$$\bar{T}_p = \begin{bmatrix} T_{xp} \\ T_{yp} \\ T_{zp} \end{bmatrix} = \begin{bmatrix} I_{xxp}\dot{\omega}_{xp} + D_{xyp}\dot{\omega}_{yp} + D_{xzp}\dot{\omega}_{zp} \\ D_{xyp}\dot{\omega}_{xp} + I_{ypy}\dot{\omega}_{yp} + D_{yzp}\dot{\omega}_{zp} \\ D_{xzp}\dot{\omega}_{xp} + D_{yzp}\dot{\omega}_{yp} + I_{zzp}\dot{\omega}_{zp} \end{bmatrix} + \begin{bmatrix} \omega_{yp}H_{zp} - \omega_{zp}H_{yp} \\ \omega_{zp}H_{xp} - \omega_{xp}H_{zp} \\ \omega_{xp}H_{yp} - \omega_{yp}H_{zp} \end{bmatrix}$$

Therefore, the net external torque about the pitch platform, y_g, y_p , axis is given by T_{yp} :

$$\begin{aligned}
 T_{yp} = & I_{yyp}\dot{\omega}_{yp} + (I_{xxp} - I_{zzp})\omega_{xp}\omega_{zp} \\
 & + D_{xyp}(\dot{\omega}_{xp} - \omega_{yp}\omega_{zp}) \\
 & + D_{yzp}(\omega_{zp} - \omega_{yp}\omega_{xp}) \\
 & + D_{xzp}(\omega_{zp}^2 - \omega_{xp}^2)
 \end{aligned} \quad \text{eq. (2-4)}$$

If the platform is suspended by its principal axes, the inertia tensor reduces to a diagonal matrix of the form:

$$\bar{I} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}$$

Equation (2-4) therefore reduces to:

$$T_{yp} = I_{yyp}\dot{\omega}_{yp} + (I_{xxp} - I_{zzp})\omega_{xp}\omega_{zp} \quad \text{eq. (2-5)}$$

Equation (2-5) defines the equation of motion for the pitch platform for its rotation about the y_g, y_p axis.

YAW GIMBAL EQUATION OF MOTION

The yaw gimbal, assumed to be suspended from its principal axes, has a tensor of inertia, \bar{I}_g , and an angular rate, $\bar{\omega}_g$, such that:

$$\bar{I}_g = \begin{bmatrix} I_{xxg} & 0 & 0 \\ 0 & I_{yyg} & 0 \\ 0 & 0 & I_{zzg} \end{bmatrix}$$

And,

$$\bar{\omega}_g = \begin{bmatrix} \omega_{xg} \\ \omega_{yg} \\ \omega_{zg} \end{bmatrix}$$

Applying eq. (2-3), the net torque on the yaw gimbal, \bar{T}_g , is given by:

$$\bar{T}_g = \bar{I}_g \cdot \dot{\bar{\omega}}_g + \bar{\omega}_g \times \bar{H}_g$$

Where,

$$\begin{aligned}
 \bar{H}_g &= \bar{I}_g \cdot \bar{\omega}_g \\
 \bar{H}_g &= \begin{bmatrix} H_{xg} \\ H_{yg} \\ H_{zg} \end{bmatrix} = \begin{bmatrix} I_{xxg} & 0 & 0 \\ 0 & I_{yyg} & 0 \\ 0 & 0 & I_{zzg} \end{bmatrix} \cdot \begin{bmatrix} \omega_{xg} \\ \omega_{yg} \\ \omega_{zg} \end{bmatrix} = \begin{bmatrix} I_{xxg}\omega_{xg} \\ I_{yyg}\omega_{yg} \\ I_{zzg}\omega_{zg} \end{bmatrix} \\
 \bar{T}_g &= \begin{bmatrix} T_{xg} \\ T_{yg} \\ T_{zg} \end{bmatrix} = \begin{bmatrix} I_{xxg}\dot{\omega}_{xg} \\ I_{yyg}\dot{\omega}_{yg} \\ I_{zzg}\dot{\omega}_{zg} \end{bmatrix} + \begin{bmatrix} \omega_{yg}H_{zg} - \omega_{zg}H_{yg} \\ \omega_{zg}H_{xg} - \omega_{xg}H_{zg} \\ \omega_{xg}H_{yg} - \omega_{yg}H_{xg} \end{bmatrix}
 \end{aligned}$$

$\overline{T_g}$ is the net torque about the yaw gimbal, therefore, the external torque applied to the yaw gimbal is given by $\overline{T_{gp}}$:

$$\overline{T_{gp}} = \overline{T_g} + \overline{L_{PG}}^T \cdot \overline{T_p}$$

If,

$$\overline{T_{gp}} = \begin{bmatrix} T_{xgp} \\ T_{ygp} \\ T_{zgp} \end{bmatrix}$$

Then,

$$\begin{aligned} T_{zgp} &= T_{zg} + T_{zp} \cos \theta - T_{xp} \sin \theta && \text{eq. (2-6)} \\ &= I_{zzg} \dot{\omega}_{zg} + (I_{yyg} - I_{xxg}) \omega_{xg} \omega_{yg} + I_{zzp} \dot{\omega}_{zp} \cos \theta \\ &\quad + \omega_{xp} \omega_{yp} (I_{yyp} - I_{xxp}) \cos \theta \\ &\quad - I_{xxp} \dot{\omega}_{xp} \sin \theta \\ &\quad - \omega_{yp} \omega_{zp} (I_{zzp} - I_{yyp}) \sin \theta \end{aligned}$$

The angular rates of the platform in terms of the gimbal are given by:

$$\begin{aligned} \overline{\omega_p} &= \begin{bmatrix} \omega_{xp} \\ \omega_{yp} \\ \omega_{zp} \end{bmatrix} = \overline{L_{PG}} \cdot \overline{\omega_G} = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix} \cdot \begin{bmatrix} \omega_{xg} \\ \omega_{yg} \\ \omega_{zg} \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix} \\ &= \begin{bmatrix} \omega_{xg} \cos \theta - \omega_{zg} \sin \theta \\ \omega_{yg} + \dot{\theta} \\ \omega_{zg} \cos \theta + \omega_{xg} \sin \theta \end{bmatrix} \\ \dot{\overline{\omega_p}} &= \begin{bmatrix} \dot{\omega}_{xp} \\ \dot{\omega}_{yp} \\ \dot{\omega}_{zp} \end{bmatrix} = \begin{bmatrix} \dot{\omega}_{xg} \cos \theta - \dot{\omega}_{zg} \sin \theta - \dot{\theta} \omega_{zp} \\ \dot{\omega}_{yg} + \ddot{\theta} \\ \dot{\omega}_{zg} \cos \theta + \dot{\omega}_{xg} \sin \theta + \dot{\theta} \omega_{xp} \end{bmatrix} \end{aligned}$$

Therefore, substituting for $\dot{\omega}_{xp}$ and $\dot{\omega}_{zp}$ in eq. (2-6):

$$\begin{aligned} T_{zgp} &= I_{zzg} \dot{\omega}_{zg} + (I_{yyg} - I_{xxg}) \omega_{xg} \omega_{yg} + I_{zzp} (\dot{\omega}_{zg} \cos \theta + \dot{\omega}_{xg} \sin \theta + \dot{\theta} \omega_{xp}) \cos \theta \\ &\quad + \omega_{xp} \omega_{yp} (I_{yyp} - I_{xxp}) \cos \theta \\ &\quad - I_{xxp} (\dot{\omega}_{xg} \cos \theta - \dot{\omega}_{zg} \sin \theta - \dot{\theta} \omega_{zp}) \sin \theta \\ &\quad - \omega_{yp} \omega_{zp} (I_{zzp} - I_{yyp}) \sin \theta \end{aligned}$$

$$\begin{aligned} T_{zgp} &= (I_{zzg} + I_{zzp} \cos^2 \theta + I_{xxp} \sin^2 \theta) \dot{\omega}_{zg} + (I_{zzp} - I_{xxp}) \sin \theta \cos \theta \dot{\omega}_{xg} && \text{eq. (2-7)} \\ &\quad + \omega_{xg} \omega_{yg} (I_{yyg} - I_{xxg}) + \omega_{xp} \omega_{yp} (I_{yyp} - I_{xxp}) \cos \theta \\ &\quad + \omega_{yp} \omega_{zp} (I_{yyp} - I_{zzp}) \sin \theta \\ &\quad + I_{zzp} \dot{\theta} \omega_{xp} \cos \theta + I_{xxp} \dot{\theta} \omega_{zp} \sin \theta \end{aligned}$$

Equation (2-7) defines the equation of motion for the pitch platform for its rotation about the z_b, z_g axis. The angular rates of the gimbal in terms of the base are given by:

$$\begin{aligned}\overline{\omega}_g &= \begin{bmatrix} \omega_{xg} \\ \omega_{yg} \\ \omega_{zg} \end{bmatrix} = \overline{L}_{GB} \cdot \overline{\omega}_b = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \omega_{xb} \\ \omega_{yb} \\ \omega_{zb} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dot{\psi} \end{bmatrix} \\ &= \begin{bmatrix} \omega_{xb} \cos \psi + \omega_{zb} \sin \psi \\ \omega_{yb} \cos \psi - \omega_{xb} \sin \psi \\ \omega_{zb} + \dot{\psi} \end{bmatrix} \\ \dot{\overline{\omega}}_g &= \begin{bmatrix} \dot{\omega}_{xg} \\ \dot{\omega}_{yg} \\ \dot{\omega}_{yg} \end{bmatrix} = \begin{bmatrix} \dot{\omega}_{xb} \cos \psi + \dot{\omega}_{yb} \sin \psi + \dot{\psi} \omega_{yg} \\ \dot{\omega}_{yb} \cos \psi - \dot{\omega}_{xb} \sin \psi - \dot{\psi} \omega_{xg} \\ \dot{\omega}_{zb} + \ddot{\psi} \end{bmatrix} \quad \text{eq. (2-8)}\end{aligned}$$

Equations (2-5), (2-7), and (2-8) define the motion of the double gimbal mechanism in terms of base motions and the external torques on each gimbal. They are used in the system block diagram model development detailed in Section 7.2.

2.10 CHAPTER CONCLUSION

A broad range of factors affecting the implementation of a stabilised platform to facilitate astronomical observations has been considered in the preceding sections. These considerations have allowed the suggestion that mounting a telescope on an active stabilised platform with automatic target tracking may feasibly facilitate the accomplishment of astronomical observations from a moving host. The factors considered here have informed the design and implementation process in various ways which will be detailed in the remaining chapters of this report.

3 SYSTEM SPECIFICATIONS

3.1 INTRODUCTION

The observations and discussion of the literature study presented in Chapter 2 helped to inform a set of system specifications which were drawn up for the project. This set of quantitative system specifications developed from a group of qualitative desired performance requirements aimed at facilitating the accomplishment of the project aims.

These specifications were developed using the initial aims of the project. Once the project had been revised to aim at approximating the initial aims with a low-cost system designed for project expansion, the target specifications developed here became idealistic design goals which informed the design decisions made in Chapters 4 to 7. For the better preservation of this document's narrative, only the final specifications developed are presented here, while the process followed to develop this set of specifications is shown in detail in Appendix A.

3.2 PURPOSE OF THE ISP

The initial aims of this project were to design, simulate implement and test a robust multi-axis ISP to facilitate the high precision automatic tracking of celestial objects through an optical telescope mounted on a moving vehicle. The project entailed the development of all subsystems associated with the overall ISP including the electro-mechanical assembly of the ISP, the control system, and electronic interfaces.

The purpose of the system is, therefore, to achieve automatic tracking of a celestial body using an optical telescope, and to ensure that high-quality celestial observations can be made through the attenuation of disturbance torques incurred onto the imaging sensor by the host vehicle motion. The following specifications, therefore, list the performance requirements of the ISP in order to achieve this purpose.

3.3 PERFORMANCE REQUIREMENTS

Table 3-1 below details the target specifications for the ISP system developed in this project. In the table below, 'Trace' values refer to qualitative requirement numbers (Rx) and quantitative specification numbers (Sx) which may be found in Appendix A. Additionally,

the ‘Importance’ (Imp.) column is populated with qualitative references high (H), medium (M), and low (L).

Table 3-1: Target specifications

Metric No.	Trace	Metric.	Imp.	Units	Marginal Value	Ideal Value
1	S5	Tracking error	H	mrad	0.75(PEAK)	0.40(PEAK)
2	S6	Jitter				
		Dynamic host	H	mrad	4.0(PEAK)	2.0(PEAK)
		Stationary host	H	mrad	1.0(PEAK)	0.5(PEAK)
3	S3	Gimbal assembly dimensions	L	mm	-	350x350x350
4	S4	Total mass	M	kg	<10	<8
5	S14	Development cost	H	R	20 000.00	10 000.00
6	S8	Min detectable rotation on image sensor	H	mrad	<0.25	<0.125
7	S1	Telescope size	L	"	3.5	3.5
8	S12	Battery run-time	L	hrs	2	3
9	S10	Maximum LOS rate	H	°/s	100	100
10	R2, R3	Tracking loop bandwidth	M	Hz	5	10
11	R3	Stabilisation loop bandwidth	M	Hz	60	80
12	R3	Minimum structural resonance bandwidth	M	Hz	>300	-
13	S11	Gyroscope bandwidth	H	Hz	>120	-
14	S8	Angle pickoff resolution	H	mrad	<0.25	-
16	R2, S2	Minimum axis rotation range				
		Yaw	H	°	250	270
		Pitch	H	°	180	250

3.4 CHAPTER CONCLUSION

These target specifications, presented above, served as design goals for the duration of the project. Chapter 4 to Chapter 7 describe the design process followed to implement a system capable of suitably approximating these parameters. Chapter 8 then details the results of testing the implemented system and compares the achieved system performance to the specifications developed here.

4

MECHANICAL DESIGN AND IMPLEMENTATION

4.1 INTRODUCTION

Chapters 4 through 7 seek to describe in detail the process followed by which an ISP with an automatic target tracker was developed capable of approximating the target systems specifications given in the previous chapter. This broad design and implementation section of the report begins in this chapter by detailing the mechanical design of the ISP assembly (item I₁ of the prime item diagram, Figure A-1, of the System Specification) which includes the telescope specification and modelling, the assembly support/mounting structure, the gimbals, the gimbal suspension design, and finally the gearbox (items I_{1.1}-I_{1.4}, and I_{2.3} respectively).

Only subsequent to the specification of the telescope to be used could the rest of the mechanical design be accomplished; accordingly, this section of the report begins with a specification of the telescope ultimately to be used should project expansion occur in future.

4.2 TELESCOPE SPECIFICATION (II.4)

On the revision of the project budget early in the project, the decision was made to continue with the project in an approximated manner, with design for expansion being a key factor in design decisions made. It became apparent that the project budget would not be able to account for the purchase of a telescope in addition to the other components required to implement a functioning stabilised platform. In response to this, it was decided that the design for expansion principle would be best applied to the telescope itself: a low-cost camera mounting platform designed to inertially and dimensionally model a specific telescope would be used instead of the telescope itself and so facilitate the remainder of the systems being developed within the revised budget.

For this project, it was decided to specify the Meade ETX90 as the telescope ultimately to be used with the stabilised platform developed in this project. The Meade ETX90 is a 3.5" aperture Maksutov-Cassegrain telescope (satisfying specification S₁) with a resolving power of 1.3 arcsec. Resolving power refers the minimum angle required between objects in the FOV for them to be distinguishable from each other. Maksutov-Cassegrain telescopes are compound telescopes which enables them to be smaller and lighter than other telescope types which achieve the same levels of performance. This was advantageous to the project as it

resulted in a smaller, more portable, overall system being developed. Figure 4-1 below shows the Meade ETX90 telescope mounted in its Alt-Az mounting forks.



Figure 4-1: Meade ETX90 telescope [58]

The light path (right to left) through the ETX90 telescope is shown below.

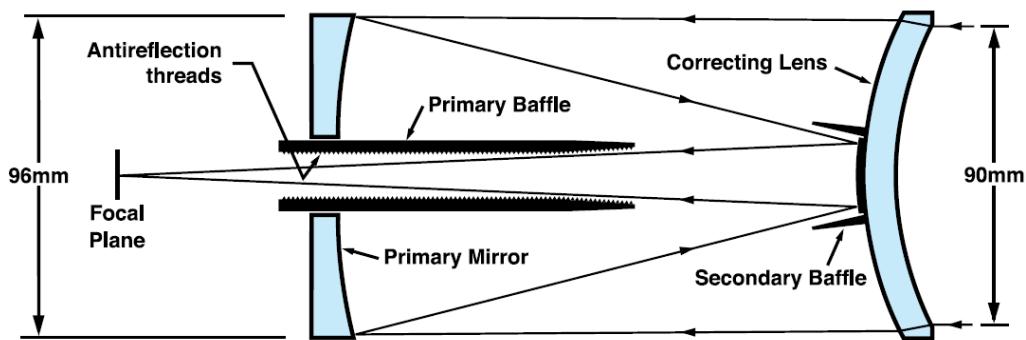


Figure 4-2: Lightpath through the Meade ETX90 [59]

Near the beginning of the project, an ETX90 was obtained in loan in order for its dimensions and mass properties to be determined. Using these properties, a SOLIDWORKS model of the ETX90 was developed. The rendering below shows this model.



Figure 4-3: SOLIDWORKS model of the ETX90 telescope

The ETX90 had a mass of 1.62 kg once removed from its mounting forks and had the following physical dimensions (the axis system shown was originally defined in Figure 2-21):

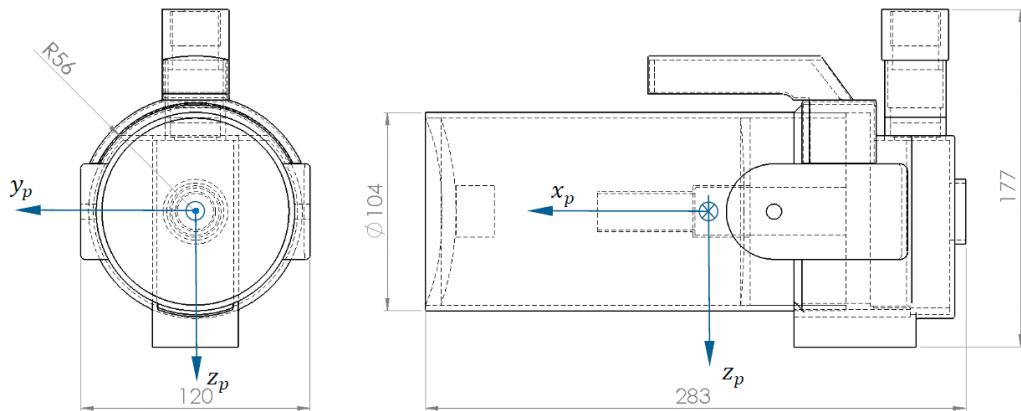


Figure 4-4: ETX90 overall dimensions

4.3 GIMBALS DESIGN (II.3)

Following from the decision to specify the Meade ETX90 for use as the telescope in the development of this and future projects on this system, this section now describes the design of the gimbal mechanism used to facilitate control of the LOS of the telescope.

4.3.1 TELESCOPE MOUNTING CONCEPTS

Here, the two main ideas considered for the telescope mounting are described. It was decided in the system specification phase of the project that rotation of the image about the LOS of the telescope would be allowed, and, therefore, two-axes of control would be sufficient for this project. Due to the physical size of a telescope, it was logical to decide at this point that the ISP to be developed would be a mass stabilised rather than a mirror stabilised system. A mechanical system was required which would ultimately be able to facilitate control of the inertial orientation of the ETX90 telescope. In addition, it also needed to be able to support the camera used in this project and accurately model the inertial properties of the platform once the telescope was mounted. This last requirement would mean that when the telescope is eventually procured it would be possible to simply replace the camera with the telescope without needing to modify the rest of the ISP system; all electronics and control systems would remain unchanged as the inertia seen by them would also remain unchanged.

The first concept, shown below, involved mounting the telescope on a tray which could be tilted up and down about the y_p (pitch) axis, as defined in Figure 4-4 above.

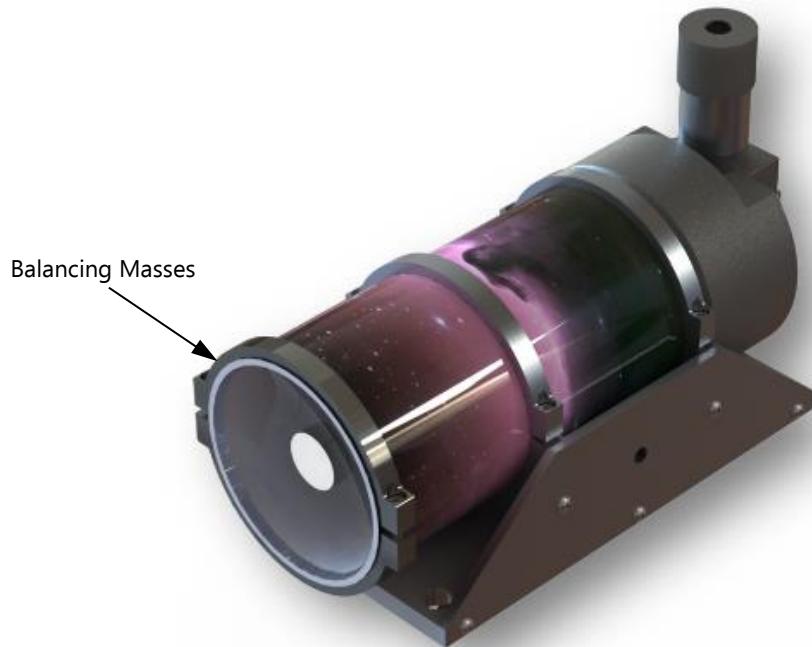


Figure 4-5: ETX90 Mounting Concept 1

This tray would also be able to mount the camera used for this project (the selection of the camera is detailed in Section 5.2.1) and would use mass blocks added to the tray to ensure the camera mounted tray had inertial properties matching those of the telescope mounted tray. Figure 4-6 shows the mounting tray concept supporting the camera and mass blocks.

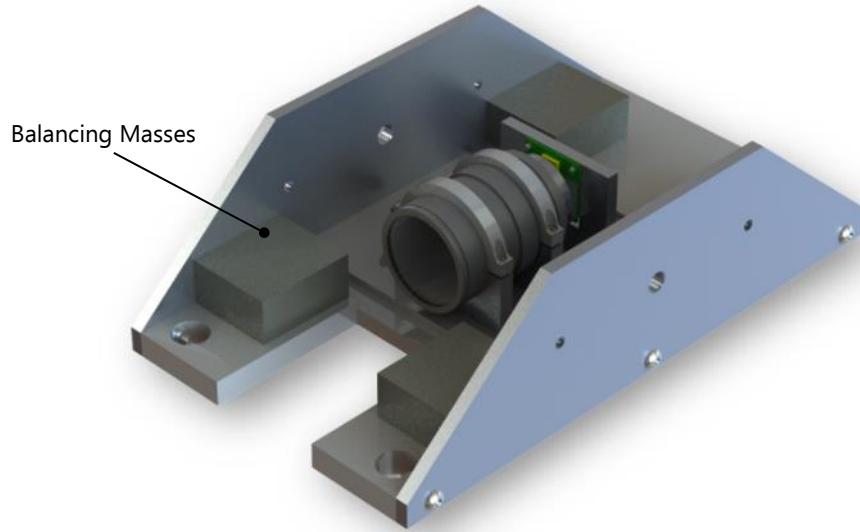


Figure 4-6: Raspberry Pi Camera mounted on Mounting Concept 1

The second main concept involved affixing the telescope between two sets of mounting clamps joined by a pivoted side frame. This is shown in Figure 4-7 below.

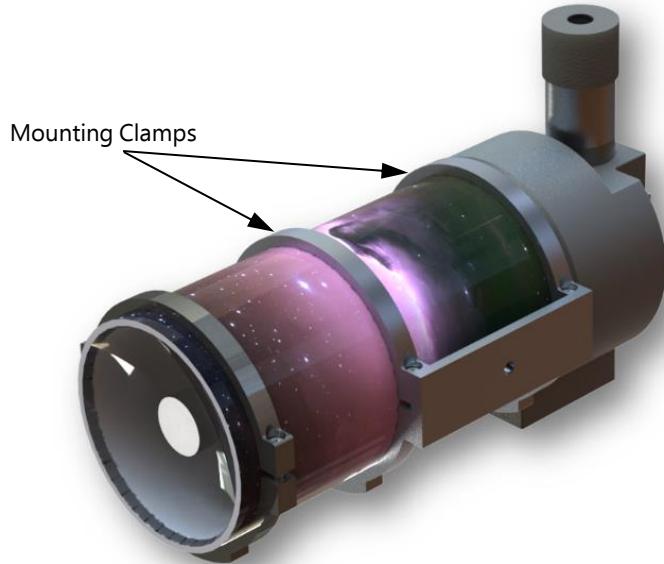


Figure 4-7: ETX90 Mounting Concept 2

Using this second scheme, a tubular mounting platform for the camera, shown below, was required in order for the mounting clamp structure to be used.

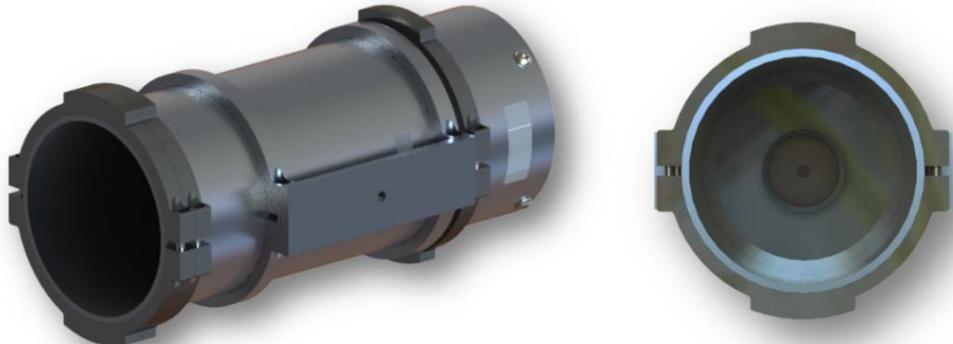


Figure 4-8: Raspberry Pi Camera mounted on Mounting Concept 2

It was shown in Section 2.9.2 that if the yaw gimbal and the pitch platform of an ISP could be suspended by their principal axes, such that their products of inertia terms were nulled, a large reduction in the number of disturbance torques exerted on the gimbals whilst under motion would result. All concepts shown above use the axis system shown in Figure 4-4, with the x_p axis being co-linear with the sensor LOS, the y_p axis to the right of the LOS in the normal sense, and the z_p axis being down from the LOS in the normal sense. Both concepts made use of balancing masses along the x_p axis (LOS) so that the telescope or camera could be balanced about the y_p and the z_p axes. Mounting Concept 1, however, has a non-uniform mass distribution about the x_p axis such that the most of its mass is situated beneath the x_p, y_p plane. This would, therefore, result in non-zero products of inertia terms for the telescope platform in the configuration of Mounting Concept 1. The

tubular structure of Mounting Concept 2, for both the telescope configuration and the camera mount configuration meant that its mass distribution about the x_p axis was far more uniform than that of Mounting Concept 1. This meant that the products of inertia terms for Mounting Concept 2 were likely to be negligible (certainly smaller than for Mounting Concept 1), resulting in lower disturbance torques being exerted on the system whilst under motion than for Mounting Concept 1. This would allow stabilisation of the telescope to be achieved by attenuating smaller torques and mean that lower performing, lower cost components could potentially be used successfully in the project. This was obviously favourable for the project and so it was decided that Mounting Concept 2 was better suited to the project.

4.3.2 FINAL TELESCOPE MOUNTING DESIGN

Once the mounting concept had been chosen, the detailed mechanical design could proceed. Using the clamping method of Mounting Concept 2, the following mounting mechanism was designed for the ETX90 telescope.



Figure 4-9: ETX90 final mounting design

The mounting above was designed such that the centre of mass of the system was aligned with the origin of the x_p, x_p, z_p axis system (the pitch platform frame). Figure 4-10 below shows the centre of mass position calculated by SOLIDWORKS.

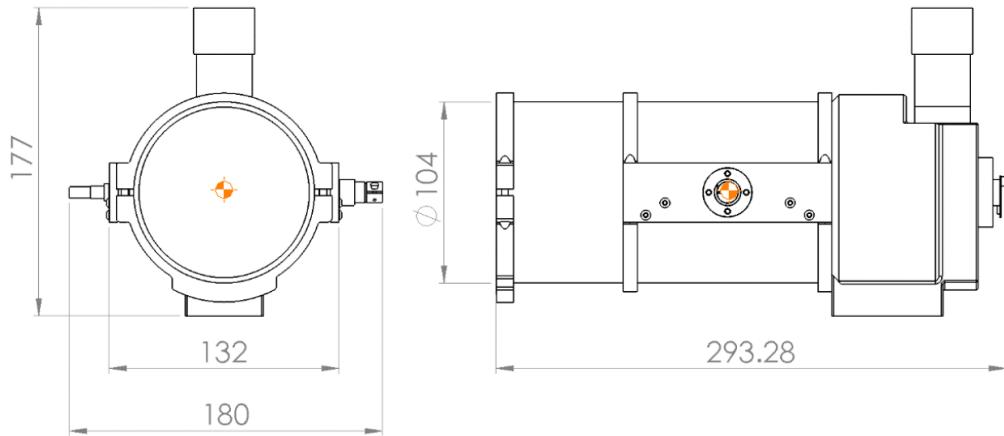


Figure 4-10: Centre of mass position for the ETX90 pitch platform mounting

The ETX90 platform shown above has an estimated mass of 1.95 kg and a tensor of inertia, $\bar{\bar{I}}_p$, about the axes defined according to Figure 4-4:

$$\bar{\bar{I}}_p = \begin{bmatrix} I_{xxp} & D_{xyp} & D_{xzp} \\ D_{xyp} & I_{ypy} & D_{yzp} \\ D_{xzp} & D_{yzp} & I_{zzp} \end{bmatrix} = \begin{bmatrix} 0.0049 & 0 & 0.0008 \\ 0 & 0.0165 & 0 \\ 0.0008 & 0 & 0.0162 \end{bmatrix} \text{kgm}^2$$

These properties, estimated by SOLIDWORKS, along with the telescope dimensions shown in Figure 4-4, were used as baseline figures against which the telescope modelling camera platform was designed. The final design of this platform is shown below in Figure 4-II.

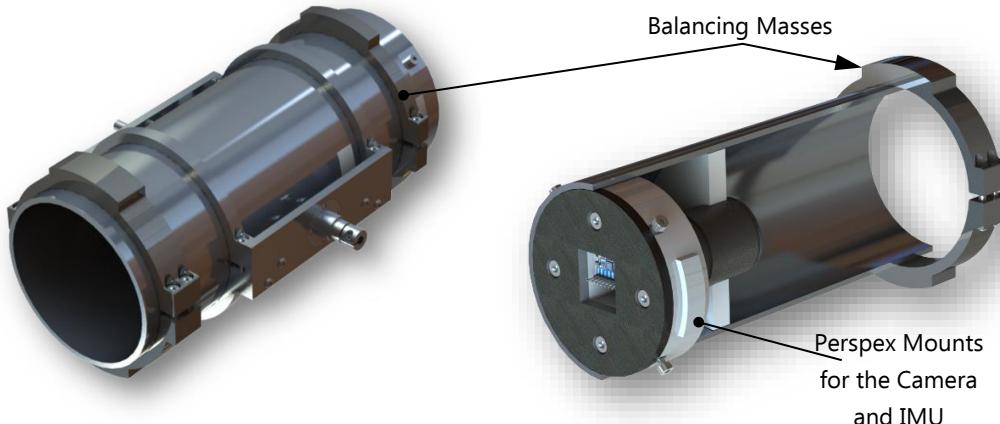


Figure 4-11: Final ETX90 modelling camera mounting platform

This platform has a centre of mass and overall dimensions as shown in Figure 4-12 below and an estimated mass of 1.90 kg and a tensor of inertia, $\bar{\bar{I}}_p$:

$$\bar{\bar{I}}_p = \begin{bmatrix} I_{xxp} & D_{xyp} & D_{xzp} \\ D_{xyp} & I_{ypy} & D_{yzp} \\ D_{xzp} & D_{yzp} & I_{zzp} \end{bmatrix} = \begin{bmatrix} 0.0048 & 0 & 0.0009 \\ 0 & 0.0164 & 0 \\ 0.0009 & 0 & 0.0166 \end{bmatrix} \text{kgm}^2$$

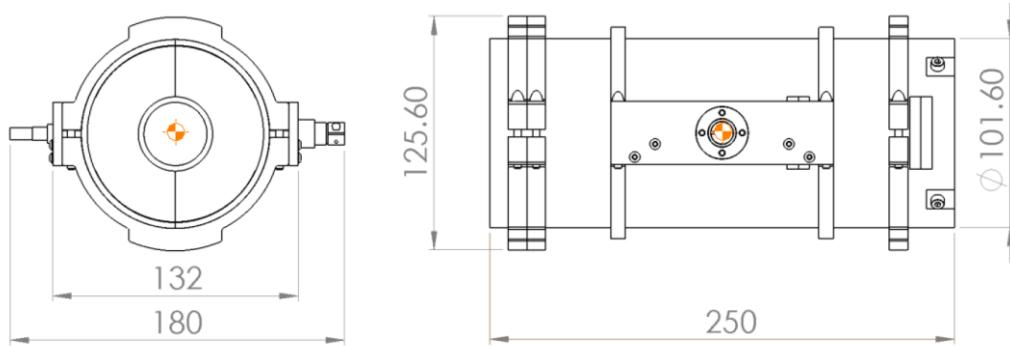


Figure 4-12: telescope modeller overall dimensions

This telescope modeller design inertially modelled the ETX90 mounting closely and was used in this project instead of the ETX90 itself. Due to the similarity of the inertial and dimensional properties of the telescope modeller with the ETX90, it is expected that future development with the ETX90 may be accomplished with minimal effort. The only changes required to mount the ETX90 are the replacement of the mounting clamps and balancing masses for parts dimensioned to fit the 104 mm outer diameter tube of the telescope rather than the 101.6 mm outer diameter of the tube used in the telescope modeller. 101.6 mm outer diameter by 3.18 mm thick aluminium tubing was the dimensionally closest standard size tube available to the 104 mm outer diameter telescope tube and so was the best available material to begin modelling the telescope with. The ETX90's primary mirror (see Figure 4-2) is manufactured from optical quality glass and so adds a significant mass to the back of telescope tube. To effectively model this, the structure designed to mount the camera and the IMU was built up from layers of 5 mm Perspex (see Figure 4-11). Although this was unnecessary from a structural point of view, this helped to add needed mass to the rear of the telescope modeller. The balancing masses designed for the telescope modeller are manufactured from plain carbon steel; this was to ensure the overall mass of the modelling platform closely matched that of the platform mounting the ETX90.

4.3.3 YAW GIMBAL DESIGN

Once the design of the telescope modeller had been completed it was possible to design the yaw gimbal. The yaw gimbal had the function of supporting the telescope modeller in such a way to allow for rotation of the telescope about the pitch axis whilst also facilitating control of the telescope modeller about the y_g (yaw) axis as defined by Figure 2-21. The final design of the yaw gimbal is shown in Figure 4-13 and Figure 4-14 below.

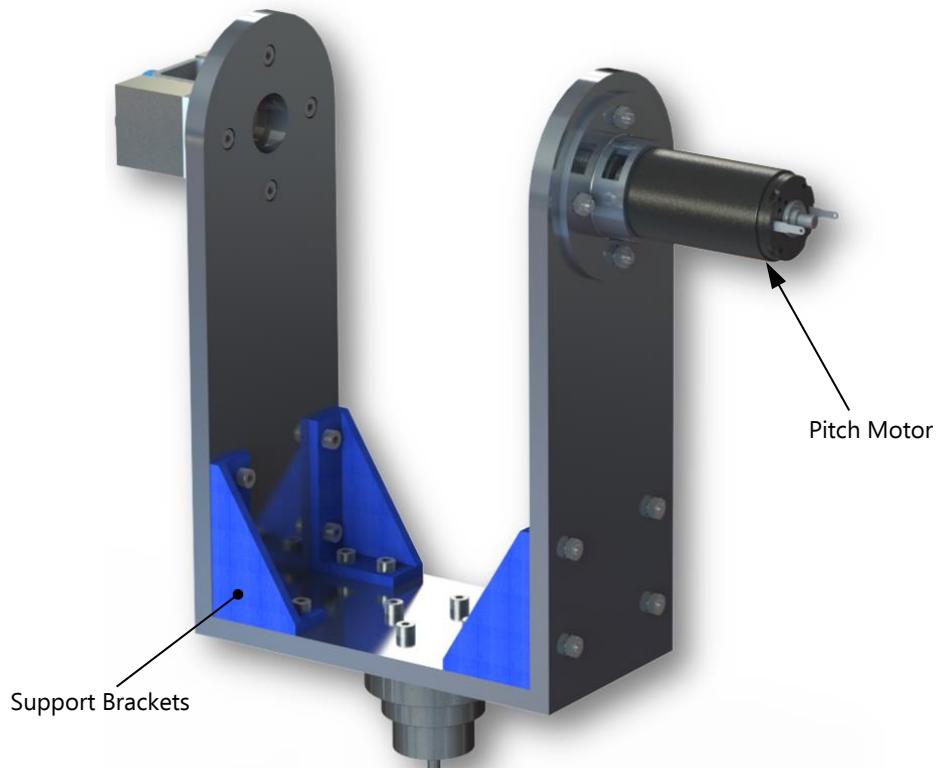


Figure 4-13: Yaw gimbal final design (front)

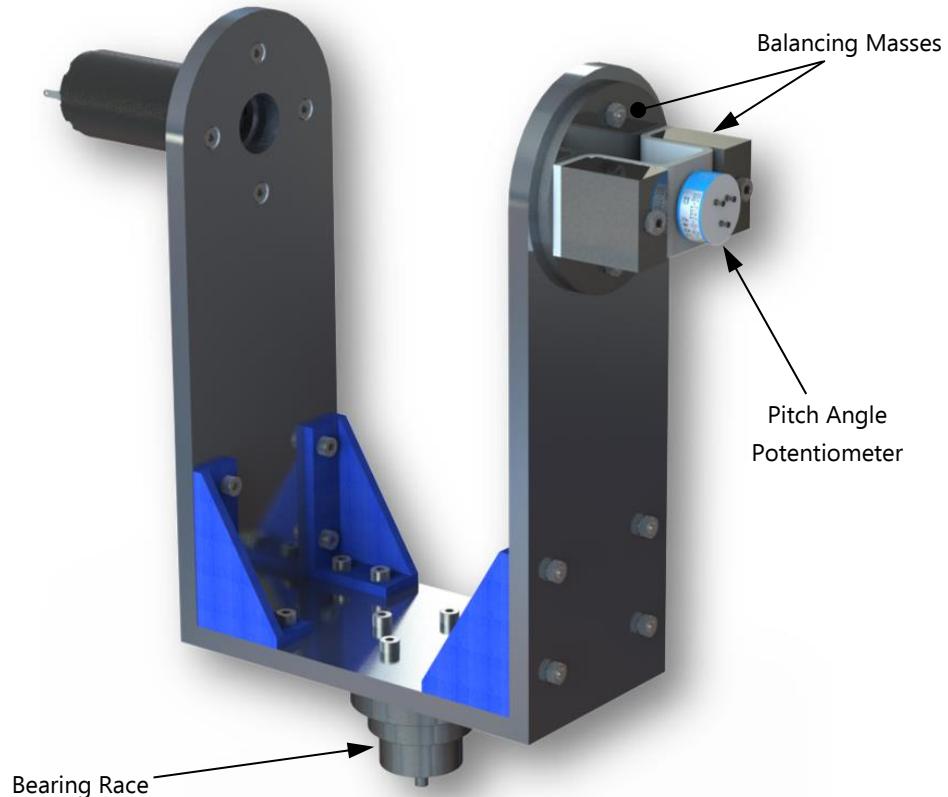


Figure 4-14: Yaw gimbal final design (rear)

The figures above show the final design of the yaw gimbal from the front and rear perspectives. In the first figure, the mounting of the DC motor chosen as the pitch actuator is clearly shown, whilst the second figure highlights the mounting of the potentiometer (pot) chosen to act as a position sensor for the pitch orientation of the telescope modeller. Initial designs had aimed at producing the main structure of the yaw gimbal from a single block of aluminium via a CNC manufacturing process, however, this proved too costly to implement in this project. To reduce the overall cost of production of the yaw gimbal, the main structure was then designed to be comprised of parts manufactured from 8 mm aluminium plate joined together by the support brackets which were 3D printed from PLA plastic with a fill density of 50 %.

As noted in Section 2.5, the structural resonances of ISPs are fundamental limiting properties in ISP performance. In light of this, although the 8 mm thickness of the plate was unnecessary from a stress point of view, it was chosen so that a stiff structure could be produced and so increase the expected frequencies of the structural resonances of the gimbal. It was hoped that these would be at frequencies higher than the bandwidth of the stabilisation control loops designed for the yaw and pitch channels. Aluminium was chosen as the main material for the gimbal due to its lower density than steel, thereby reducing the overall mass of the gimbal and reducing the inertial load on the yaw motor.

The bearing race used to mount the yaw gimbal to the support stand and balancing masses were manufactured from plain carbon steel. The higher density of steel caused its use in the balancing masses which were added to offset the mass of the DC motor on the other side of the gimbal, whilst its lower cost, compared to aluminium, drove its use in the bearing race which was manufactured through a turning process of a large diameter aluminium bar. The yaw gimbal has an estimated mass of 2.06 kg and has a tensor of inertia, \bar{I}_g :

$$\bar{I}_g = \begin{bmatrix} I_{xxg} & D_{xyg} & D_{xzg} \\ D_{xyg} & I_{yyg} & D_{yzg} \\ D_{xzg} & D_{yzg} & I_{zzg} \end{bmatrix} = \begin{bmatrix} 0.0267 & 0 & 0 \\ 0 & 0.0159 & 0 \\ 0 & 0 & 0.0123 \end{bmatrix} \text{kgm}^2$$

Figure 4-15 below shows the overall sizes of the yaw gimbal and its centre of mass.

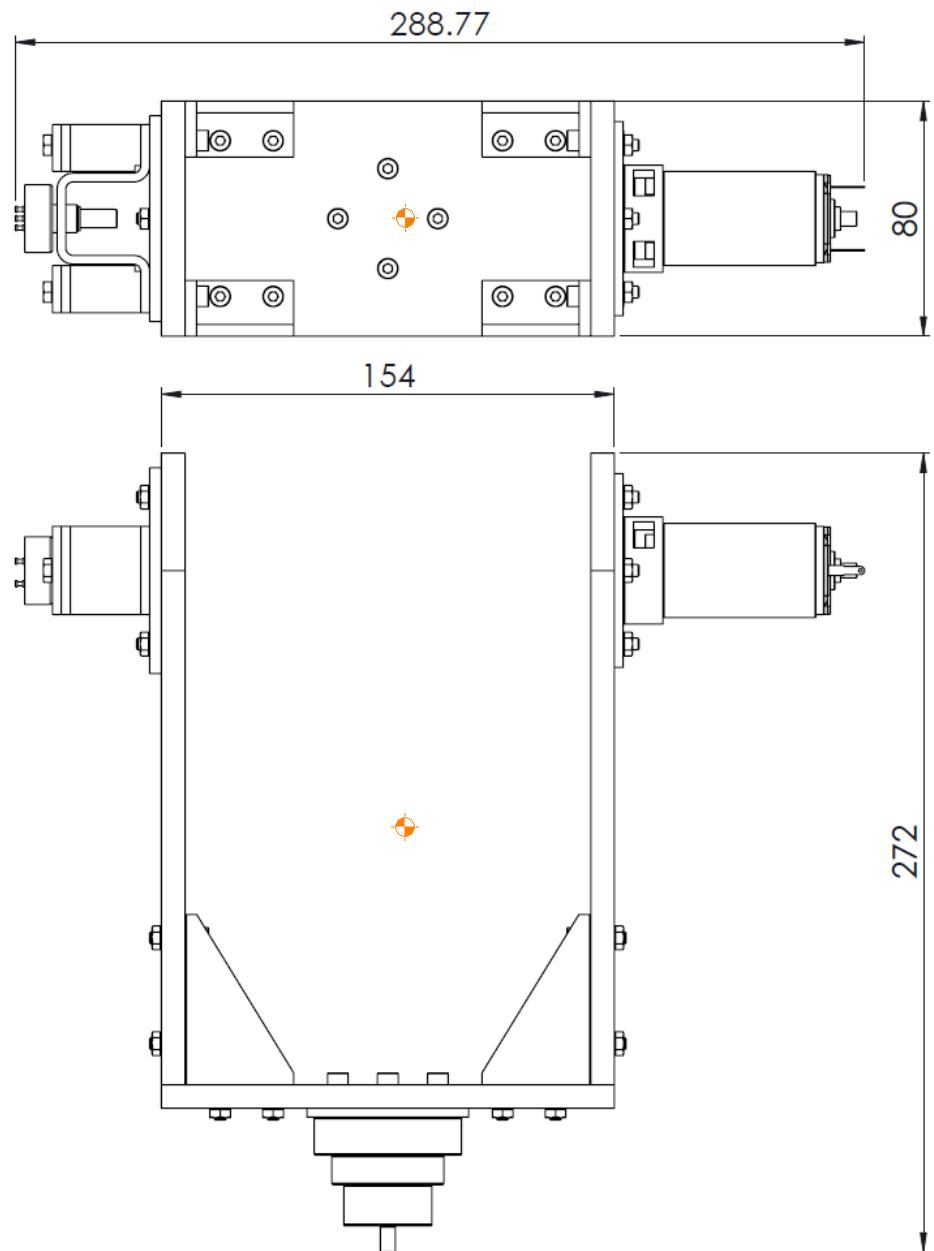


Figure 4-15: Yaw gimbal overall dimensions

4.4 TELESCOPE MOUNT TO YAW GIMBAL COUPLING (I I.2 - PITCH)

This section shows the inter gimbal coupling mechanism between the telescope modeller and the yaw gimbal. As shown in Figure 4-16 below, the telescope modeller is supported in a simply supported beam configuration and allowed to rotate by bearings mounted on the two vertical arms of the yaw gimbal.

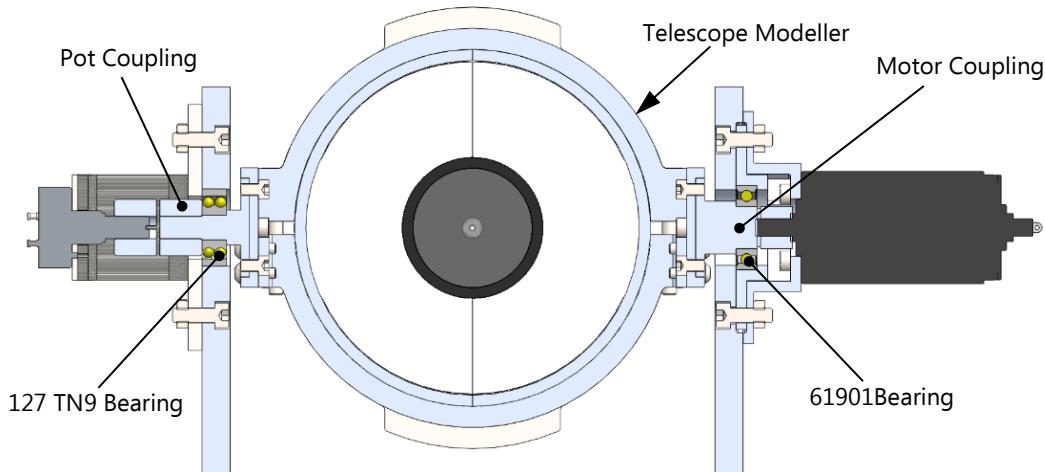


Figure 4-16: Section view of the telescope modeller to yaw gimbal coupling mechanism

The telescope modeller is actuated by the DC motor shown on the right of the above image, whilst the pitch angle is measured by the pot on the left of the image. The shafts of the motor and pot are coupled to the telescope modeller by two aluminium coupling parts designed for use in the project. These are shown in Figure 4-17 below. The reasons behind the choice of a direct coupling between the pitch motor and the telescope modeller (and between the yaw motor and yaw gimbal) are given in Section 5.2.4. Prime item I_{3.2}, therefore, was not a gearbox in the typical sense, but rather a direct, 1:1 coupling of the motors to the gimbals.



Figure 4-17: Motor coupling (left) and pot coupling (right) for the telescope modeller

On the potentiometer side, the telescope modeller is supported by a 127 TN9 self-aligning ball bearing able to accommodate up to three degrees of angular misalignment between the telescope modeller mounting shaft, and the bore through the vertical arm of the yaw gimbal (which acts as the outer race of the bearing) on that side. On the motor side, the telescope modeller is supported by a 61901 deep-groove ball bearing mounted in an outer race designed

to be able to float between the motor mount and the vertical arm of the yaw gimbal. The 127 TN9 bearing is rated for basic dynamic loads of 2.65 kN and a basic static load of 0.56 kN [60], whilst the 61901 bearing is rated for basic dynamic loads of 2.91 kN and a basic static load of 1.46 kN [61]. Therefore, these bearings are more than sufficiently rated to support the 1.95 kg (19.13 N static load) telescope platform. Figure 4-18 below shows a detailed view of the motor side mounting.

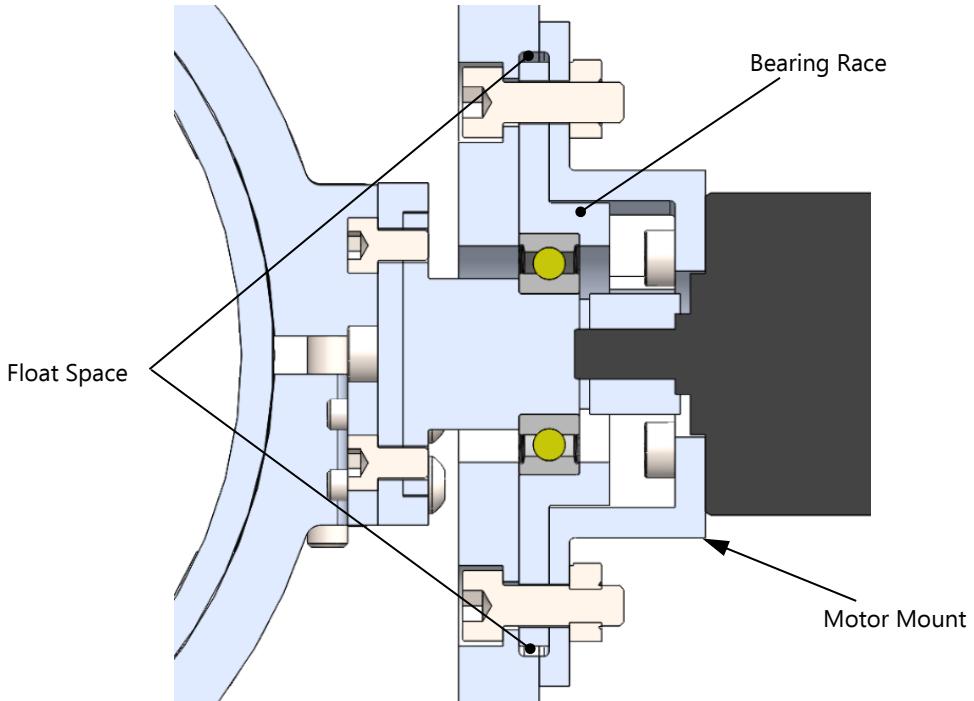


Figure 4-18: Detailed section view of the motor-side mounting of the telescope modeller

The mounting configuration described above was chosen due to high chance of misalignment on the assembly of the yaw gimbal and telescope modeller clamping tray from multiple parts to be bolted together. This configuration allowed for some misalignment in that the motor could be moved up to 1 mm in any radial direction from the centre of the bore through the vertical arm of the yaw gimbal whilst the self-aligning bearing on the pot side allowed for the angle changes associated with that motion.

4.5 SUPPORT STAND DESIGN (II.1)

Following the design of the telescope mounting platform, the telescope modeller, and yaw gimbal assemblies, the support structure for the two gimbals could be designed. This assembly was required to support the gimbals and system electronics, and facilitate the mounting of the ISP system to the host. Figure 4-19 below shows the final design of the support stand.

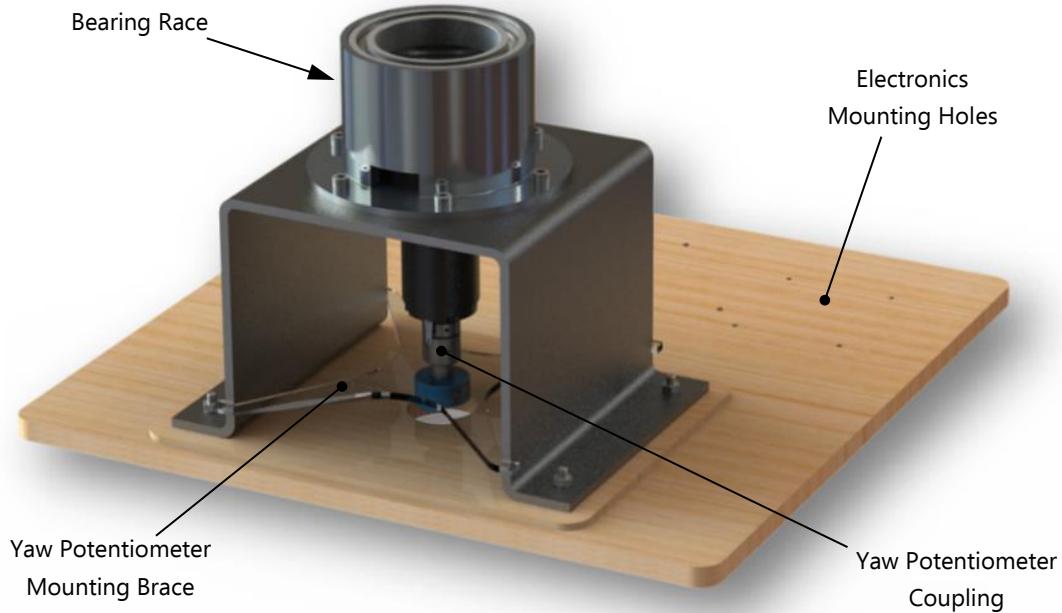


Figure 4-19: Support stand final design

Initially, a tripod type structure was intended to be used as the support stand for the system, however, due again to cost considerations, it was simply decided to use 4 mm thick steel plate cut and bent to create a top-hat profile onto which the gimbals would be mounted. This offered suitable stiffness and strength to effectively support the gimbals. It can also be seen in the figure above that the support stand mounting the yaw gimbal motor is able to accommodate a larger motor than that chosen for this project. The motor ultimately chosen for use helps the control system to achieve suitable performance for the overall system in the operating conditions defined for this project. However, the simulation results shown in Figure 6-50 of Section 6.4.2, indicate that under harsher operating conditions, the motor will require replacement with one able to provide greater torque. Consequently, it is beneficial that this stand facilitates this possible development with minimal modifications being required.

To minimise the lengths of cables required for the project, the steel mount was affixed to a laser-cut wooden board onto which all system electronics were also mounted in close proximity to the ISP. The bearing race was manufactured from plain carbon steel due to its lower cost than aluminium, whilst the pot mounting brace was laser-cut from 3 mm Perspex. The support stand had an estimated mass of 2.40 kg excluding the system electronics and cables.

4.6 YAW GIMBAL TO SUPPORT STAND COUPLING (II.2 – YAW)

This section shows the coupling mechanism used between the yaw gimbal and the support stand. Figure 4-20 below details how the yaw gimbal is mounted onto the support stand.

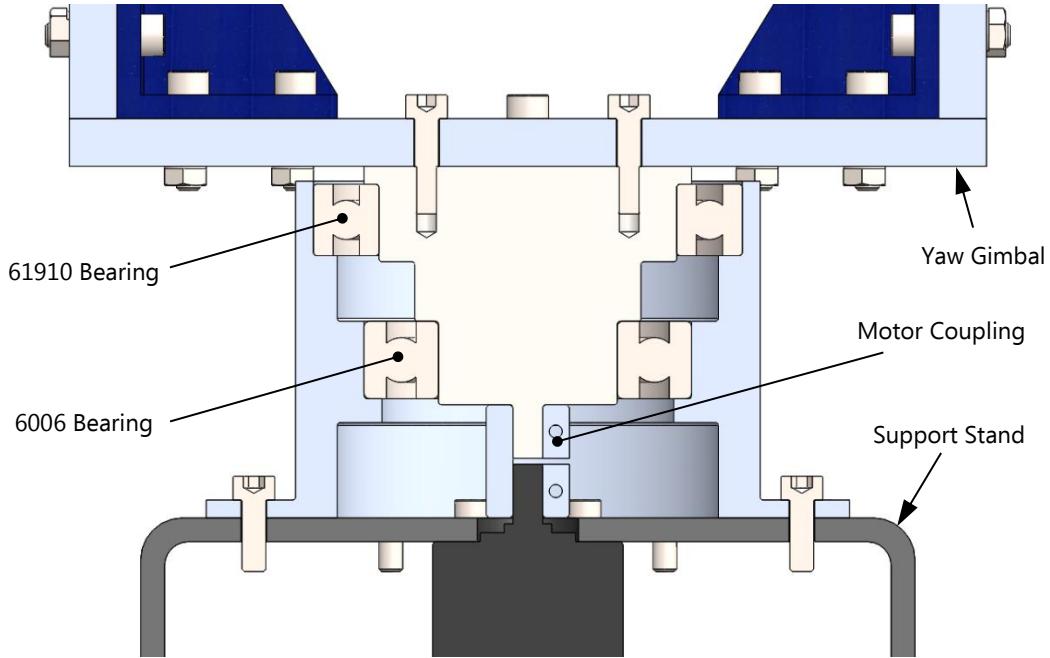


Figure 4-20: Section view of the yaw gimbal mounted on the support stand

The yaw gimbal was coupled to the support stand using two standard deep groove ball bearings as shown in the figure above. The 61910 bearing is rated for a basic static load of 11.8 kN whilst the 6006 bearing is rated for 8.3 kN [62], [63]. According to SKF documentation, their deep groove ball bearings have an axial load bearing capacity of up to 50 % of their basic static load rating [64]. In the worst case, when the weight of the two-axis gimbal system is entirely applied as an axial load to the bearings above, 39.34 N (4.01 kg) would act axially on the bearings. As this is significantly lower than half of the basic static load rating of either of the bearings chosen, the design was deemed suitable for the project even though deep groove ball bearings are designed for radial and not axial loads. This configuration was chosen over designs which made use of angular contact bearings or thrust bearings due to potential problems with supporting the load of the gimbals when the ISP is in inertial orientations other than when vertically upright. The yaw motor is coupled to the gimbal, and the yaw pot is coupled to the gimbal through the motor shaft using a motor coupling similar in design to the pot coupling used on the pitch channel.

4.7 FINAL MECHANICAL ASSEMBLY

The sub-assemblies and their coupling mechanisms detailed in the preceding sections are here shown in the completed overall system assembly shown in Figure 4-21 and Figure 4-22 below.

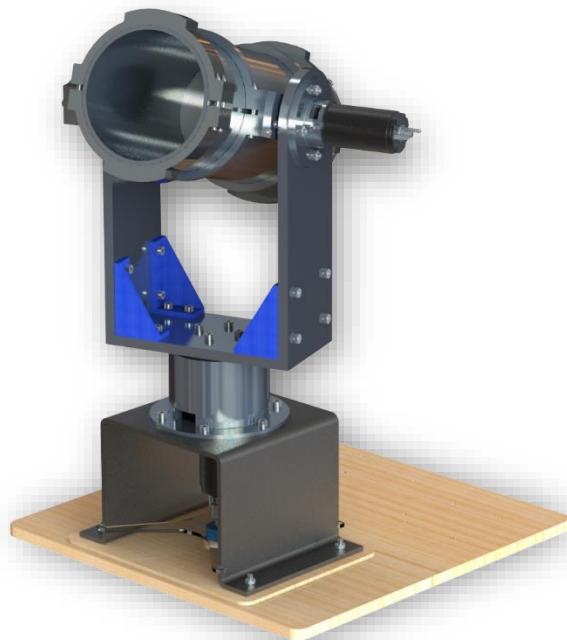


Figure 4-21: ISP assembly with the telescope modeller mounted

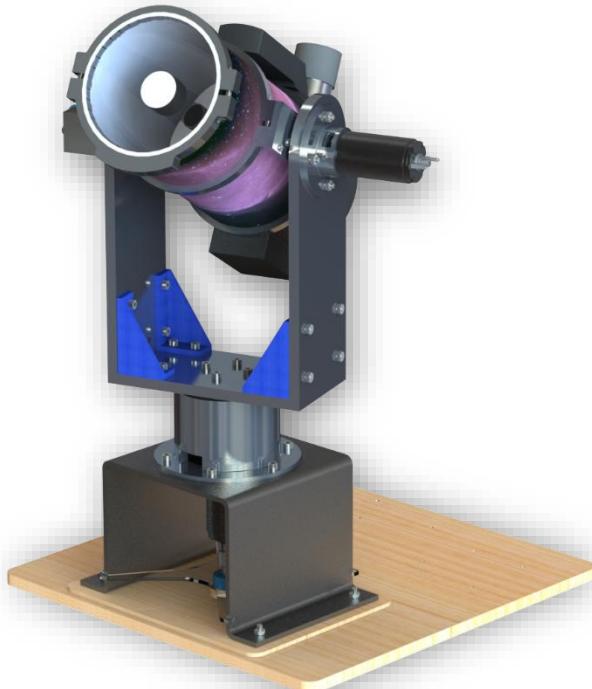


Figure 4-22: ISP assembly with the ETX90 telescope mounted

The figures above show the ISP assembly when mounting the telescope modeller and the ETX90. Below shows the final ISP implemented, with the system electronics mounted on the wooden base. Due to material being available for the fabrication of multiple parts at no cost from UCT, the mechanical system was implemented for a total cost of R787.14.

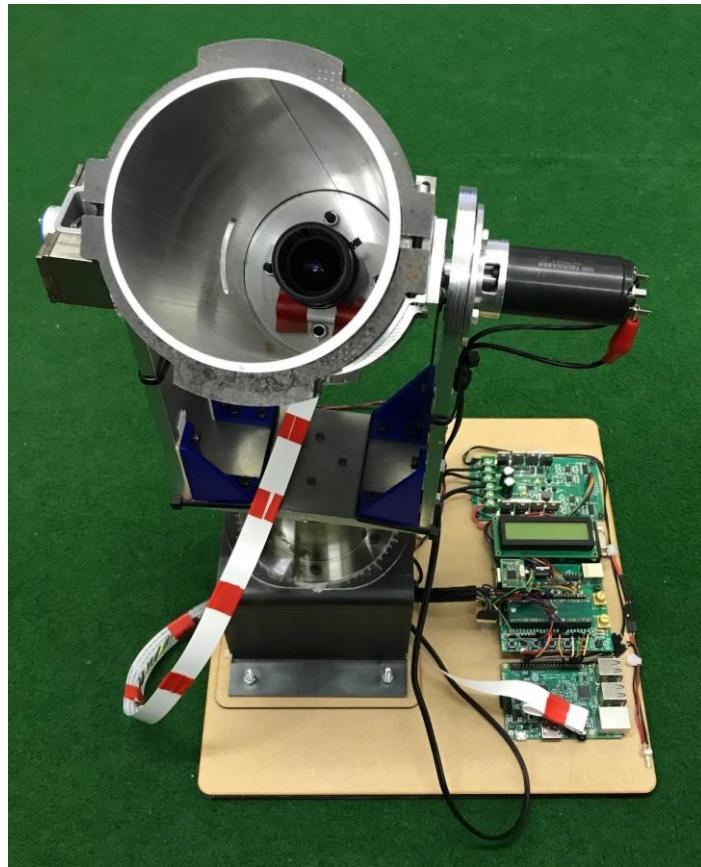


Figure 4-23: Final implementation of the ISP system

The system had an estimated mass of approximately 6.40 kg and had dimensions as shown below.

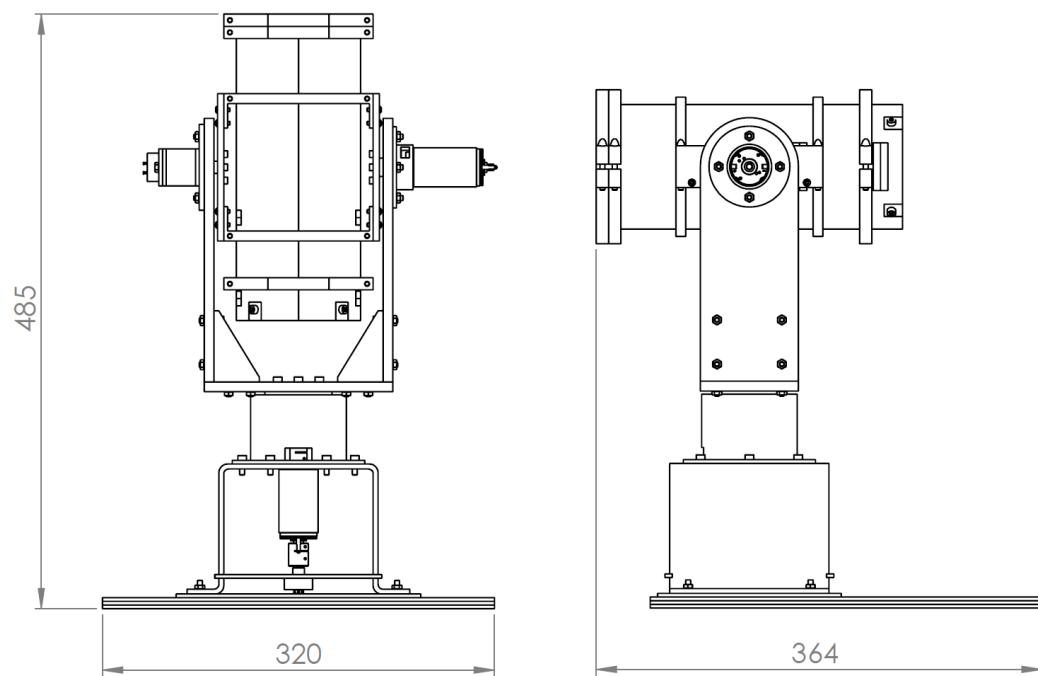


Figure 4-24: ISP system overall dimensions

4.8 CHAPTER CONCLUSION

This chapter detailed the mechanical design of the overall system assembly. A two-axis gimbal assembly was designed and implemented which could facilitate the accomplishment of specifications S₁, S₂, S₄ directly whilst contributing to the accomplishment of many of the operational specifications and the project budget constraint of R5000.00. Ultimately prime items I_{1.1} - I_{1.4} and I_{2.3} were successfully implemented. Technical drawings of all parts designed for the implementation of the ISP system developed, including the telescope modeller and its parts, as well as some engineering design calculations used to verify their implementation may be found at the repository linked in Appendix B. Moving from the mechanical design of the ISP assembly, the next chapter describes the implementation of the electrical systems used in the project including the motors and potentiometers already mentioned in this chapter.

5

ELECTRICAL DESIGN AND IMPLEMENTATION

5.1 INTRODUCTION

This section aims to detail the selection of the electronic components and the control hardware and configuration used in the system developed in this project. A discussion of how the specific electrical components and control hardware was selected is first given before a discussion of how these components were configured for use in the ISP system is shown. This chapter details the design and implementation of prime items I_{2.1}-I_{2.2}, I₄, I₅, and I₃ from a hardware perspective.

5.2 ELECTRICAL COMPONENTS SELECTION

The choice of electrical components used in this project is here discussed. These range from the components comprising the sensor payload mounted on the telescope modeller to electrical systems facilitating the operation of the tracking and stabilisation controllers such as power systems, motors, computers and microcontrollers (MCUs), and auxiliary electronics such as angle pickoffs. The section begins with a description of the camera system chosen to be employed on the ISP.

5.2.1 CAMERA SELECTION (I_{4.1})

For the system to achieve the RMS tracking error of less than 0.25 mrad (S₅) the optical image sensor must be able to detect a rotation of less than 0.25 mrad (S₈). For this to be accomplished the pixel size of the image sensor and the focal length (f) of the lens must be specified such that a 0.25 mrad rotation of a point source of light relative to the lens produces a linear displacement (x) on the image sensor greater than the width or height of a pixel on the image sensor. In Figure 5-1 below, which describes the geometry of a simplified camera setup, α is the angle of view covered by the camera FOV relative to the camera lens, whilst β is the angular rotation of a point relative to the lens.

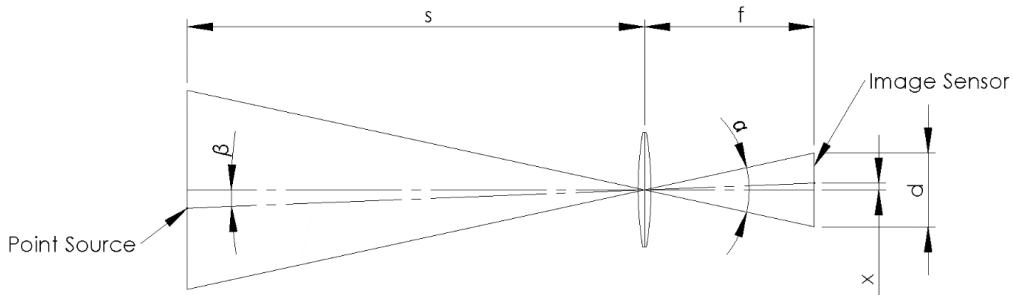


Figure 5-1: Optical geometry

The relationship between β and x is given by the simple geometric relationship:

$$x = f \tan(\beta)$$

Following an extensive search of the available technology, several different image sensors were evaluated to determine their minimum detectable rotation. The sensors evaluated were selected base on availability and price. As with most other components used in this project, cost was a driving factor in the choice of the camera sensor. A camera and lens can easily cost more than the total project budget and so it became a challenging task to find a camera system capable of achieving specification S8 at a low cost. Of the modules evaluated only one module was determined to be capable of achieving the performance specified in S8: Aptina's MT9Po31 Demo Kit. However, this module was priced at R6182 [65]; more than the entire revised project budget, accordingly, an alternative solution was required.

The dominant problem with the other modules was that the standard lenses built into the modules had focal lengths too short to create a large enough linear displacement on the image sensor in response to 0.25 mrad rotation. Except for the MT9Po31 module, all displacements were less than the width or height of a pixel on the sensor.

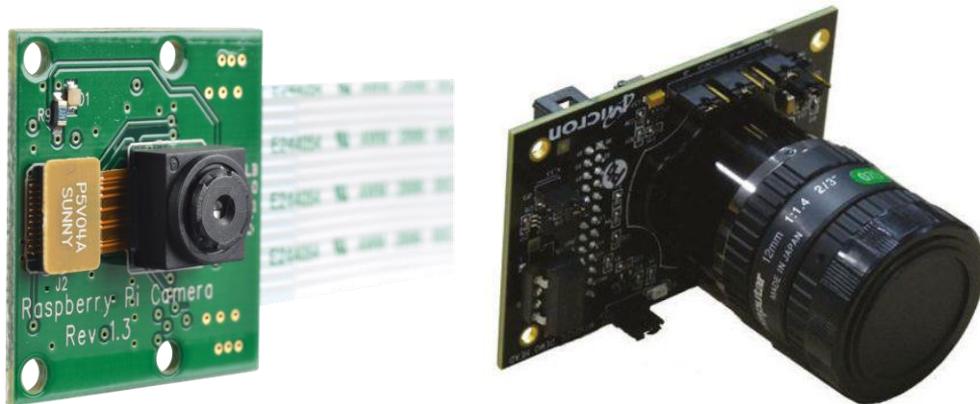


Figure 5-2: Raspberry Pi Camera [65] and Aptina MT9P031 Demo Kit 2 [66]

It was noted that the Raspberry Pi Camera R1.3 featured a 5 MP image sensor with the smallest pixel size ($1.40 \times 1.40 \mu\text{m}$) of the 9 modules evaluated [67]. For this application, small pixel size is an obvious advantage as it would minimise the focal length required to produce a linear displacement greater than the pixel size in response to a 0.25 mrad rotation. Additionally, the Raspberry Pi Camera has been designed to work with the Raspberry Pi

computing platform which supports many image processing techniques which were required in the development of the target tracker. Both components were available from multiple suppliers for a combined cost of less than R800.00.

The low cost of the Raspberry Pi system, as well as its ease of use and extensive support, made the system an attractive option for use in the ISP system. Additionally, the image sensor on the Raspberry Pi Camera was one of the best performing sensors on the modules evaluated. Due to these factors, it was decided that the Raspberry Pi Camera and Computer would be used to accomplish the imaging components of the project. It was, therefore, necessary to replace the lens on the Raspberry Pi Camera for one with a longer focal length for S8 to be achieved. The required focal length for a 0.25 mrad rotation to produce a linear displacement greater than a pixel size was given by:

$$f \geq \frac{1.40e^{-6}}{\tan(0.25e^{-3})}$$

$$f \geq 5.60 \text{ mm}$$

The minimum focal length required, therefore, was 5.60 mm, but longer focal lengths would produce better performance. A CS-mount lens with focal length of 12 mm was available for use at no cost from UCT. This lens would produce a linear displacement of 3.0 μm (or 2.14 pixels) on the image sensor in response to a 0.25 mrad rotation. A CS adapter designed for the camera module and the stock lens was removed and replaced with the 12 mm CS-mount lens. Figure 5-3 below shows the defining characteristics of the C-mount lens system to which the CS-mount is almost identically defined.



Figure 5-3: C-mount Defined [68]

The only difference between the two standards is that the flange focal distance is defined as 12.52 mm for the CS-mount rather than 17.52 mm for the C-mount. Figure 5-4 below shows the CS-mount adaptor and how it facilitates the CS-mount lens being mounted on the Raspberry Pi Camera board.



Figure 5-4: CS-mount adapter shown with the Raspberry Pi Cam and the 12 mm lens

This lens was focused such that a horizontal angle of view of 0.326 rad was visible from the full frame of the imaging sensor, and a vertical angle of view of 0.245 rad. With design for project expansion in mind, a mounting adaptor was also designed for the ETX90 telescope chosen to be used in future projects. Figure 5-5 below shows the Raspberry Pi Camera mounted on the ETX90.

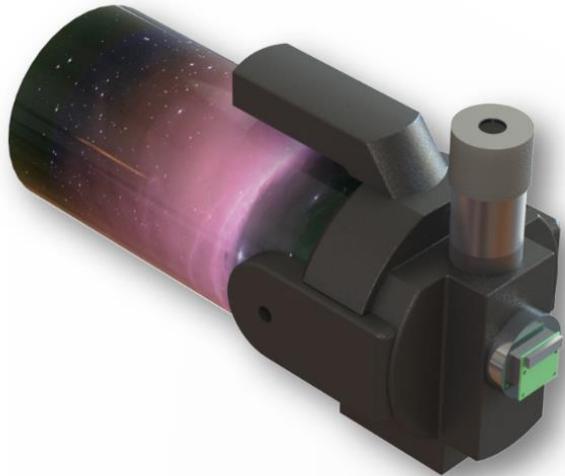


Figure 5-5: Raspberry Pi Camera mounted on the ET90 telescope

5.2.2 IMU SELECTION (I4.2)

As previously discussed, the choice of the gyroscope to be employed in the system was a critical design decision for this project as gyros have been noted to be the main performance-limiting components of small-sized ISPs. Noise incurred in the gyro sensor is directly coupled into the control system and thus is a key source of error in the system. Accordingly, the gyro

chosen needed to have acceptable noise properties to keep the noise introduced to the system to a minimum, and have a high enough bandwidth not to limit the control system's performance (S11). The gyro was also required to be able to measure the expected angular rates during system operation (S10).

Following an extensive search of available gyroscopes, it was decided that a MEMS gyro would be employed in the system. This was primarily driven by the costs associated with other gyroscopic sensor types. The project was initially constrained by a budget of R20000.00 (S14), yet even high-grade MEMS gyros, which are the least costly of high-grade gyroscopes, were noted in some instances to cost up to R15000.00 [69]. However, many MEMS devices are priced far lower than this and have suitable performance capabilities. Further advantages of MEMS sensors for this application were their small size and very low power consumption, both of which helped to achieve specifications S3, S4 and S12, regarding system size and the battery runtime. Additionally, many MEMS gyros sense rotation about more than one orthogonal axis, removing the need for multiple gyros to be used to achieve S2.

EVALUATION OF MEMS GYROSCOPES

Four gyroscopic sensors were initially considered in depth for use in the system; Analog Devices' iSensor ADIS16137, Epson's AP-6110LR, and InvenSense's MPU-9150 and MPU-3300. Table 5-1 below compares some of the important parameters of the four sensors.

Table 5-1: Comparison of gyroscopes [70]–[73]

	ADIS16137	AP-6110LR	MPU-9150	MPU-3300
Number of Axes	1	6	6	3
Output Type	SPI	Analogue	I2C	SPI, I2C
Full-Scale Range (°/s)	±1000	±300	up to ±2000	up to ±450
Nonlinearity (%)	0.01	0.05	0.2	0.2
Temperature range (°C)	-40 to +85	-40 to +85	-40 to +85	-40 to +105
Sensitivity Scale Factor	±0.008 (max)	±0.04	±0.04	±0.02
Variation Over Temperature (%/°C)				
Bandwidth (Hz)	400	200	27k to 33k	27k to 33k
Sampling Rate (Hz)	-	-	4-8000	4-8000
Rate Noise Density* (°/s/√Hz)	0.0036	0.004	0.005	0.005
Bias Stability (°/hour)	2.8	-	-	-

*Rate Noise Density (RND) is an alternative measure of the gyro's white noise such that:

$$ARW \left[^\circ/\sqrt{hr} \right] = 60 \times RND \left[^\circ/s/\sqrt{Hz} \right]$$

It can be seen from Table 5-1 above that all four gyros are capable of measuring angular rates up to 100 °/s as specified by S10 and have bandwidths that exceed the 120 Hz specified by S11. However, the four gyros differ in other parameters. These are evaluated as follows.

ADIS16137

In terms of noise and stability, the Analog Devices iSensor ADIS16137 was the best gyro considered for use in the system. It has the lowest RND at 0.0036 °/s/√Hz and the least change in output variation with temperature at ±0.008 %/°C. Additionally, it shows the best output linearity and was the only gyro of the four for which the bias stability was specified; at 2.8 °/hr, its stability is near the limit of tactical grade MEMS gyros (Figure 2-8).

However, the ADIS16137 has two major drawbacks which lead to it not being employed in this system. First and foremost was its cost. Priced at approximately R15000.00 the sensor would have accounted for three-quarters of the initial project budget and clearly was suitable for use once the budget had been revised. Secondly, compounding the first problem, was that the sensor measures rate about only one inertial axis and therefore to achieve stabilisation about both yaw and pitch axes, at least two sensors would be required.

AP-6110LR

Epson's AP-6110LR is a 6-axis (3-axis gyro and 3-axis accelerometer) IMU capable of measuring angular rates about the required axis and in the required range. It shows the second-best nonlinearity performance at 0.05 % and RND at 0.004 °/s/√Hz and has the strong advantage over the ADIS16137 of measuring rotation about multiple axes in one package.

Of the four sensors, the AP-6110LR is the only sensor which has an analogue output. Analogue outputs are simple to evaluate with a microcontroller by using an analogue to digital converter (ADC). Generally simple to program and use, ADCs on microcontrollers may also allow for higher resolution readings than the 16-bit digital output typically used by the other sensors. However, the uncertainty associated with these readings may be high depending on the operating environment. Analogue signals are susceptible to noise which causes low voltages fluctuations of the output line. Noise interference is likely to occur in an ISP system due to the presence of various electronic components as well as the gimbal motors. Without filtering, the microcontroller is unable to distinguish noise on the line from the true output signal and so additional hardware or software is required to improve the signal quality so that noise is not mistaken for small rotation effects. Digital signals are also susceptible to noise but the discrete logic levels differing by more than one or two volts between the high and low voltages mean that noise will not affect the output reading.

For this reason, it was decided that the sensor should have a digital output and therefore, the AP-6110LR was not used for the project.

MPU-9150 and MPU-3300

InvenSense' MPU-9150 and MPU-3300 have identical bandwidths, RND and nonlinearity properties. They differ slightly in their temperature stability with the MPU-3300 having scale factor variation of 0.02 %/°C compared to the 9150's 0.04 %/°C. A notable difference is the dual output of the MOU-3300 which supports both I₂C and the higher speed SPI.

UCT had a number of MPU-9150 IMUs available for use and so was an attractive choice from a budget perspective. As part of the decision-making process, the Allan Variance test described previously was performed on the MPU-9150's output to test its noise performance against its specifications. The test was run using an STM32F051 MCU to communicate with the IMU and send the gyro data to a laptop running a LabVIEW VI written to log the data. Figure 5-6 below shows the hardware configuration used in these tests.



Figure 5-6: IMU test hardware configuration (adapted from [74])

The test was performed three separate times by fixing the gyro to a stable test bench with one of each of the gyro's three axes aligned with gravity (g) in each test. Common to each test was a sampling rate of 20 Hz, a digital low pass filter at 188 Hz applied to the gyro output, and a data collection time of 12 hr 20 min. The Allan Deviation for each axis was plotted against averaging time for each test, as shown in Figure 5-7 to Figure 5-9 below.

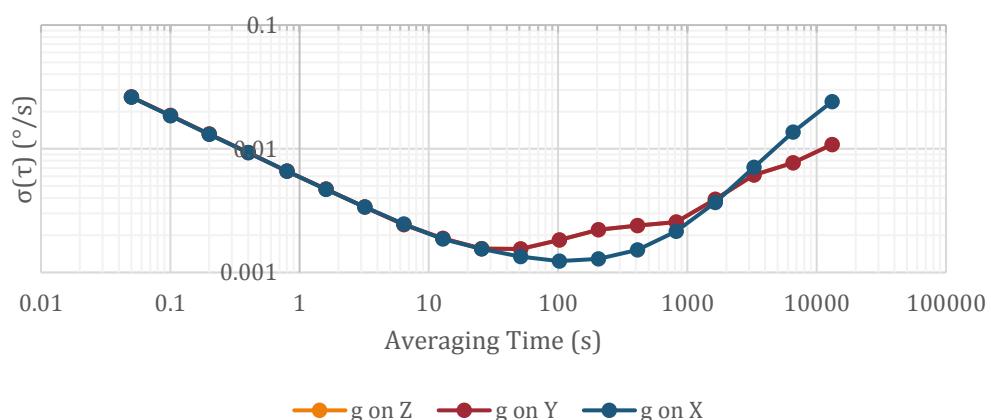


Figure 5-7: X-Axis Allan Deviation

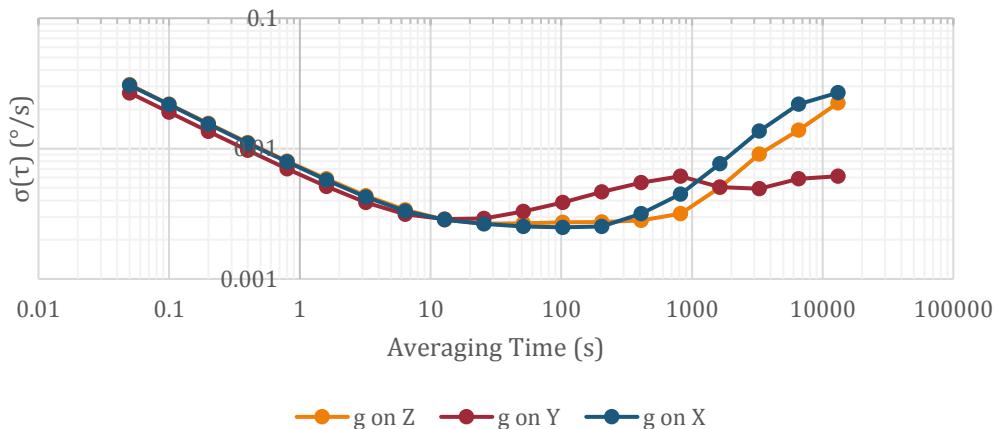


Figure 5-8: Y-Axis Allan Deviation

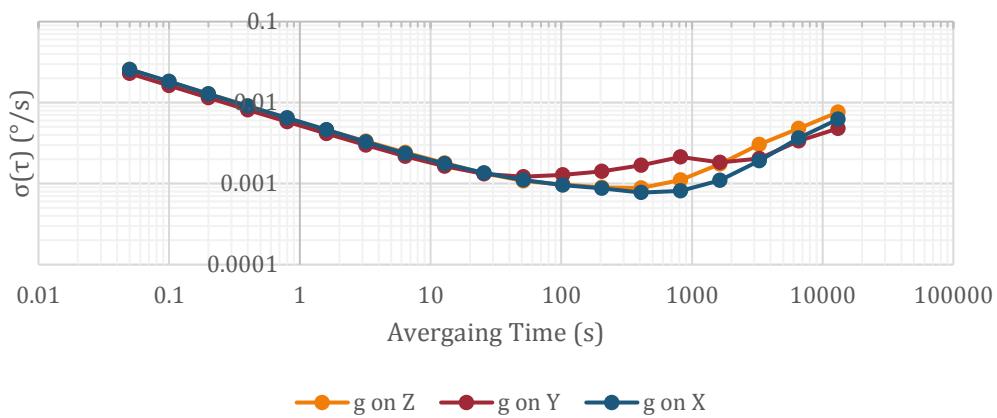


Figure 5-9: Z-Axis Allan Deviation

The RMS values of both the bias stability and ARW were calculated for each test, and then finally the average of the two measures across the three axes was calculated to obtain the average measure of each parameter for the gyroscope. These are detailed in Table 5-2 below.

Table 5-2: MPU-9150 ARW and BS readings

	X-Axis	Y-Axis	Z-Axis	Ave.
ARW (°/√hr)	0.354	0.404	0.330	0.363
RND (°/s/√Hz)	0.0059	0.0067	0.0055	0.006
BS (°/hr)	5.07	9.74	3.53	6.11

It can be seen from the comparison of the experimentally determined RMS value of the RND for the MPU-9150 at $0.006 \text{ } ^\circ/\text{s}/\sqrt{\text{Hz}}$, and the specified value of $0.005 \text{ } ^\circ/\text{s}/\sqrt{\text{Hz}}$ (Table 5-1) that the gyroscope performs closely to its specifications. In addition, the Allan Variance test produced a bias stability measure for the gyroscope which helped to further aid the decision-making process. With a Bias Stability of $6.11 \text{ } ^\circ/\text{hr}$, it can be seen from Figure 2-8 that the MPU-9150 is suitable for mid-range tactical applications.

GYROSCOPE IMPLEMENTATION

Ultimately, the MPU-9150 was chosen for use in the ISP system because it has suitably low noise and nonlinearity characteristics for the application, it has a digital output, measures angular rate in the required range, and has a high enough bandwidth and sampling frequencies so as not to limit the control system beyond its specifications. However, the most significant advantage was the fact that the gyro was available for use at no cost to the project, whilst still being suitable to achieve specifications S10 and S11 directly, and facilitating the achievement of S2, S3, S4, S12 and S14. Figure 5-10 below shows the MPU-9150 and its mounted location on the rear of the telescope modeller.

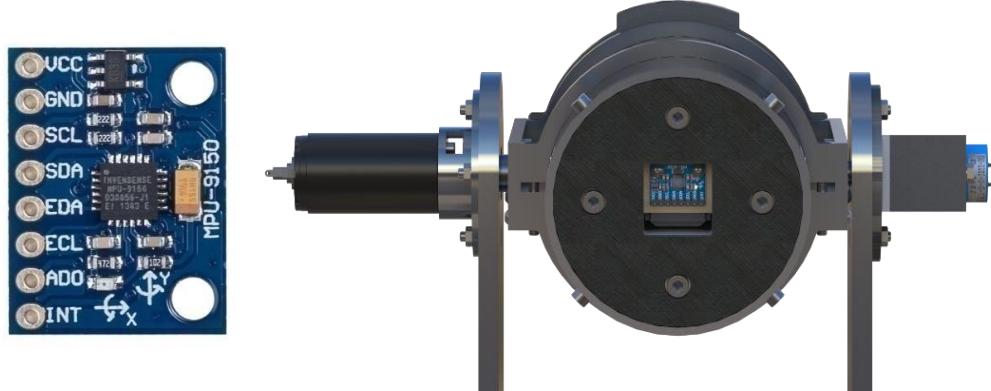


Figure 5-10: MPU-9150 [75] and its mounted location

5.2.3 ANGLE PICKOFFS (I4.3)

The angle pickoffs are auxiliary sensors used for determining the orientation of the ISP's gimbals. They measure the relative angle between the gimbals and provide position feedback for the manual position control loops detailed in Section 6.2. They also provide the data used to orient the simulated ISP model shown in the User Interface, detailed in Section 7.4, and for the monitoring of the gimbals' rotational positions to ensure they do not move outside of their allowable limits.

EVALUATION OF ANGLE SENSOR TECHNOLOGIES

Relative motion sensors which make use of various technologies were considered for use in this project; these included optical rotary encoders, Hall-effect sensors, inductive resolvers and potentiometers. Each type of sensor considered have their own advantages and disadvantages; here these are briefly discussed.

Rotary encoders are sensors which output a digital signal in response to rotational motion. Optical encoders make use of light to provide non contact rotation sensing. Figure 5-11 below shows how this is accomplished.

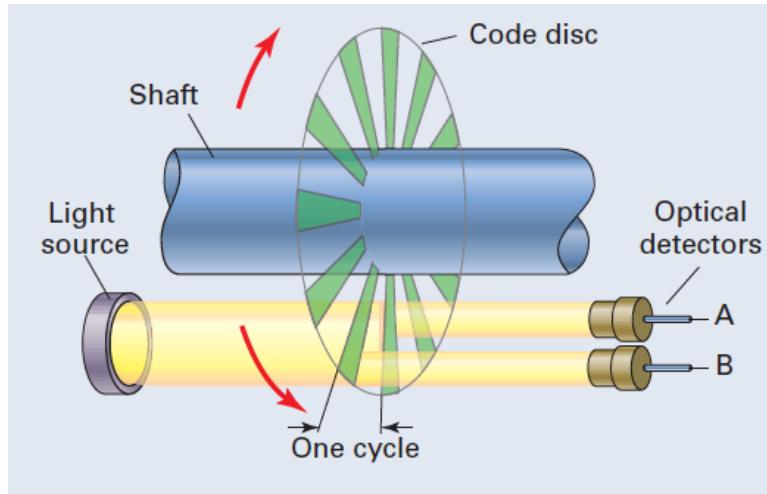


Figure 5-11: Workings of an Optical Encoder [76]

A light source is shone through a code disk which either blocks or allows the light path to reach the optical detectors depending on shaft position. The detectors are normally offset from each other to allow two out of phase square waves to be produced from their outputs. These signals are used to determine direction and speed of rotation. By counting the number of wavelengths between measurements and knowing the number of counts per degree, the angle through which the shaft has rotated may also be determined. In this configuration, the encoder is known as an incremental encoder and provides angle measurements relative to the previous measurement. Some optical encoders provide absolute angle measurements by using Gray code disks such as the one shown below. These disks provide a unique reading at each angle of their resolution.

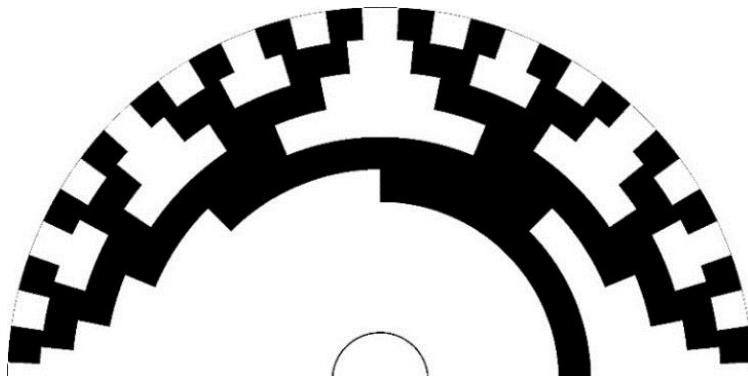


Figure 5-12: Gray code disk section [77]

Rotary encoders can be manufactured to have very high resolutions (in the sub μrad range [1]) and are therefore suited to high precision applications. High-resolution encoders also have long lifespans as there are no moving parts in contact with each other. Unfortunately, high-resolution encoders are costly to produce and purchase, and are susceptible to damage in high shock environments [78].

Hall-effect sensors make use of magnetic effects to accomplish rotational measurements. As a magnet rotates past a magnetic sensor such as a Hall-effect switch, the strength of the

magnetic field across the sensor varies. This effect can be used to measure rotation if several magnetic sensors or several magnets are placed around the shaft as shown in Figure 5-13 below.

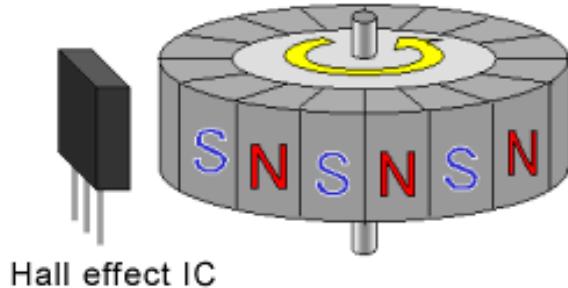


Figure 5-13: Hall-effect rotary sensor [79]

These sensors have lower resolutions than optical encoders and may cause undesired electromagnetic effects on electrical systems located near the rotating shaft. They are, however, robust sensors and have long life-spans due to their non-contact mode of operation.

Inductive resolvers are special types of electrical transformers that are used to measure angular rotation. As shown in Figure 5-14 below, inductive resolvers have three coil windings; a primary energiser coil, and two, secondary, phase coils which are coupled to the energiser coil by the inductively conductive rotor arm.

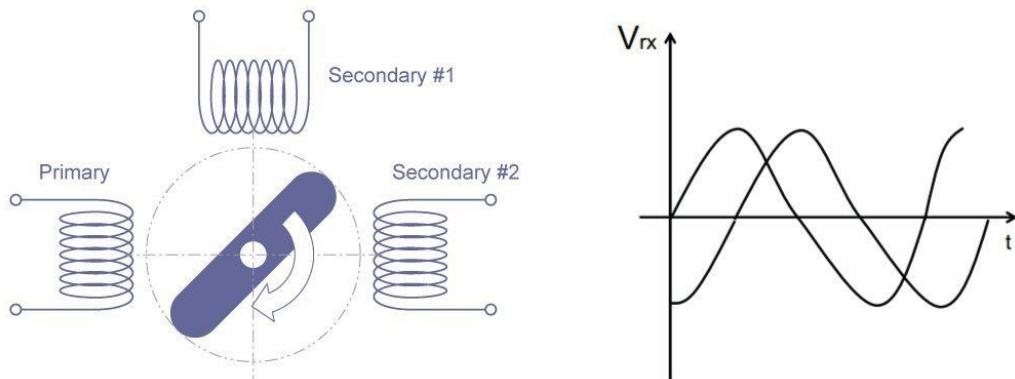


Figure 5-14: Workings of an Inductive Resolver [80]

The primary coil is energised with an AC signal of which differing amounts of energy are inducted into each of the secondary coils depending on the rotor angle. Each secondary coil will produce an output voltage out of phase with the other. The relative magnitudes of the signals are then used to determine shaft angle.

Inductive resolvers are the dominant technology used for angle pickoffs in stabilised platforms [1]. This is due to resolvers being robust, low noise, and the fact that they can be produced to achieve very high-resolution measurements in the arc-second order of magnitude. They are, however, costly sensors and therefore are not suited to low-budget applications.

The final type of angular motion sensor evaluated were **potentiometers**. As shown in Figure 5-15, all potentiometers are analogue potential dividers which use a contact (wiper) to

measure the voltage across a section of a resistive track, the length and hence, resistance of which changes with rotation angle.

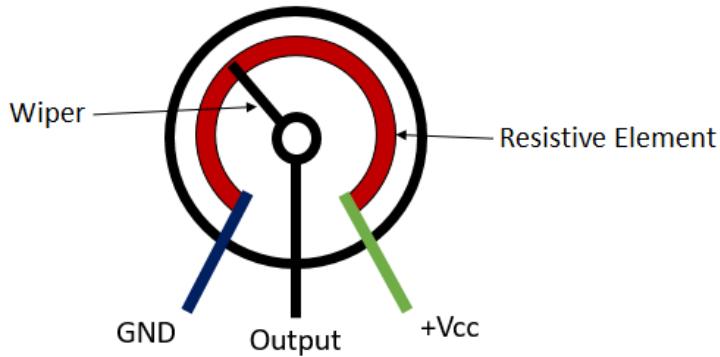


Figure 5-15: Workings of a potentiometer [81]

As potentiometers are analogue sensors their output is required to be converted to a digital signal using an ADC before they may be used on a digital system. Pots generally show the poorer noise properties and resistance to vibration and foreign objects, such as dust, than optical encoders and inductive resolvers due to their contact based sensing. They are however low cost, simple to implement, and can offer high accuracy measurements.

Various technologies which affect performance and cost are used in the resistive elements of potentiometers. Table 5-3 below compares available pot technologies and shows their performance against criteria such as cost, linearity, noise, smoothness, and temperature stability.

Table 5-3: Comparison of resistive element materials [82]–[85]

Resistive Material	Notes
Carbon	These are the most common and lowest cost type of resistive element used in pots. They have the lowest lifespans and poorest noise characteristics of the available technologies. They show good temperature stability and fair linearity properties.
Cermet	Pots making use of Cermet elements are more expensive than carbon pots but have much longer lifespans and the most stable temperature performance of the different pot types. Their linearity and noise properties are similar to carbon element pots.
Conductive Plastic	Conductive Plastic pots, along with Carbon and Cermet pots, offer essentially infinite resolution limited only by the resolution of the ADC digitizing the voltage measurement. They exhibit the lowest friction on rotation, have the longest lifespans, high linearity, and the lowest noise of the different pot types. They are, however, more expensive than other element types and the most sensitive to temperature variation.

Wire-wound	Wire-wound element pots show the best linearity and highest power capacities of the available pot types. They also have low noise properties, life spans better than Carbon or Cermet pots and better temperature stability than Conductive Plastic pots. Their resolution is limited by the diameter of the wire element and they have a rough feel due to the wire element in contact with the pot wiper.
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The different elements of pots are configured in either linear or logarithmic implementations. The outputs of linear pots are linearly proportional to the angle of rotation whilst the output of a logarithmic pot varies according to the logarithm of the input angle. Additionally, pots may be manufactured to rotate within defined angular ranges, be multi-turn in limit, or may allow for continuous rotation.

ANGLE PICKOFF IMPLEMENTATION

It was decided to make use of Conductive Plastic (CP) potentiometers as the relative motion sensors for the gimbals of the ISP developed in this project. Ideally, inductive resolvers would have been chosen due to their robust, low noise, and high precision measurement capabilities. However, in accordance with the budget constraints of the project, it was deemed that CP pots were the best available sensor technology for this project. Their long life-spans coupled with low noise and rotational friction properties were suited to implementation on the EM assembly of the ISP. Section 2.4 introduced the important concept of reducing internal sources of Coulomb friction in the ISP. Any sources of torque disturbance negatively impact the performance of the overall system and are required to be overcome by the gimbal actuators. Therefore, the low friction properties of CP pots were the primary motivation for their choice over pots which make use of other types of resistive element. In addition, their high linearity and resolution meant they are well suited to accurately measure the angular position of the assembly gimbals.

The specific pots chosen for use in the project were continuous rotation, linear resistive element Vishay 357 CP pots shown in Figure 5-16 below. They were available for a combined cost of R530.78.



Figure 5-16: Vishay 357 potentiometer [86]

The main specifications [87] of this pot are summarised in Table 5-4 below.

Table 5-4: Vishay 357 specifications

Parameter	Specification
Resistance	10 kΩ
Linearity	2 %
Shaft Diameter	6.35 mm
Shaft Length	22 mm
Electrical Load Life	1000 hrs
Life-span	5 000 000 revolutions

Unfortunately, the choice to use the Vishay 357 pots as angle pickoffs meant that S9 was not achieved. The ADC, through which the wiper voltage on these sensors was read, had a maximum resolution of 12-bits. This meant that the minimum detectable rotation was:

$$\theta = \frac{2\pi}{2^{12}} = 1.53 \text{ mrad}$$

Precision of this level, approximately 6 times lower than the specification of 0.25 mrad, was also unachievable due to noise on the wiper line and an inherent error of ± 1 bit on the ADC reading. This rendered the minimum detectable rotation to be approximately 3 mrad, far from the original specification. However, the costs of using digital sensors such as inductive resolvers capable of providing measurements of the order specified were unjustifiable, and it was decided that failing to achieve the low priority specification S9 would be acceptable in this project. Figure 5-17 and Figure 5-18 below show the mounting of the yaw and pitch pots respectively. The yaw pot measures the angle of the yaw gimbal relative to the system base, ψ , defined in Section 2.9.1, whilst the pitch pot measures the angle of the telescope modeller relative to the yaw gimbal, defined previously as θ .

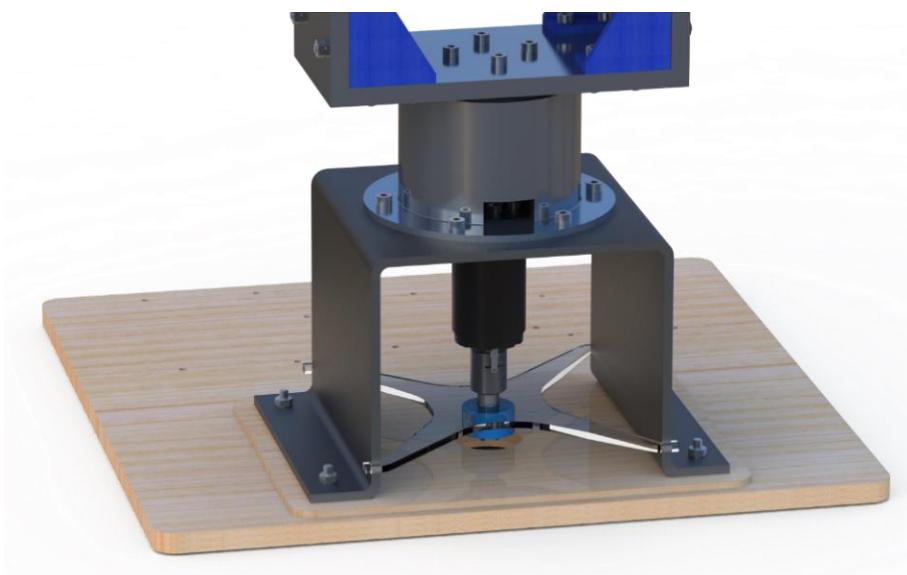


Figure 5-17: Yaw pot mounting position

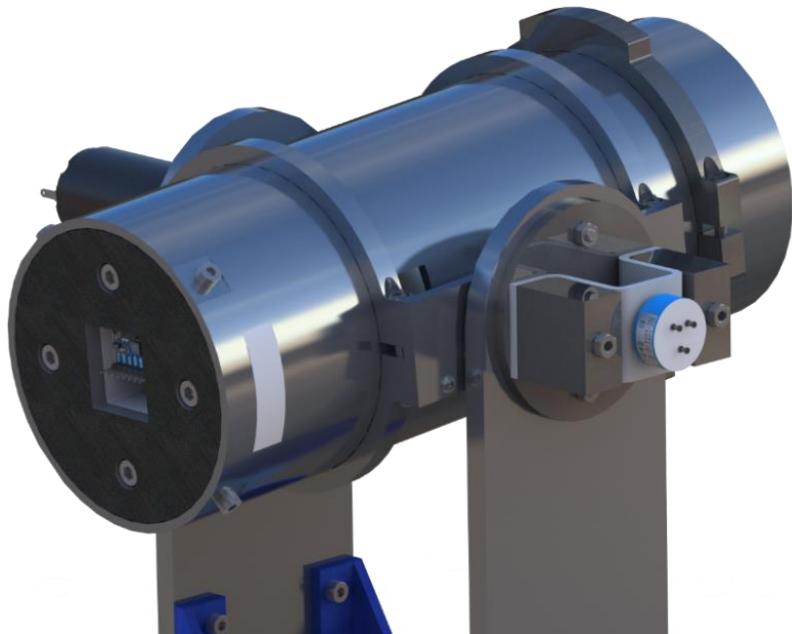


Figure 5-18: Pitch pot mounting position

5.2.4 MOTOR SELECTION (I2.2)

Simple DC motors were chosen as the gimbal actuators for this project as they are readily available, simple to operate, reliable and require no specialised knowledge for successful design and implementation such as would have been the case with hydraulic or pneumatic actuators. The gimbal motors and drive electronics are tasked with the actuation of the gimbals such that successful target tracking is achieved whilst torque disturbances from various sources are simultaneously attenuated to prevent jitter on the camera sensor. The motors then, are critical components of the ISP and directly affect the level of performance in terms of target tracking and base motion attenuation that is achievable. Accordingly, they must be specified such that they can provide adequate torque to overcome the disturbances and achieve the tracking rates required for the application. They must also have minimal hysteresis and show low levels of Coulomb and viscous friction for overall system performance to be maximised.

A previous project in the Department of Mechanical Engineering at UCT in 2014 aimed to develop a one-axis stabilised platform with automatic video point-source tracking. That project was ultimately unsuccessful in achieving stabilisation of the camera. The initial phase of this project was to bring this one-axis system to a working level so as to evaluate its deficiencies and draw useful outcomes to inform the development of the two-axis platform in focus in this project. The primary outcome from this phase of the project was that the motor that had been employed in the one-axis project was not capable of producing adequate performance for the development of a stabilised platform and that careful attention should be paid to the motor selection for the two-axis platform. Figure 5-19 below shows the one-

axis platform build and the 12 V geared DC motor used to actuate the camera mounting platform.



Figure 5-19: One-axis stabilised platform and its DC motor [88]

The motor used was the limiting factor in the performance of the one-axis system. The gearbox attached to the motor allowed a greater torque to be transmitted to the camera platform than would have been possible by the motor alone. However, the gearbox affixed to the motor was of poor quality, allowing a few degrees of play on its output shaft. In response to this, there was a high level of backlash incurred to the system which drastically reduced the possible system performance by actually causing a high level of jitter to be present on the camera LOS; precisely the opposite of the desired characteristics for an ISP.

Accordingly, it was decided that a direct drive coupling between the motors and the gimbals was to be implemented on the two-axis platform in order to prevent the jitter-causing backlash effects observed in the one-axis system. This, however, meant that the motors themselves were required to be directly capable of meeting the torque requirements for the system which would, unfortunately, mean they would likely be high-cost components relative to the project budget. Due to the drastic performance limitation imposed on the one-axis system by its poor actuator, it was decided that these were most important components to be procured for use in this project and that, if necessary, the largest portion of the project budget would be allocated to their purchase.

EVALUATION OF MOTOR REQUIREMENTS

In response to the decision to allocate the dominant portion of the project budget to the motor selection, it was important to rigorously analyse their requirements in the project before their purchase so that their successful performance once implemented could be predicted as far as possible. This subsection details the process by which these motor requirements were evaluated and the motors were chosen.

Given that the application of this project was to track astronomical objects from a moving vehicle, it was expected that the dominant requirement for the motors would be to attenuate torque disturbances incurred to the telescope modeller by the moving vehicle rather than to achieve the tracking of celestial objects. As celestial bodies move at very slow rates (the earth rotates at approximately $15^{\circ}/\text{hr}$), the performance required from the motors to achieve this is

very small relative to requirements for removing base motions which may have angular rates far greater than the rate of motion of celestial bodies. It was, therefore, necessary to evaluate the magnitudes and frequencies of the disturbance torques expected to be incurred on the telescope modeller under the expected operating conditions; when mounted on a moving vehicle. Only once these were known it would be possible to determine the specifications for the motors such that these disturbances might be overcome and adequate performance be achieved. However, it became apparent that such data was either not readily available or easily accessible and that it would be necessary to experimentally determine the base motion disturbance torques expected to be incurred from a moving vehicle.

A direct, experimental, measurement of these disturbance torques was, however, difficult and impractical to achieve directly in practice and would have required the development of a specific piece of hardware capable of measuring those torques. Instead, it was decided that the angular rates of the base motion would be measured as the vehicle moved. This data would then be analysed to develop a simulation base motion signal representative of the experimental test data. A simulation model of the two-axis stabilised platform and its two DC motors would then be developed using the double-gimbal dynamics derived in Section 2.9 which define how the base motion rates transfer to torques on the yaw gimbal and pitch telescope platform as a function of inertia, angular position, and angular rate. By designing rudimentary stabilisation and inertial position controllers for the two gimbal channels in the simulation it would then be possible to observe the performance of the given motors at attenuating base motion disturbances from the simulation signal and to monitor the estimated disturbance torques incurred by the expected signal on the telescope platform whilst it was positioned in various orientations.

EXPERIMENTAL DETERMINATION OF VEHICULAR BASE MOTIONS

To determine the expected base motions the set of hardware and software used in Section 5.2.2 to gather data for the Allan Variance tests on the MPU-9150's output was then used to measure and record the base motions of a vehicle as it moved. The IMU was affixed to a vehicle with its axes, denoted by the subscript $_{imu}$, aligned with the Base-fixed frame, B, defined in Section 2.9.1 according to Figure 5-20 below.

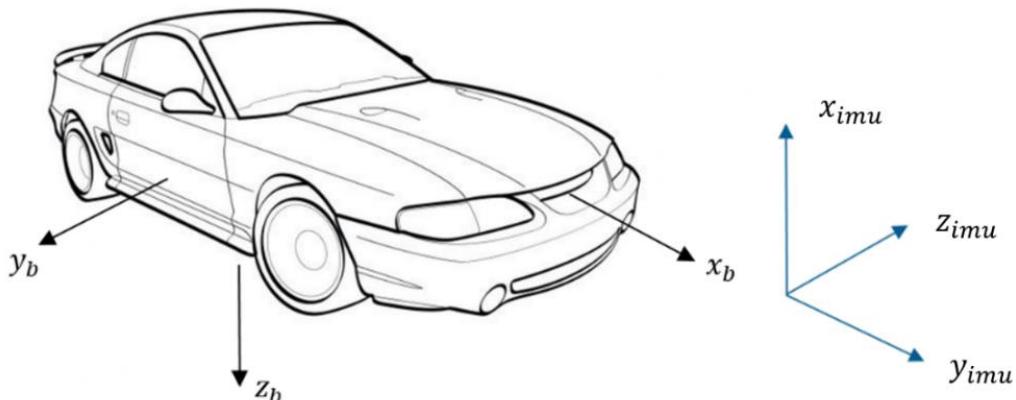


Figure 5-20: IMU axes alignment with vehicle axes (image adapted from [89])

The three gyro axes were sampled at a rate of 200 Hz over an I₂C interface by the STM32 MCU. This data was then sent to the LabVIEW data logging VI using a USART RS₂₃₂ over USB interface. The VI was used to record the data-logs for each axis in a spreadsheet file. This software used to gather and record the data from these tests may be found in Appendix C.

Eight separate tests were run, where vehicle motion data was recorded from all three gyro axes. An example of the sampled vehicle rotation data is shown in Figure 5-21 below. This dataset was recorded from the second of the eight tests.



Figure 5-21: Vehicle motion from Base Motion Test 2

All three axes for each of these eight data sets were then analysed using a LabVIEW VI that was written to perform a Fast Fourier Transform (FFT) on the time signal for each axis using the Hanning and Flat Top window functions to obtain the amplitude vs. frequency and phase vs. frequency components of the time signal. In addition to these components, the RMS average magnitude of the time signal was determined for each axis using the VI. This VI may also be found in Appendix C. Two window functions were used to increase the accuracy of frequency domain data. The FFT is defined assuming that the dataset on which it operates represents a continuous spectrum representing one period of the signal, with the first and final data points being identical positions on the waveform separated by one wavelength [90]. In practice, the dataset is not a continuous spectrum nor is it a single period of the signal, therefore, window functions are used to reduce the amplitudes of the edges of the signal such that they are equal in value. These window functions are effectively scaling factors which vary according to a data point's position in the dataset. Different window functions have different shapes and therefore influence the FFT output of a dataset in different ways. Figure 5-22 and Figure 5-23 below compare the shape of the Hanning and Flat Top window functions.

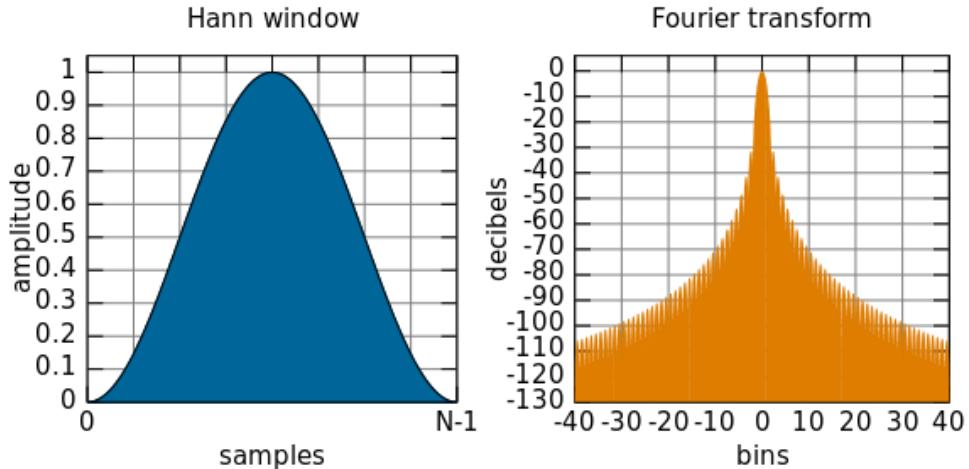


Figure 5-22: Hanning window function [91]

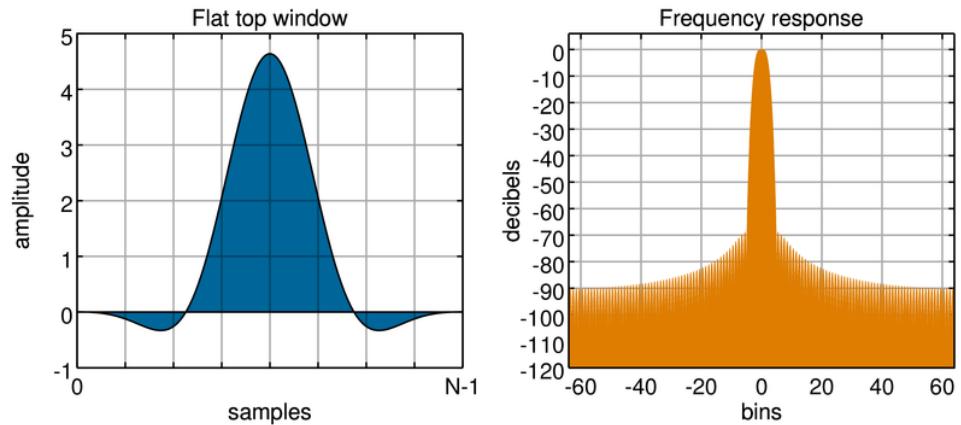


Figure 5-23: Flat Top window functions [92]

Hanning windows are suited to applications where the nature of frequency content of a signal is unknown or is likely to be composed of a combination of sinusoidal signals. It is one of the most commonly used windows in signal analysis as it has good frequency resolution. The Flat Top window, by contrast, shows poor frequency resolution and is sensitive to noise but shows accurate amplitude results [90], [93]. By comparing the results of these two window functions, a more accurate picture of the frequency domain representation of the base motion data could be determined: The Hanning window revealed the frequency components with greater precision than the Flat Top Window, whilst the Flat Top window was used to obtain the magnitude of peaks close to the peaks of the Hanning window result with greater accuracy than the Hanning window was able to provide. Figure 5-24 and Figure 5-25 below show the frequency domain representation of the magnitude of the x_{imu} axis of Test 2 under the Hanning and Flat Top window functions, respectively.

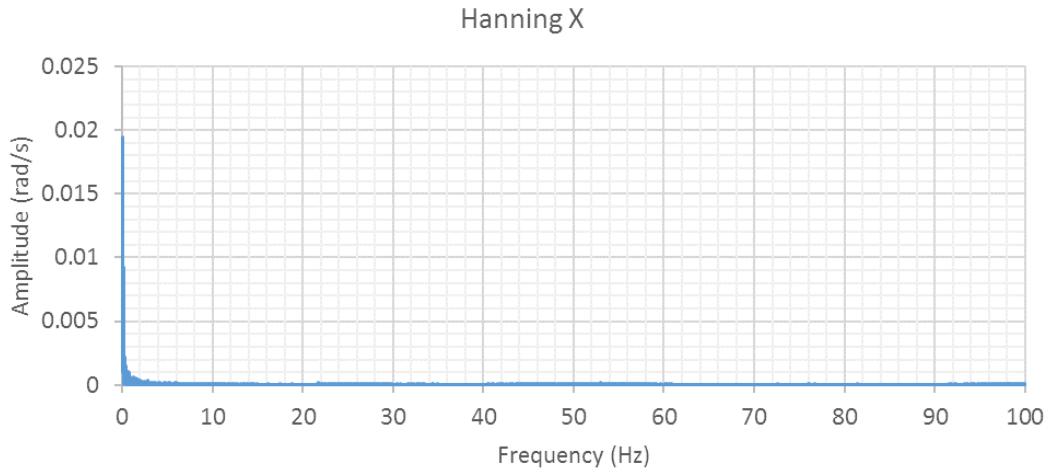


Figure 5-24: Amplitude vs Frequency of the x_{imu} data of Test 2 under the Hanning window

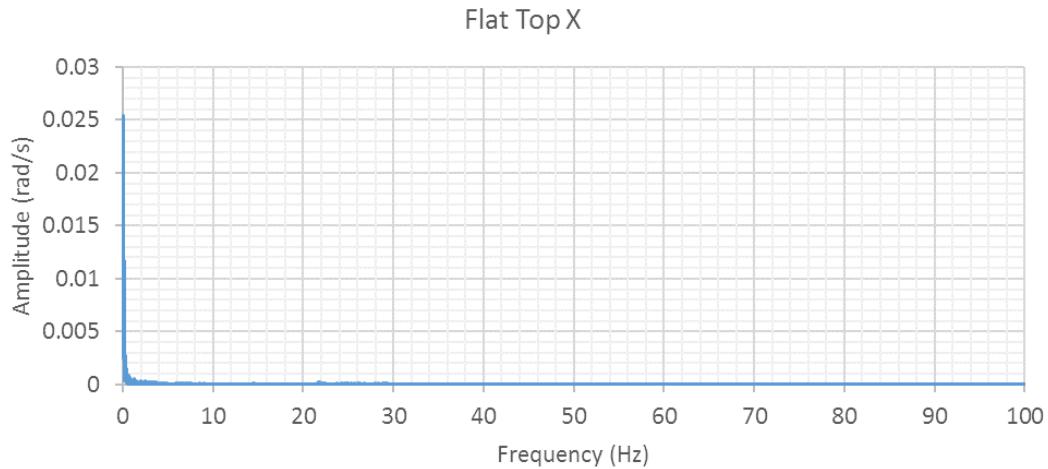


Figure 5-25: Amplitude vs Frequency of the x_{imu} data of Test 2 under the Flat Top window

It can clearly be seen the low-frequency peak in the two tests differ in magnitude. The Hanning window places the peak of 0.019 rad/s at 0.057 Hz whilst the Flat Top window places the peak at 0.071 Hz with a magnitude of 0.025 rad/s. It was therefore decided to model the peak as 0.025 rad/s at 0.057 Hz using the more accurate magnitude from the Flat Top window and the frequency from the Hanning window. Figure 5-26 and Figure 5-27 below show the frequency domain representation of the magnitude of the z_{imu} axis of Test 2 under the Hanning and Flat Top window functions, respectively.

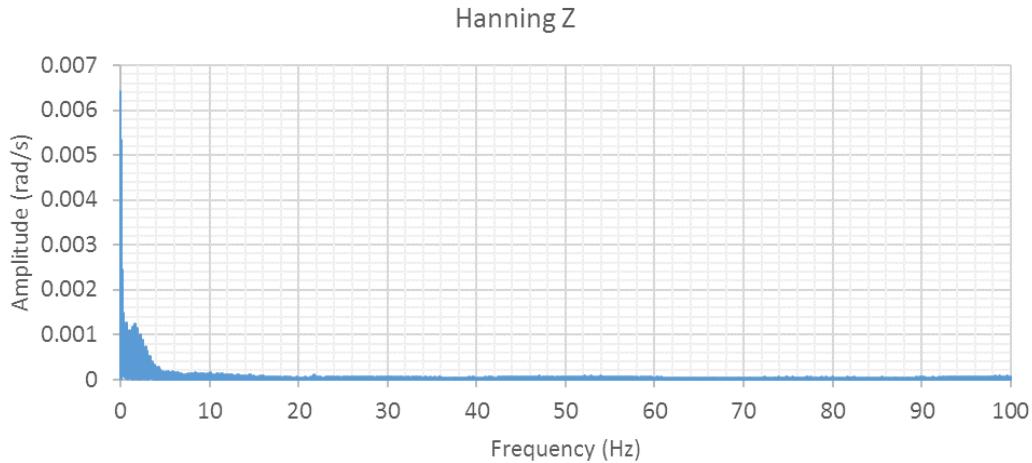


Figure 5-26: Amplitude vs Frequency of the z_{imu} data of Test 2 under the Hanning window

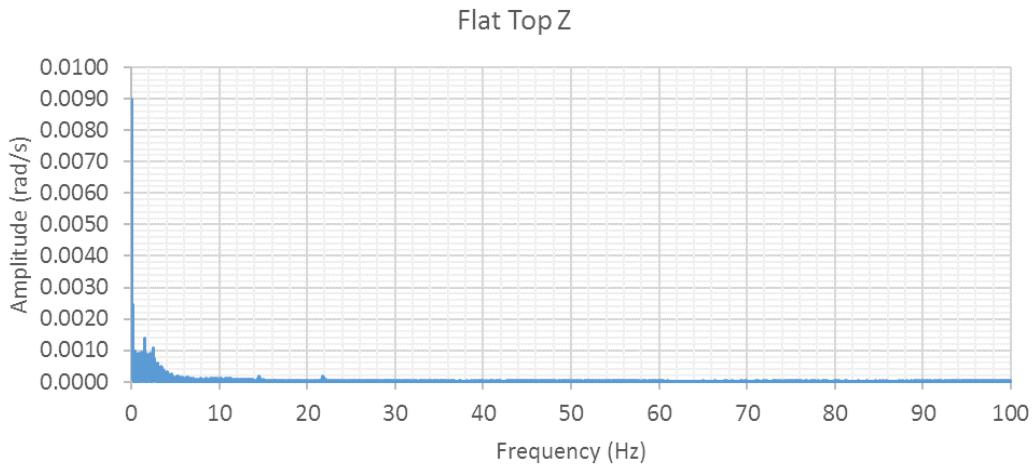


Figure 5-27: Amplitude vs Frequency of the z_{imu} data of Test 2 under the Flat Top window

By comparing the dominant peaks of the amplitude vs. frequency plots for each axis across the eight tests, using the method described above, taking amplitude data from the Flat Top window results and frequency data from the Hanning window results, an estimated representation of the expected base motion peaks could be developed. This signal, representative of the peak data for the vehicle motion, was then added to a Gaussian white noise which was used to achieve an RMS average of the simulated base motion signal which was similar to the tested RMS signals. It should also be noted that the x_{imu} datasets were used to develop the simulated base motion signal for the z_b axis, the y_{imu} datasets for the x_b signal, and the z_{imu} datasets for the y_b signal, in order to account for the axes misalignments shown in Figure 5-20. Table 5-5 below details the RMS values of the base motion test for each axis and shows how the simulated signal compares well.

Table 5-5: Comparison of RMS magnitudes of the base motion tests with the simulated motion signal

	x_{imu} (rad/s)	y_{imu} (rad/s)	z_{imu} (rad/s)
Test 1	0.083	0.063	0.039
Test 2	0.082	0.045	0.048
Test 3	0.120	0.050	0.057
Test 4	0.108	0.056	0.057
Test 5	0.117	0.038	0.062
Test 6	0.111	0.050	0.058
Test 7	0.096	0.033	0.038
Test 8	0.125	0.033	0.037
Ave.	0.105	0.046	0.049
Simulation	0.113	0.044	0.055

Figure 5-28 to Figure 5-30 below show the frequency domain representation of the axes of the simulated base motion signal developed. The peaks, obtained through the careful inspection of the test results, can clearly be seen, as can the low amplitude white noise which operates on all frequencies of the signal. This white noise was added to the peak signal using the MATLAB white Gaussian noise generator function.

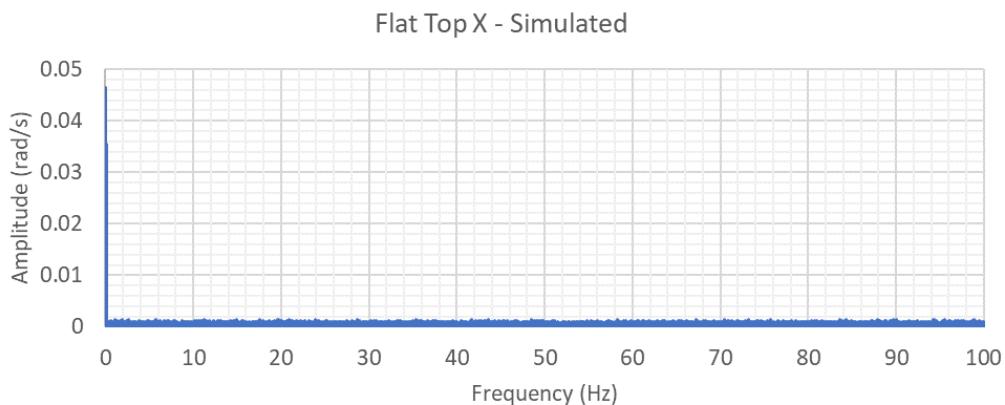


Figure 5-28: Frequency domain representation of the simulated signal x axis

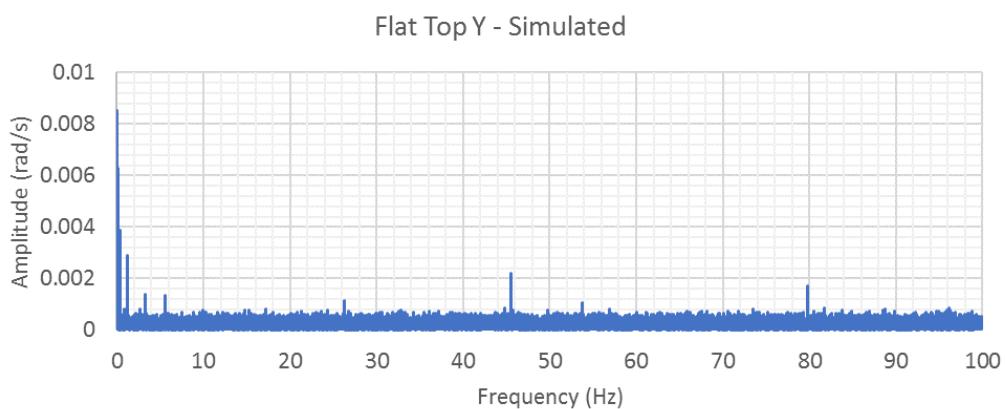


Figure 5-29: Frequency domain representation of the simulated signal y axis

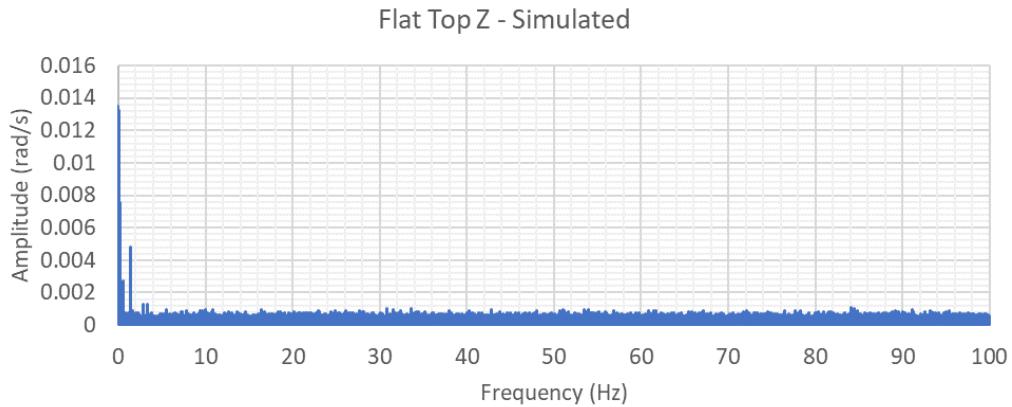


Figure 5-30: Frequency domain representation of the simulated signal z axis

The simulated base motion signal developed above adequately represented the signals measured in the eight tests and was then used in the simulation model as the base motion actuation from which disturbance torques were exerted on the gimbals in the model.

MOTOR SELECTION BY MODELLING AND SIMULATION

This section details the modelling of the ISP system in MATLAB Simulink and the simulations run by which the motor selection process was completed. Note that all definitions not explicitly defined in this section are used according to the definitions and derivations of Section 2.9.

The initial step in modelling the system was the system identification process. This involved breaking the overall system down into parts which could be represented by a dynamic set of equations represented in a block diagram format. For the motor selection process Figure 5-31 represents the highest-level breakdown of the system components required to design and simulate stabilisation and position control loops for the two-axis gimbal system in question.

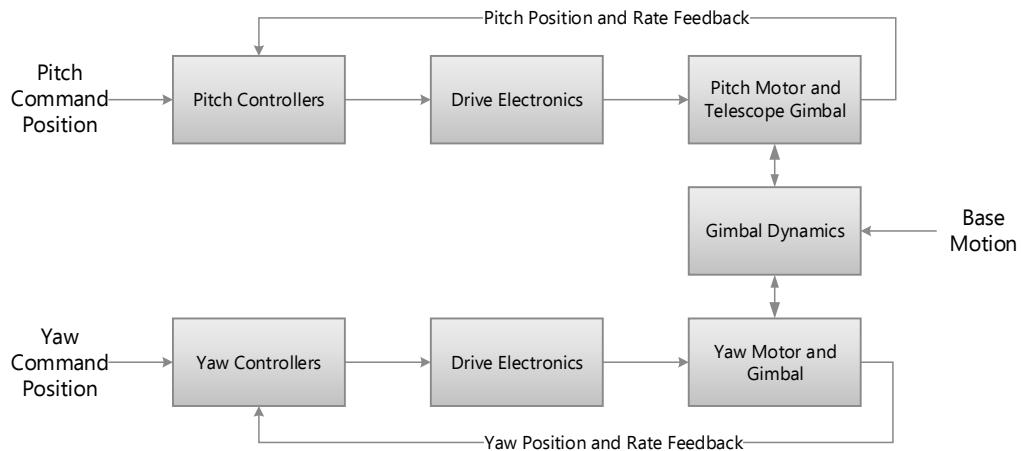


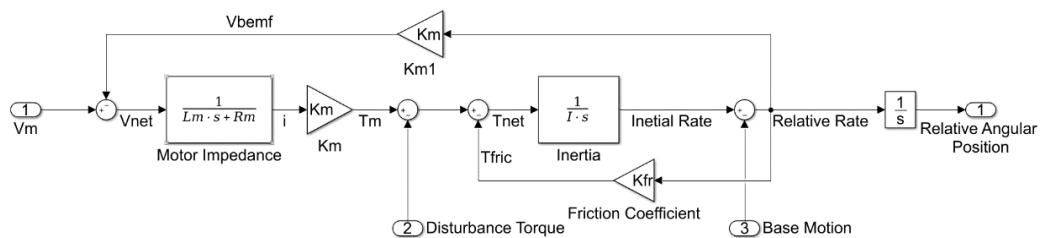
Figure 5-31: System identification diagram for a two-axis gimbal system

The system was broken down into three main blocks for each gimbal channel: A block representing the tracking and stabilisation controllers to be designed, a block representing the

drive electronics and a block representing the motor and inertia of the gimbal being controlled. These channels are interconnected in a manner defined by the system dynamics. It can be noted here that for this rudimentary model, aimed only at informing the motor selection process, the inertial position and rate data feedback to the controllers was modelled as a direct connection, not accounting for any sensor dynamics at this stage.

Motor and Drive Electronics Model

Looking at the motor and gimbal blocks in more detail, the block diagram of how the motors were modelled along with the gimbal inertias they drive and their frictional properties is here presented in detail.



Where, V_m = Motor Voltage, V_{bemf} = Back EMF, V_{net} = Net Voltage, L_m = Motor Inductance, R_m = Motor Resistance, i = Current, K_m = Motor Constant, T_m = Motor Torque, T_{fric} = Motor Friction, T_{net} = Net Torque, I = Rotor Inertia, and K_{fr} = Friction Coefficient.

Figure 5-32: DC Motor block diagram used in the motor selection simulation

For both gimbals, this block diagram was used to model each motor, with the only difference being the inertia terms for each channel: The inertia seen by the pitch motor is that of the telescope modeller about the y_p axis, such that $I = I_{yyp}$, whilst the inertia seen by the yaw motor is that of the yaw gimbal about the z_g axis and the instantaneous inertial value of the telescope modeller about the z_g axis, such that $I = I_{zzg} + I_{zzp} \cos^2 \theta + I_{xxp} \sin^2 \theta$.

As indicated in the block diagram, for this system model, friction was treated as an overly simplistic coefficient of friction, rendering friction to be simply linearly proportional to the relative angular rate between the rotor and stator of the motor. Frictional effects arising from the gimbal mounting mechanisms were also assumed to be negligible at this stage.

The preferred motor choice for the project was the Faulhaber 3257024CR DC motor. This was due to the fact that one of these motors had been used on the second iteration of the single axis stabilised platform and was available for use on this project at no cost. Additional motors were also available for purchase locally in South Africa at a reasonable price. The simulation, therefore, used the specifications for this motor in the model and attempted to validate their potential use on the two-axis platform. Its specifications are given in Table 5-6 below.

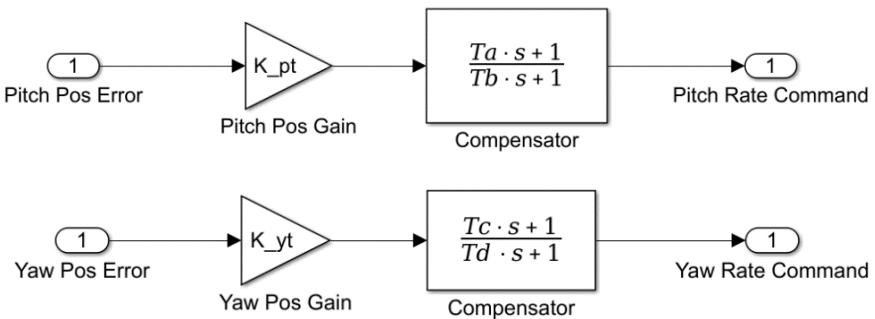
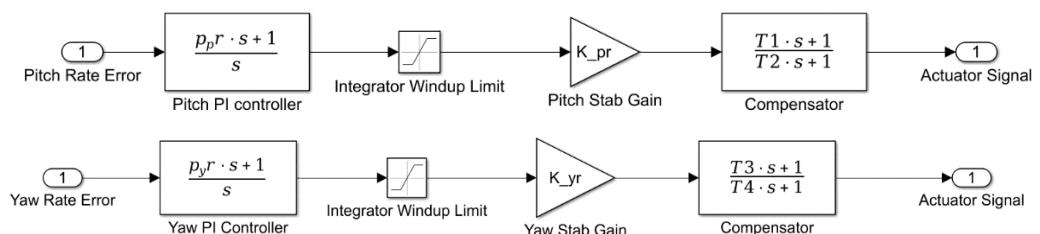
Table 5-6: Faulhaber 3257024CR specifications

V_m	24 V
R_m	1.63 Ω
L_m	270 μH
K_m	37.7 mNm/A
Stall Torque	539 mNm
Rated Torque (Continuous)	71 mNm
Rated Current (Continuous)	2.3 A
Rated Speed (Continuous)	5210 rpm
K_{fr}	0.876 mNm/(rad/s)

The drive electronics at this point were treated simply as a saturation limit on the output of the controller blocks at the amplifier voltage limit.

Controller Design

The controller design made use of a cascade structure as is typically used in classical control designs for ISPs (see Figure 2-7), with a stabilisation loop being driven by a position loop for each gimbal loop. For each channel, a simple P controller with a lag compensator was used for the tracking (or position) loop and a PI controller along with a lag compensator was used for the inner stabilisation loop. Figure 5-33 and Figure 5-34 below show the detailed block diagrams of the position controllers and the stabilisation controllers, respectively, for the simulation.


Figure 5-33: Pitch and Yaw position controllers

Figure 5-34: Pitch and Yaw stabilisation controllers

These controllers were connected in the manner shown in Figure 5-35 below. In both loops position (pos) feedback data is compared to a position command to produce a position error signal upon which the position controller acts. The position controller output is then compared to the rate feedback to produce a rate error signal upon which the stabilisation controller acts to produce the motor actuation signal.

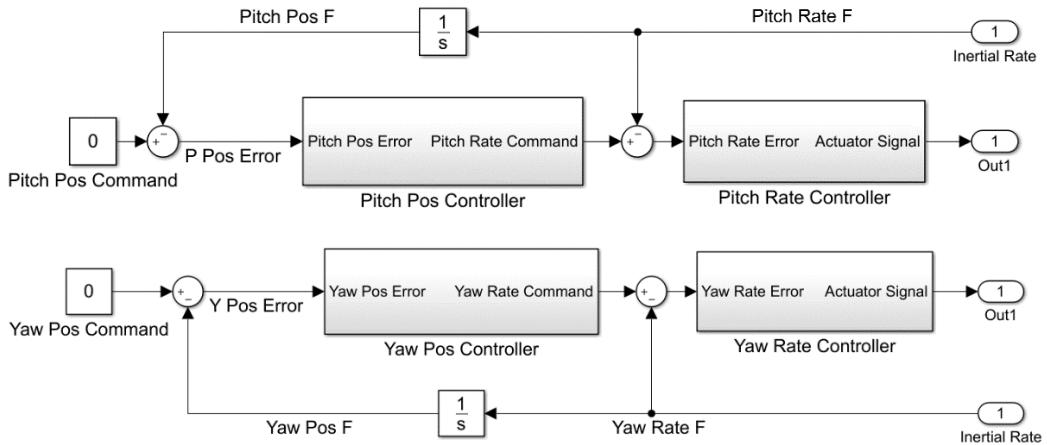


Figure 5-35: Controller structure for the Yaw and Pitch channels

Gimbal Dynamics

The gimbal dynamics block defines how the motion of the gimbals dynamically affect each other and how the base motions affect the motion of each gimbal. These relationships are derived in Section 2.9.2. The Laplace block diagram presented in Figure 5-36 overleaf represents these relationships.

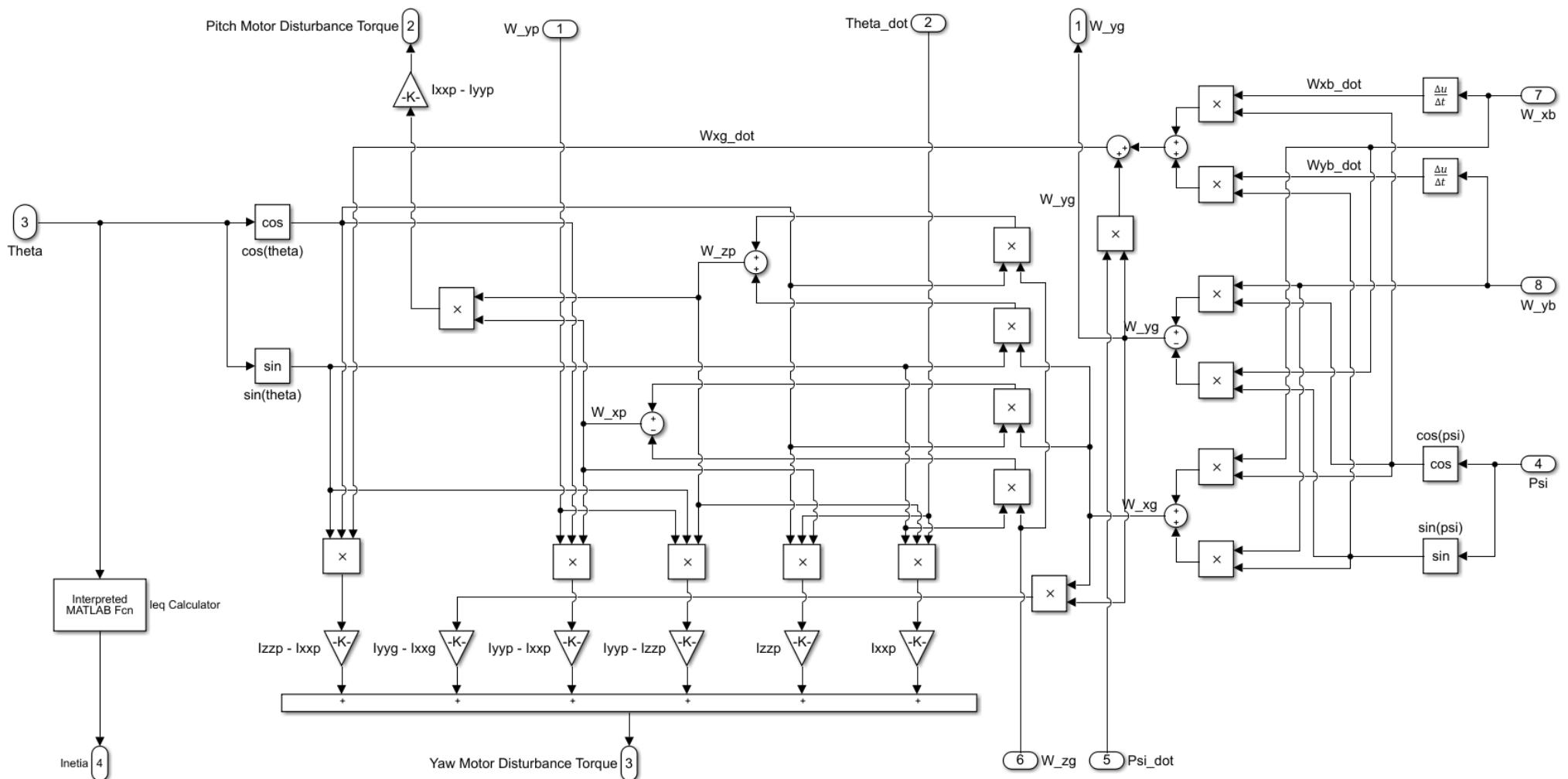


Figure 5-36: Gimbal dynamics block diagram

Simulation Model

The sub-system models described above were then connected form the complete simulation block diagram as shown in Figure 5-37 overleaf. The simulation was run as an analogue model with no sampled components. As such, it was an overly idealistic model but was sufficient for the choice of motors to be made before detailed design had been completed. Table 5-6 above and Table 5-7 below details the parameters used in the motor selection simulation. The inertial properties used below were the most accurate parameters available for use in the simulation prior to the completion of the mechanical design after component selection had been completed.

Table 5-7: Motor selection simulation parameters

I_{xg}	0.02612 kgm^2
I_{yg}	0.01579 kgm^2
I_{zzg}	0.01195 kgm^2
I_{xop}	0.00486 kgm^2
I_{ypy}	0.01570 kgm^2
I_{zpz}	0.01591 kgm^2
K_{pt}	50
K_{yt}	80
T_a	0
T_b	$\frac{1}{2\pi 30}$ s
T_c	0
T_d	$\frac{1}{2\pi 30}$ s
K_{pr}	2500
K_{yr}	2900
p_{pr}	$\frac{1}{2\pi 0.5}$ s
p_{yr}	$\frac{1}{2\pi 0.5}$ s
T_1	0
T_2	$\frac{1}{2\pi 200}$ s
T_3	0
T_4	$\frac{1}{2\pi 200}$ s
Integrator Windup Limit	$\frac{1.5V_m}{K_{pr}}$
Pitch Amp Limit	V_m
Yaw Amp Limit	V_m

The signals ω_{xb} , ω_{yb} , and ω_{zb} shown the block diagram below represent the simulated base motion signals shown in Figure 5-30 of the previous section.

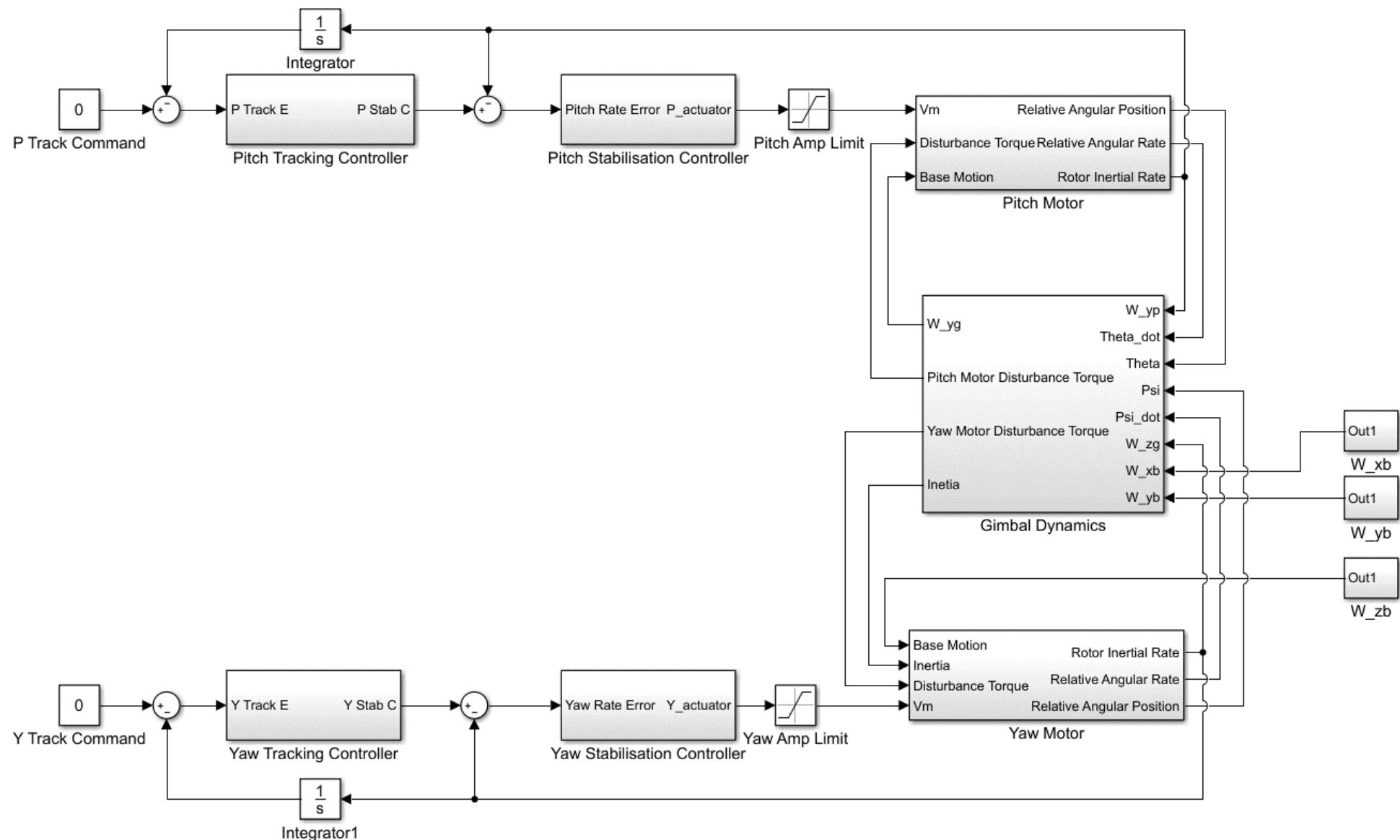


Figure 5-37: Motor selection Simulink block diagram

The Bode design technique was used to design and evaluate the stability of the system under linear and saturated operating conditions for the designed controllers. The aim in developing these controllers simply to design stable controllers which could facilitate a simulation of the expected motor torques. In the Bode plots that follow, linear and saturated curves are shown together for given control loops. Classical control design in the frequency domain implicitly assumes the linearity of the modelled system, however, in the system above, certain elements, such as the integrator windup limits on the PI stabilisation controllers and the amplifier limits, exhibit non-linear behaviour for input conditions beyond defined limits. The system, therefore, is linear within certain operating regions and non-linear at others. During these non-linear conditions a linear approximation of the system may be made about a certain operating point and valid approximated results be drawn for conditions close to this point. Figure 5-38 illustrates the approximate equivalence of a linearisation of a non-linear transfer function for a small region about a given operating point.

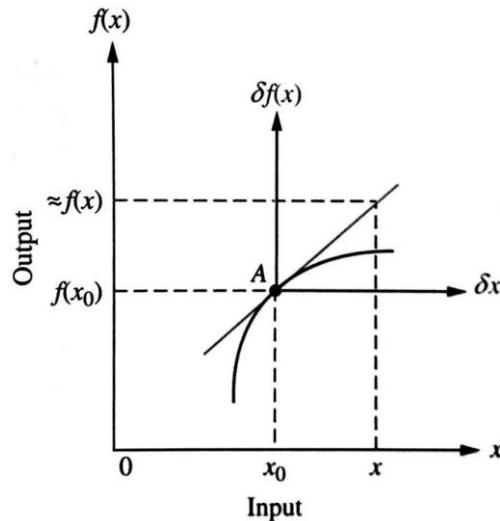


Figure 5-38: Linear approximation of a non-linear curve about point A [94]

Saturated loop responses shown in the plots below, therefore, represent the output of the relevant transfer function only at the operating point for which the plot was generated. Changes in either frequency or amplitude of input function would therefore alter the profile of the saturated response. Accordingly, input signal conditions were chosen to be representative of the expected operating environment of the ISP system.

Yaw Rate Loop Responses: Yaw Rate Command to Yaw Rate F

Figure 5-39 and Figure 5-40 below show the linear and saturated, open and closed loop responses of the yaw stabilisation control loop.

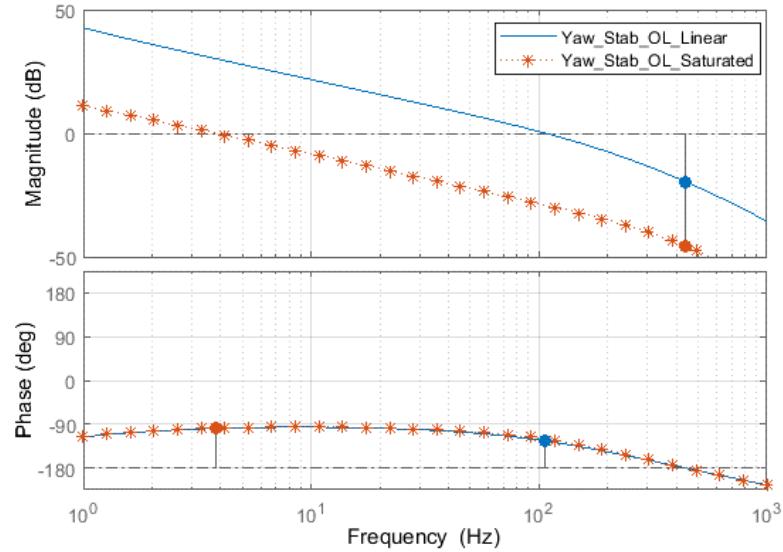


Figure 5-39: Motor selection simulation - Yaw rate open-loop bode plot

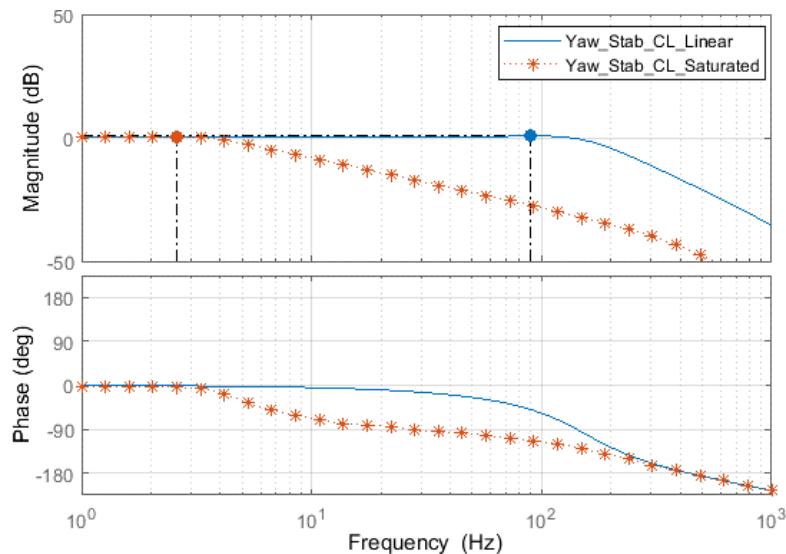


Figure 5-40: Motor selection simulation - Yaw rate closed-loop bode plot

Figure 5-41 below shows the setpoint tracking response of the yaw stabilisation loop in response to a 1.0 rad/s step input.

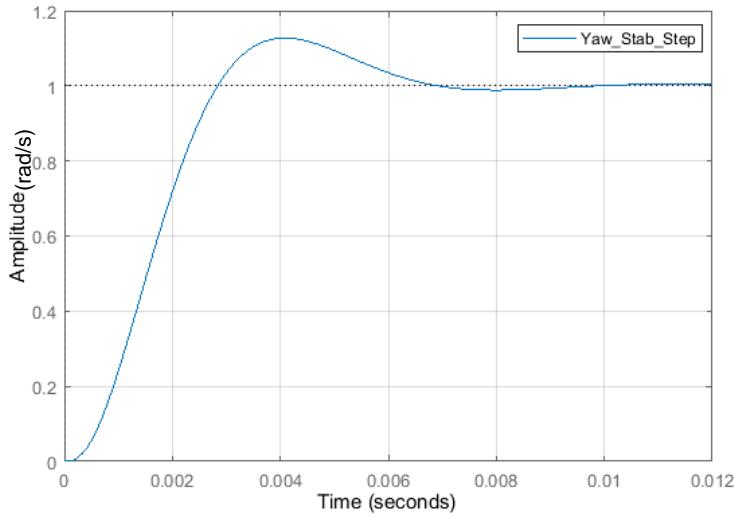


Figure 5-41: Motor selection simulation - Yaw rate step following

The saturated response curves in the plots above were produced using the Frequency Response Estimation tool in Simulink with a varying frequency sine signal of amplitude 2 rad/s, whilst the linear curves were produced using the Linear Analysis tool in Simulink. The yaw rate loop designed above was stable and had the following properties.

Table 5-8: Motor selection simulation - Yaw rate loop properties

Gain Margin	15.9 dB (min)
Phase Margin	44.5 ° (min)
Resonance Peak	2.42 dB (max)
Linear Bandwidth	254 Hz

Pitch Rate Loop Responses: Pitch Rate Command to Pitch Rate F

Figure 5-42 and Figure 5-43 show the open and closed loop responses of the pitch rate loop.

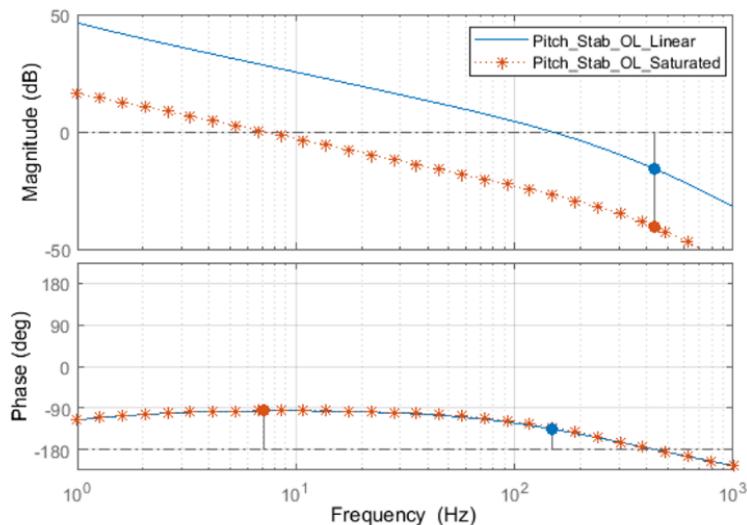


Figure 5-42: Motor selection simulation - Pitch rate open-loop bode plot

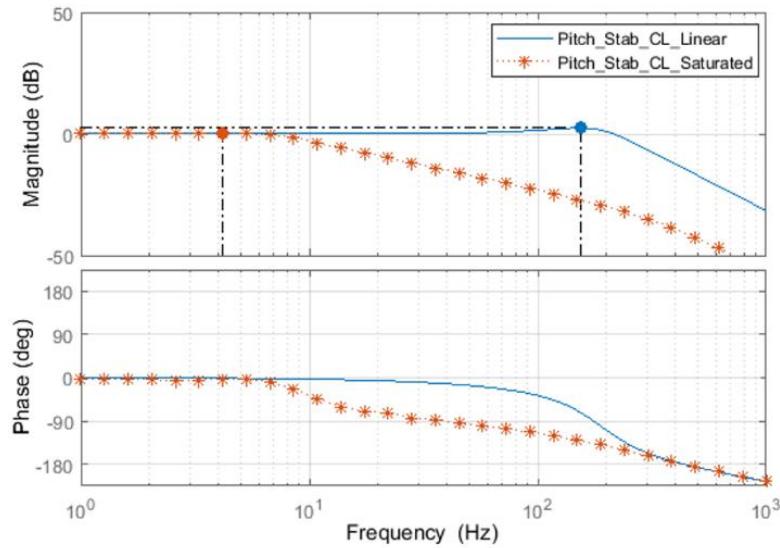
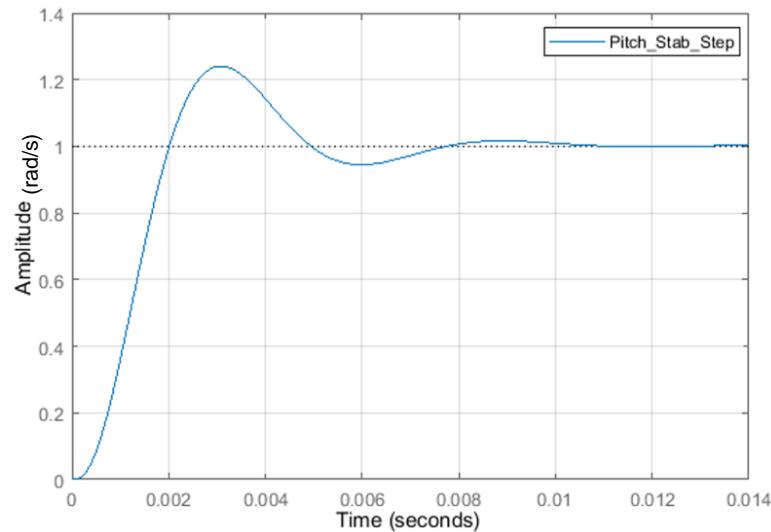
**Figure 5-43: Motor selection simulation - Pitch rate closed-loop bode plot**

Figure 5-44 below shows the setpoint tracking response of the pitch stabilisation loop in response to a 1.0 rad/s step input.

**Figure 5-44: Motor selection simulation - Pitch rate step following**

The same tools and input signals were used to determine the pitch rate loop responses as were used for the yaw rate loop. The pitch rate loop's properties are shown below.

Table 5-9: Motor selection simulation - Pitch rate loop properties

Gain Margin	19.5 dB (min)
Phase Margin	55.3 ° (min)
Resonance Peak	0.7 dB (max)
Linear Bandwidth	184 Hz

Once the stabilisation loops had been designed such that they were stable, the position loops which drive the rate loops were designed. These facilitated the control of the telescope modeller's orientation in the simulation. The same tools were used as in the stabilisation loops to evaluate the controllers under linear and saturated conditions, however, a 1 rad amplitude sine signal of varying frequency was used to determine the saturated responses of the position loops.

Yaw Position Loop Responses: Yaw Pos C to Yaw Pos F

Figure 5-45 and Figure 5-46 below show the linear and saturated, open and closed loop responses of the yaw position control loop.

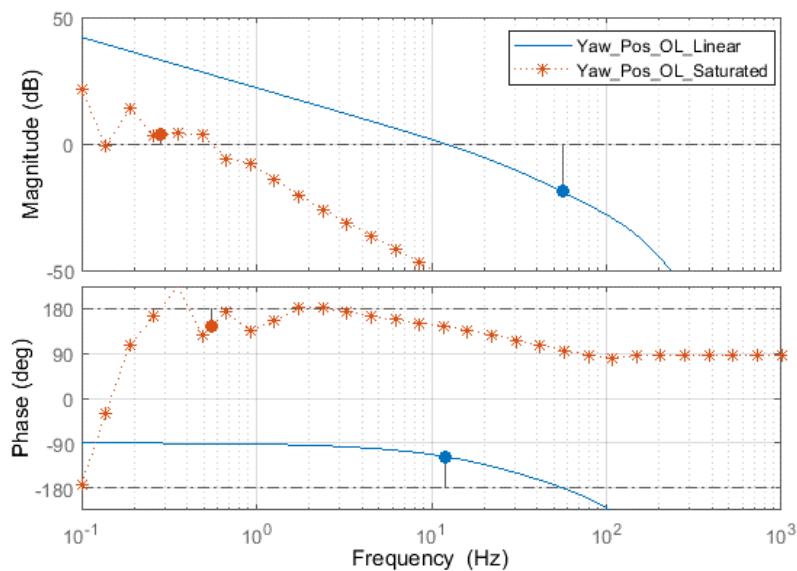


Figure 5-45: Motor selection simulation - Yaw position open-loop bode plot

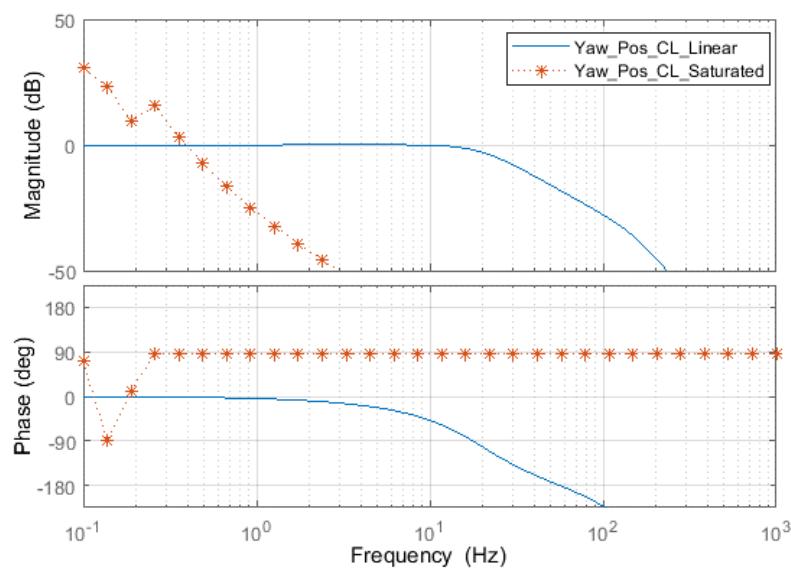


Figure 5-46: Motor selection simulation - Yaw position closed-loop bode plot

Figure 5-47 below shows the setpoint tracking response of the pitch stabilisation loop in response to a 1.0 rad step input.

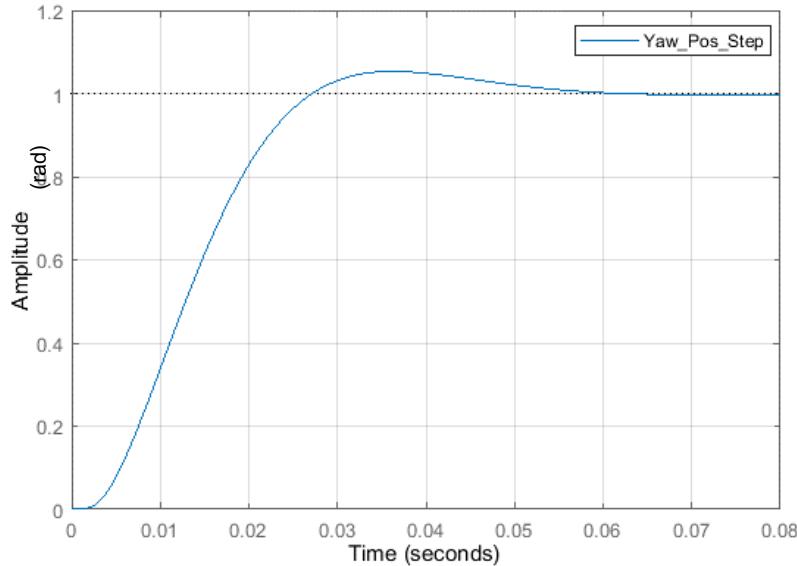


Figure 5-47: Motor selection simulation - Yaw position step following

The yaw position loop is clearly stable under linear conditions. However, the saturated response is less clear; the curves of both the open-loop and closed-loop Bode plots are unusual in shape and do not provide useful information as to the loop's stability. The step response, however, indicates a stable loop under a step command equal in magnitude to the amplitude of the sine signal used to test the saturated conditions. The linear properties of this loop are given below.

Table 5-10: Motor selection simulation - Yaw position loop properties

Gain Margin	19 dB
Phase Margin	62.7 °
Resonance Peak	-
Linear Bandwidth	20 Hz

Pitch Position Loop Responses: Pitch Pos C to Pitch Pos F

Figure 5-48 and Figure 5-49 below show the linear and saturated, open and closed loop responses of the pitch position control loop.

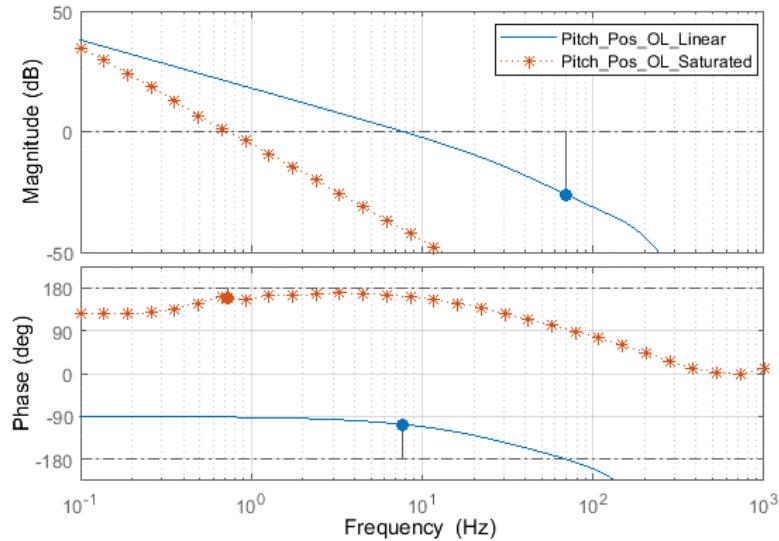


Figure 5-48: Motor selection simulation - Pitch position open-loop bode plot

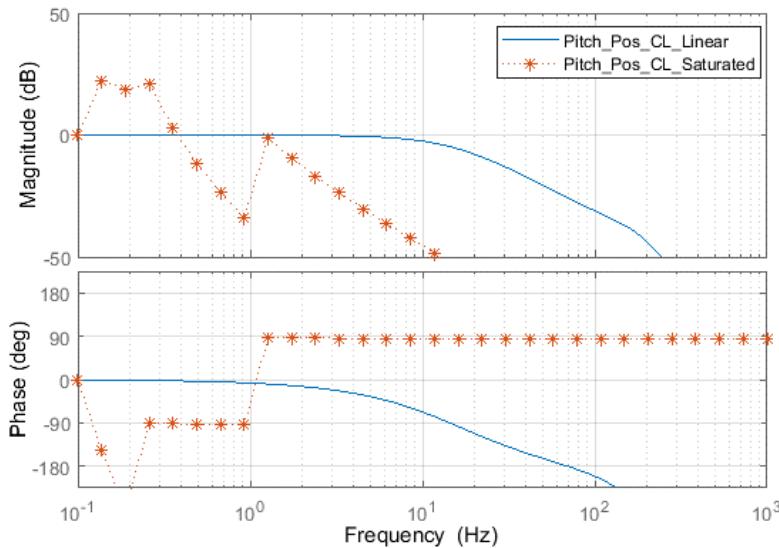
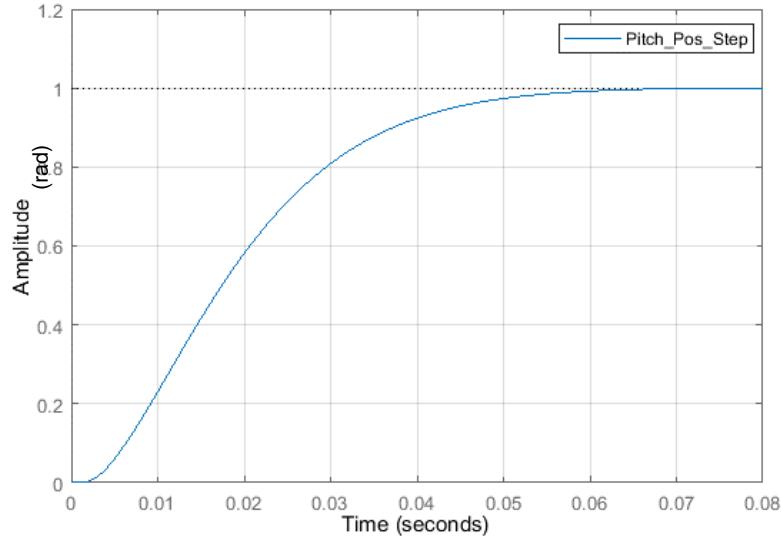


Figure 5-49: Motor selection simulation - Pitch position closed-loop bode plot

Figure 5-50 below shows the setpoint tracking response of the pitch stabilisation loop in response to a 1.0 rad step input.

**Figure 5-50: Motor selection simulation - Pitch position step following**

In a similar way as for the position loop for the yaw channel, the linear response clearly showed loop stability but the saturated response to the bode plots was unclear. Again, however, the step response indicated that the loop was, in fact, stable under step commands equal in magnitude to the sine actuation signal of the bode plot. The properties of the loop under linear conditions are once again highlighted below.

Table 5-11: Motor selection simulation - Pitch position loop properties

Gain Margin	26.1 dB
Phase Margin	73.2 °
Resonance Peak	-
Linear Bandwidth	11.2 Hz

Torque Results and Motor Verification

By running the simulation model above with the gimbals oriented in various inertial configurations whilst under the influence of the simulated base motion signal, it was possible to estimate the torque required from each motor to maintain stabilisation of the telescope modeller. Testing the various configurations showed that the worst-case orientation of the system was at when the yaw position command was at -45° , and the pitch position command was at 45° . The results to follow show the motor torques required for stabilisation under the base motion signal shown in Figure 5-51 below. Tests results are from the ‘home’ position where $\psi = \theta = 0^\circ$, and the worst-case position where the motor torques required for stabilisation were greatest at $\psi = -45^\circ, \theta = 45^\circ$.

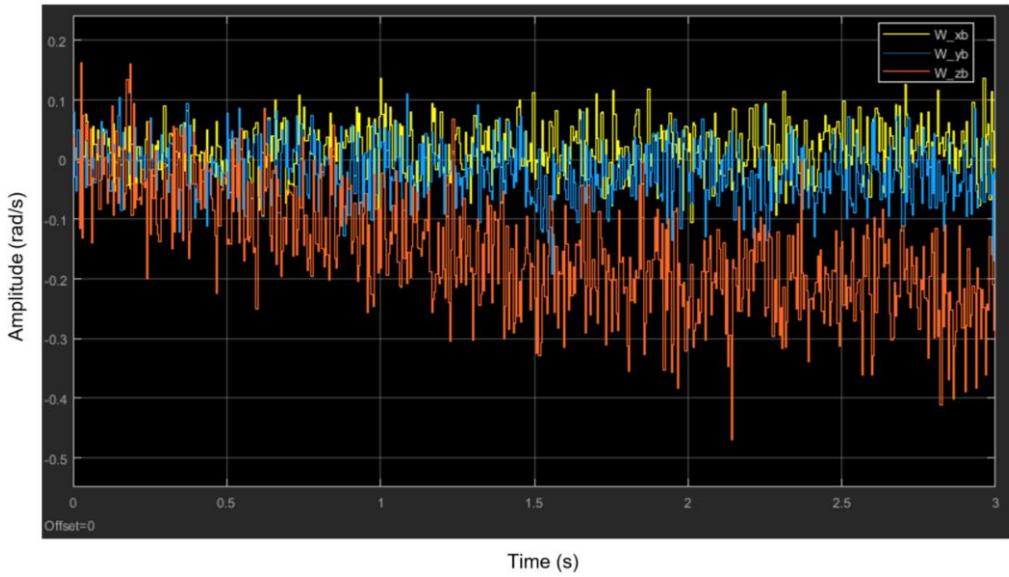


Figure 5-51: Simulated base motion signal

$$\psi = \theta = 0^\circ:$$

Figure 5-52 below shows the setpoint tracking response of the yaw and pitch tracking controllers under the influence of the simulated base motion signal above. Both command signals are set to zero to model the ISP in the home position.

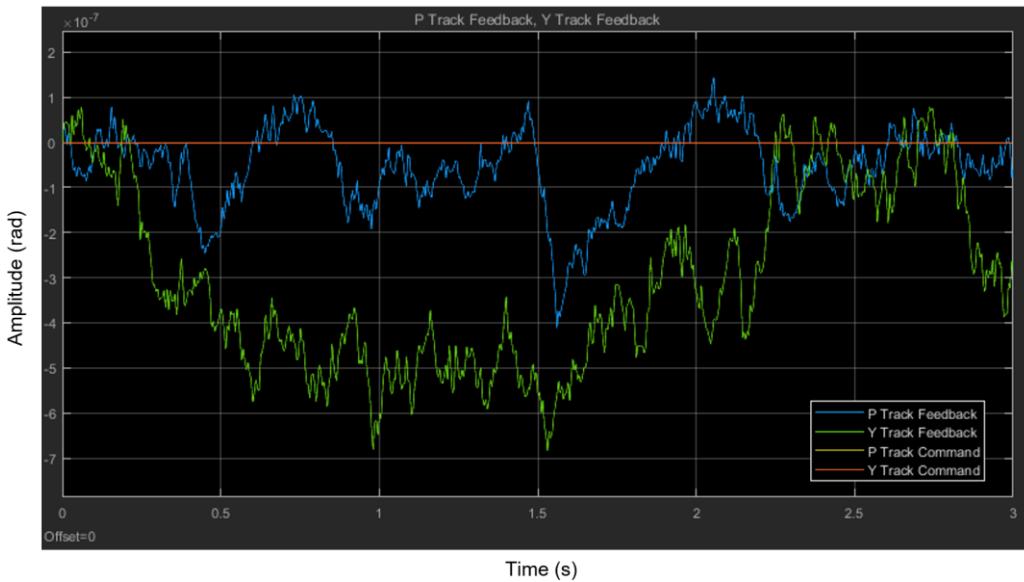


Figure 5-52: Home orientation position command following

In the figure above, the P Track Command signal has the same value, and is hidden by the Y Track Command signal. Concurrently, the inertial rates about the y_p and z_p axes are given by Figure 5-53 below.

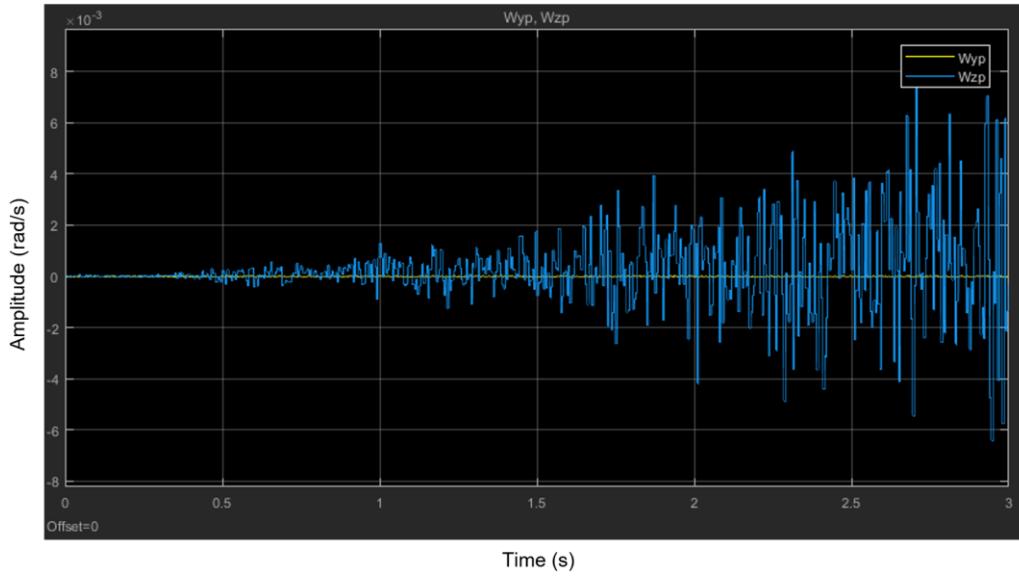
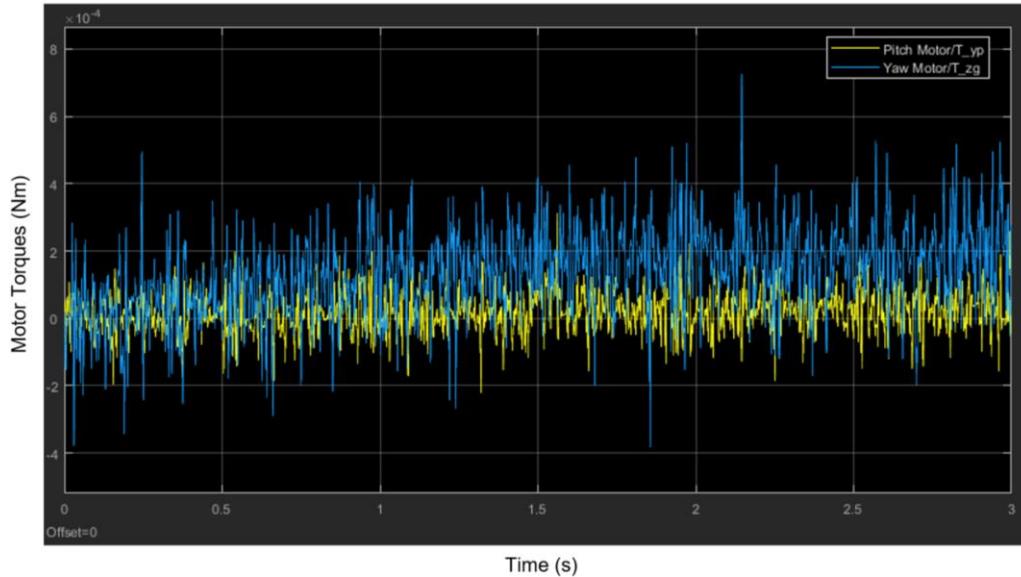
**Figure 5-53: Inertial rates of the telescope for the home position**

Figure 5-54 below shows the torques exerted by the pitch and the yaw motors as the controllers drive them to attenuate the base motion disturbance applied.

**Figure 5-54: Motor torques for the home position**

The controllers can be seen to be operating as expected in the result above where the position feedback signals do not deviate from the zero by more than approximately $7e^{-7}$ rad in response to the simulated base motion signal. The RMS torque for the pitch motor in the simulation was 0.051 mNm with a peak torque of approximately 0.18 mNm, whilst the yaw motor had an RMS torque of 0.18 mNm and a peak of 0.53 mNm.

$\psi = -45^\circ, \theta = 45^\circ$:

Figure 5-55 below shows the position command following properties of the system when the gimbals are oriented such that $\psi = -45^\circ$ and $\theta = 45^\circ$, whilst under the influence of the simulated base motion signal.

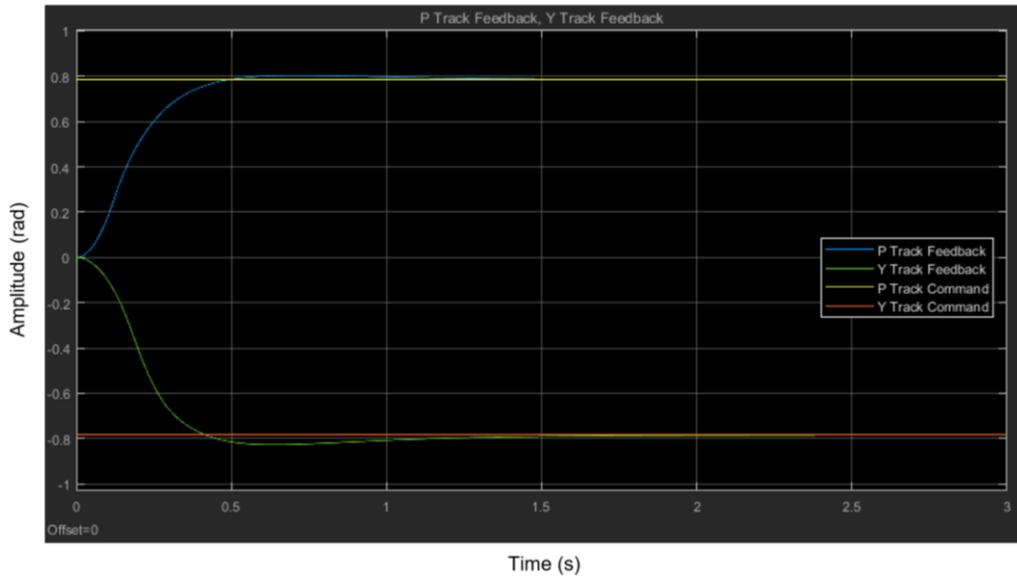


Figure 5-55: Position command following for the worst-case position

Concurrently, the inertial rates about the y_p and z_p axes are given by Figure 5-56 below.

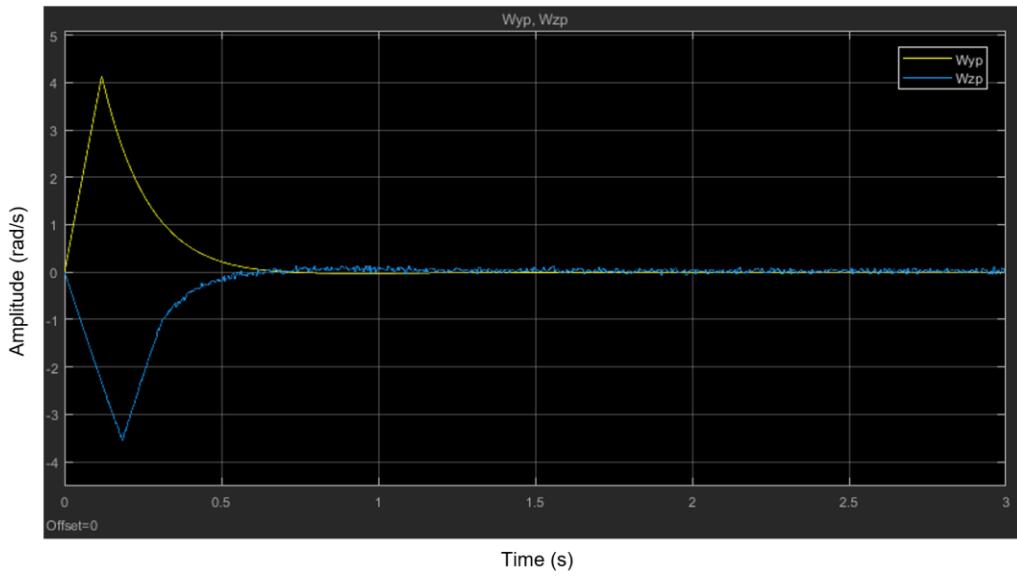


Figure 5-56: Inertial rates of the telescope in the worst-case position

Figure 5-57 below shows the motor torques required for to achieve the stabilisation and tracking responses above.

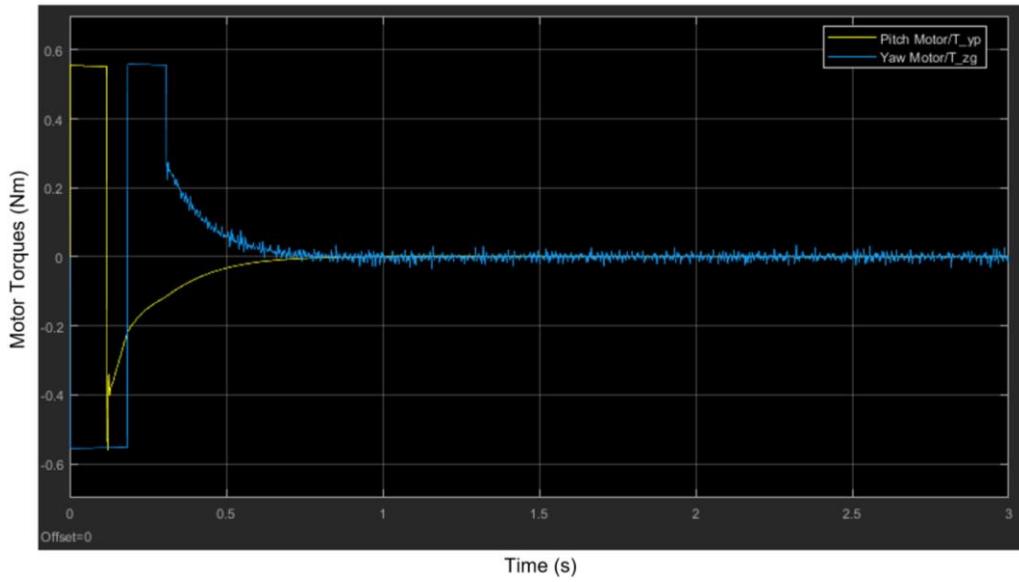


Figure 5-57: Motor Torques for the worst-case position

It can be seen in the figure above that the pitch and the yaw motors saturate on receipt of the step commands causing them to accelerate at their maximum rates. As the tracking feedback on both controllers approach the setpoint, the torques exerted by the motors are reduced. Once the gimbals are at the worst-case position, the RMS torque for each motor was determined considering only the data from the last second of the above simulation. Here, the motor torques required are small with an RMS torque for the pitch motor of 0.065 mNm and 2.5 mNm for the yaw motor being exerted once the gimbals had reached their target inertial positions and the system was simply attenuating the base motion disturbances.

In the orientations tested, the torques exerted in the simulation were well below the specifications of the Faulhaber 3257024CR motor which are rated for a continuous torque of 71 mNm and have a stall torque of 539 mNm. Due to their sufficient torque capacities and their availability for use, Faulhaber 3257024CR DC motors were chosen to be used as the actuators for both gimbals on the two-axis platform to be developed.

5.2.5 DRIVE ELECTRONICS (12.1)

The choice of Faulhaber 3257024CR DC motors for use as the gimbal actuators for the system drove the choice of drive electronics. A motor driver module capable of providing a continuous current of 2.3 A at 24 V was required to ensure the motors could be used to their full capacity. Several different implementations of drive electronics were used in the project as development and testing progressed. Initial testing of gimbal positioning and tracking/stabilisation control was begun using low voltages between 6 and 9 V, far from the 24 V limit of the motors chosen. As the speed of an ungeared DC motor is directly proportional to the voltage applied to its terminals, these low voltages facilitated testing of the systems at low rotational rate limits whilst control firmware was in its infancy and likely to encounter errors. Accordingly, lower cost drive electronics rated for lower voltages and

currents could, therefore, be used in these initial testing phases. The two main implementations of the drive electronics used at various stages of development are here shown. All implementations were driven by a Pulse-Width Modulation (PWM) signal used to provide rate command, and a signal used to provide direction commands.

The first implementation of the drive electronics hardware made use of the **L298 dual H-bridge** shown below.

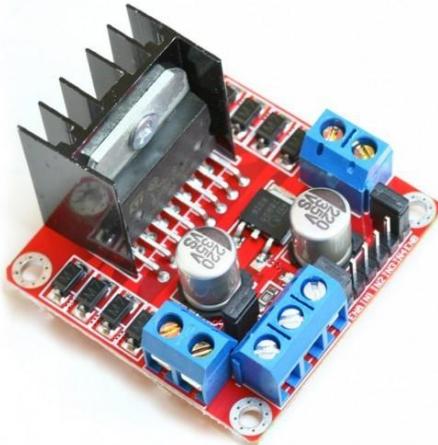


Figure 5-58: L298 Dual Full Bridge Driver [95]

This module was rated for a current of 2 A (continuous) per channel at 7 - 24 V [95]. It was suited for low voltage testing of the system as it was available for a low-cost of R165.00. However, the L298 IC was only rated for a maximum power dissipation of 25 W. As a maximum of 48 W could conceivably be required from the module if the motors were driven at their full capacity, the module was not suitable for final implementation on the system.

Ultimately the **Quimat Dual Motor Driver Board** shown below was chosen to be used as the drive electronics module for the project. The module above was capable of driving two motors with a 15 A (continuous) at a maximum of 36 V and was therefore suitable to drive the motors at their full rating if required. Additionally, the module makes use of MOSFET transistors rather than the BJT type transistors used in the L298 module. This results in better switching noise performance and lower losses. This module accepts PWM signals for 0-99 % duty cycles, and so firmware written to drive the motors required a minor adjustment to limit the maximum duty cycle to 99 % when this board was used.



Figure 5-59: Quimat Dual Motor Driver [96]

5.2.6 CONTROL HARDWARE (I3 - HARDWARE)

Various factors influenced the choice of hardware that was used to achieve the control operations of the ISP system developed. The system specifications introduced the following constraints on the control hardware chosen:

- S₃ and S₄ defined maximum allowable dimensions and mass for the system, therefore control hardware was required to be small and light.
- S₆ defined a maximum allowable on the jitter of the LOS implying that the control hardware needed to be capable of processing system data and applying corrective control actions fast enough to prevent angular rate disturbances from moving the LOS further than the allowable tolerance.
- S₁₂ defined a minimum battery runtime for the system introducing a lower power consumption requirement to the decision of choice of control hardware.
- S₁₃ specified that the system should be controlled using a computer program so that operation could be achieved in a safe, user-friendly manner and allow data logging of relevant runtime data gathered during the operation of the system.
- Finally, S₁₄ defined the maximum budget for the project placing a cost limitation on the control hardware used.

In addition to the influence of the system specifications on the choice of control hardware, the choice of certain electronic components also placed constraints on the decision:

- The choice to use the Raspberry Pi Camera as the imaging sensor was coupled with the decision to use the Raspberry Pi computer to accomplish the target tracking requirements of the project.
- The need to facilitate and manage comms between multiple devices and sensors and to perform control actions at a fixed sampling rate based on the data provided by those comms meant that the Raspberry Pi computer chosen could not facilitate all the control tasks of the project: Raspberry Pis are not suited to precise, fixed sampling rate operations at high frequencies, therefore a microcontroller capable of handling all time-critical, fixed frequency control and communication tasks was required.

The factors described above influenced the choice of control hardware used in the development of the ISP system of this project. The sub-sections to follow describe the hardware chosen for use.

LABVIEW USER INTERFACE (I3.1)

It was decided to make use of the LabVIEW development environment to write a user interface for the high-level control and the data-logging needs of the ISP developed. LabVIEW is a graphical programming environment suited to the development of user

interfaces for various control tasks. Programs are written by connecting various blocks, having specific functions, in a configuration which accomplishes the desired operation. LabVIEW VIs may be run on any computer which has the correct version of LabVIEW and appropriate device drivers installed. A Windows laptop was used in this project to run the UI (detailed in Section 7.4) which communicated with the other control hardware chosen in the sub-sections to follow.

RASPBERRY PI 3 MODEL B (13.2)

As indicated earlier, the decision to use the Raspberry Pi Camera as the imaging sensor for the project caused the decision to use a Raspberry Pi computing module to achieve the image processing tasks required to implement the target tracker of the system. All versions of the Raspberry Pi computers are compatible with the Raspberry Pi Camera except for the Industrial Compute Module range. The Raspberry Pi 3 Model B (henceforward called the RPi), shown below, was chosen to be used as it has a quad-core 1.2 GHz 64-bit CPU, 1 GB of RAM, and a dual-core GPU [97]. It was therefore expected to offer sufficient image processing performance for the project.

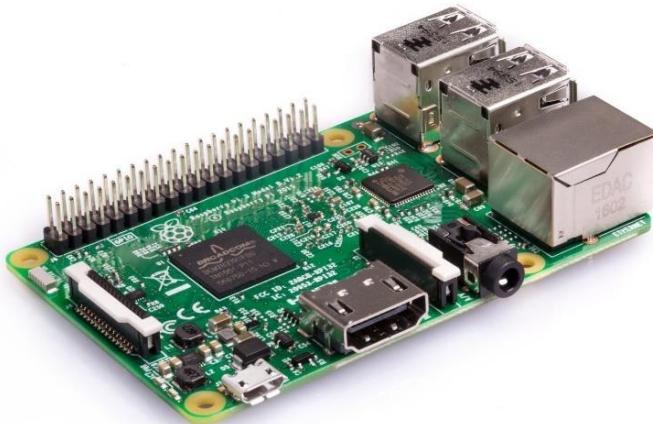


Figure 5-60: Raspberry Pi 3 Model B [98]

In addition to the performance specifications indicated above, the RPi is small and light measuring only 85x56x19 mm and is suited to provide onboard image processing for the overall system without taking up excessive space. The RPi may be powered through a Micro USB input or by a 5 V supply to the GPIO header and runs on a 3.3 V logic level. The RPi supports a variety of operating systems but is most commonly run using Raspbian, a lightweight version of Linux. This enables the RPi to be run using a familiar GUI operating system if user-friendly operations using a display, mouse and keyboard are required. Additionally, the RPi may be operated through the Linux terminal if GUI operations are not required. A diverse range of applications is possible for the RPi as programs which make use of the 40 GPIO pins and other peripherals available may be written in several different languages. These programs may be configured to run on startup, therefore, facilitating the RPi's use in embedded applications if user interaction through a GUI or terminal is not required.

STM32F051 MICROCONTROLLER (I3.3 & I3.4)

In order to effectively achieve control operations in a controlled, designed manner, it was required that they are performed by a system capable of running the controller algorithms for the tracking and stabilisation loops at a precise, fixed sampling rate at a high frequency. As the RPi system is not suited to achieving this requirement it was decided to make use of a microcontroller to handle all fixed sampling rate operations and sensor comms excluding the imaging operations.

It was decided that the STMicroelectronics STM32F051 MCU would be used to accomplish these tasks. The STM32F051 is a mid-range, 32-bit MCU within the STM32 family. It features a 48 MHz ARM Cortex M0 CPU, 32 kB of flash storage, 8 kB of RAM and 33 configurable GPIO pins (48 pins in total). The MCU's peripherals of interest to this project include a 16 channel 12-bit ADC, two I²C interfaces, two USARTs, and seven 16 or 32-bit timers capable of PWM and various other counting functions. The board is powered by a USB-B port or via a 5 V rail and runs on a 3.3 V logic level. The development board shown below was designed at UCT and includes the STM32F051 MCU, an ST-LINK V2 debugger, an LCD display, and comms outputs in the form of a USB-B port and an RS-232 output via a D-Sub 9 port.



Figure 5-61: STM32F051 Microcontroller Board

The board was available for use at no cost from UCT and had specifications which were expected to be sufficient for the requirements of this project. Additionally, as the programming specifics of the board had already been learnt and firmware already written to communicate with the MPU-9150 IMU for a previous part of the project (see section on “Experimental Determination of Vehicular Base Motions” in Section 5.2.4), no additional technical familiarisation with the board would be required before firmware development for the ISP could begin. For these reasons, the board was chosen for use. A disadvantage of using the board, however, was its lack of floating-point unit (FPU). These modules facilitate the efficient handling of floating-point mathematical operations externally to the CPU thereby speeding up program execution times. As floating-point operations were expected to be required in the running of the controller algorithms, this presented a potential problem with

using the STM32F051. However, The STM32Fo forms part of a wide range of STM32Fx MCUs which share a common architecture, some of which incorporate floating-point units. This range of MCUs may be programmed in a hardware abstraction layer common to the devices in the range which ensures majority code compatibility between MCUs and facilitates the swift upgrading of MCU if improved performance is required. It was therefore decided to continue with the STM32Fo as the project developed and to only switch to a higher range MCU if increased performance from an FPU was required.

5.2.7 POWER SOURCE (15)

It was decided to use a DC power supply to provide power for the motors of the ISP system for all development and testing. However, two 12 V batteries in series were used to test the system in an outdoor, moon-tracking test detailed in Section 8. The results of this test verified the performance of the system against system specification S12. The RPi is powered by an independent 5 V external power supply, whilst the MCU is powered by a USB port on the laptop running the UI software.

5.3 CONTROL ARCHITECTURE DESIGN

This section describes the architecture design of the control hardware of the ISP system developed. The overall control structure is here presented along with the schematic circuit diagrams which describe the configuration of the electrical systems of this project.

5.3.1 CONTROL HARDWARE CONFIGURATION

The control hardware described above was chosen because it was expected that they would be capable of fulfilling (or contributing to the fulfilment of) Specifications S3, S4, S6, and S12 - S14. The hardware was configured as described in the block diagram shown in Figure 5-62 below.

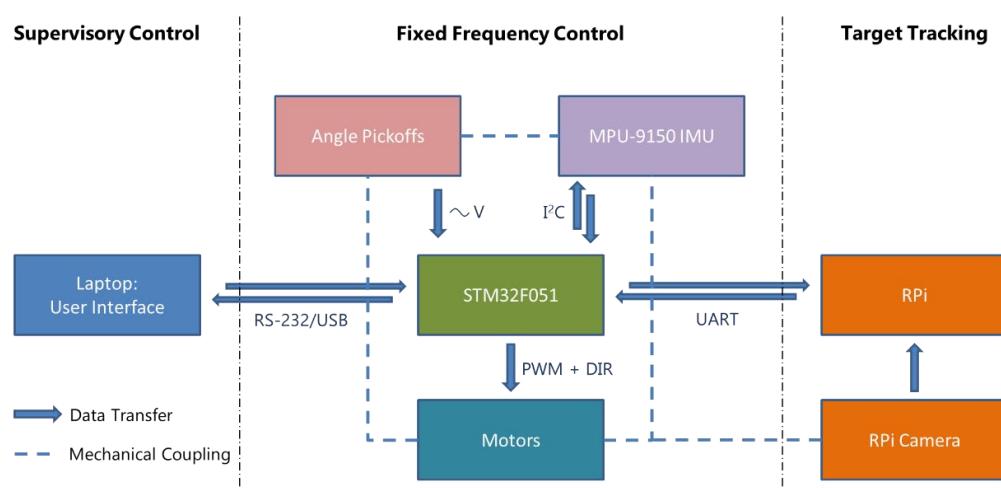


Figure 5-62: Control hardware configuration

A three-part control scheme was decided upon, with control operations being broken down into supervisory control, fixed frequency control, and target tracking control tasks. The LabVIEW UI facilitates supervisory control operations such as system start/stop, switching between manual gimbal positioning and automatic tracking and stabilising modes, as well as performing data logging tasks. It communicates with the STM32F051 MCU via a bi-directional serial interface over either an RS-232 or USB interface at a baud rate of 115200 bps. The MCU is tasked with reading the angle pickoffs, communicating with the MPU-9150 IMU over an I²C interface, managing comms with the RPi which sends target position (pixel position) data to the MCU via a direct pin-to-pin UART connection when the MCU initiates a target data request, and running the control loops, which produce the actuation signals for the yaw and pitch motors which are each controlled using a PWM (speed) and direction signal. Additionally, the MCU is tasked with sending the system runtime data to the UI for data logging. The RPi is tasked with processing the image produced by the RPi Camera to determine the pixel position of the target centroid, which is then sent to the MCU when the MCU initiates the data request.

ELECTRICAL SCHEMATICS

Figure 5-63 overleaf provides a reference for the electrical connections discussed in the subsections to follow and shows the electrical schematic of the overall system.

Systems Development of a Two-Axis Stabilised Platform to Facilitate Astronomical Observations

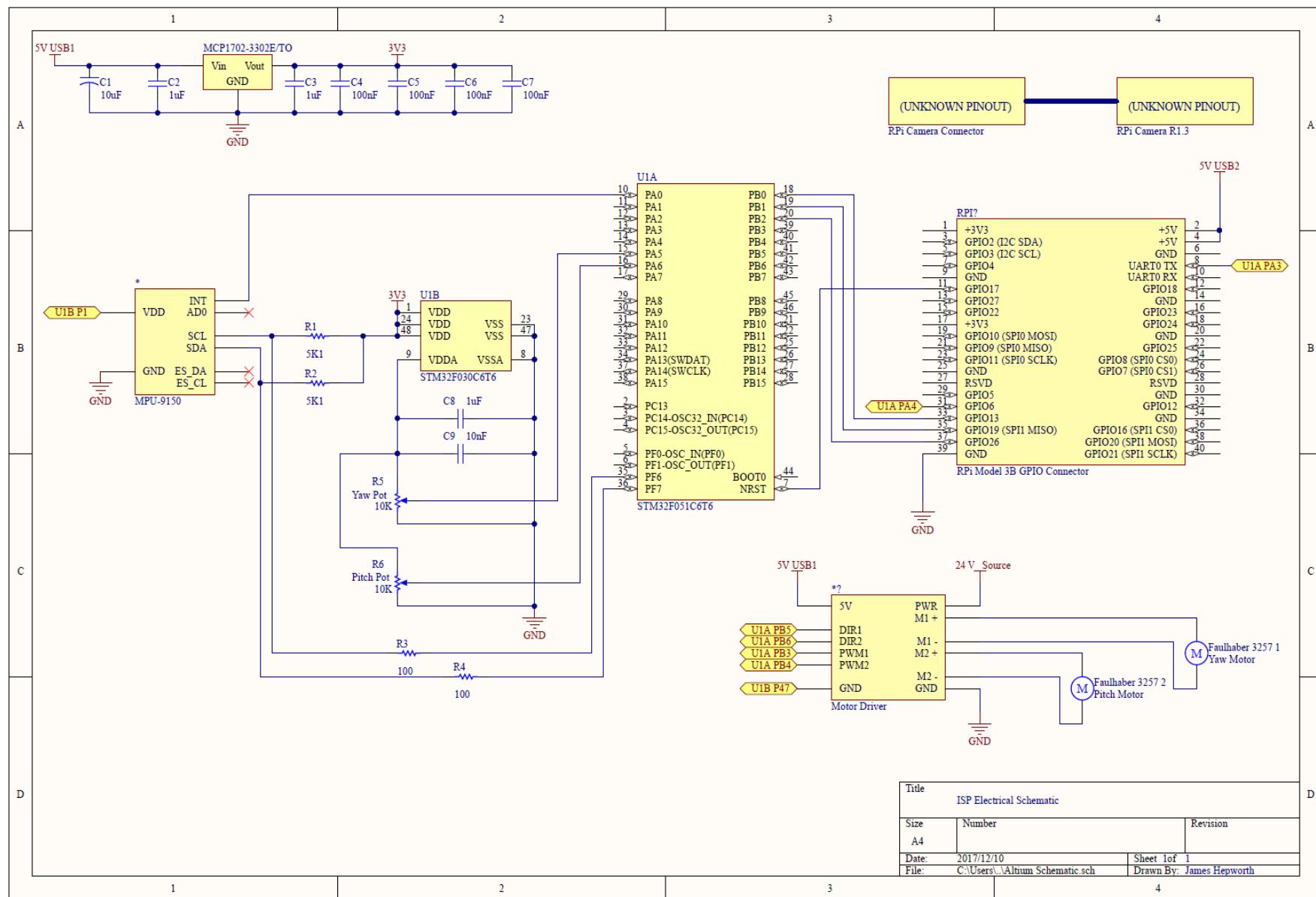


Figure 5-63: Overall electrical schematic for the ISP system

MCU to IMU Connection

The MCU communicates with the IMU using the I²C protocol, a two-wire interface capable of facilitating comms between multiple Master devices and multiple Slave devices at rates of up to 5 MHz (although it is most common for devices to communicate at 100 kHz or 400 kHz). I²C was designed for comms over short distances normally on a single board. The bus drivers for the two lines are configured as open drain lines able to pull the line low but unable to force it high. Resistors R₁ and R₂ are 5.1 kΩ pull-up resistors used on the I²C clock (SCL) and data (SDA) lines to raise the line voltage to 3.3 V when either line is released from 0 V by either the IMU (configured as the slave device) or the MCU (configured as the master device). Figure 5-64 below shows the I²C protocol for I²C comms between devices with 7-bit addresses as used in this project.

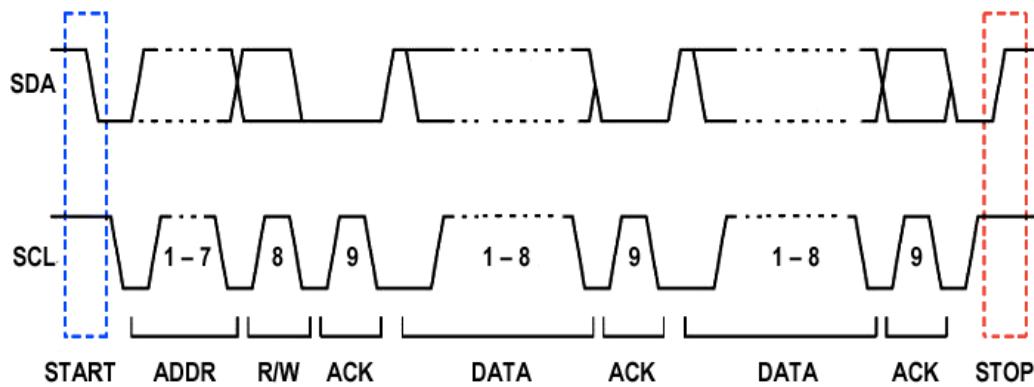


Figure 5-64: I²C protocol for 7-bit address devices [99]

To initiate comms, the master creates a START condition by lowering the data line whilst leaving the clock high. The master then sends the address of the slave being communicated with on the data line followed by a bit indicating whether the transfer is a read (high) or write (low) transfer. The slave then lowers the data line before the 9th clock pulse as the 9th data bit of the transfer to acknowledge (ACK) comms initiation. At this point, the master generates a series of clock pulses and either the master (write transfer) or the slave (read transfer) transmits 8 bits of data after which the receiver lowers the data line before the 9th clock pulse to acknowledge the transfer. When the desired number of bytes have been transferred the master generates a STOP condition by raising the data line whilst clock is high. START and STOP conditions are distinct from other transfers as they are the only conditions where the data line changes whilst the clock is high. All other level changes on the data line occur when the clock line is low. If an ACK is not received at a relevant point, the master takes an appropriate action, defined by firmware, to deal with the error. [100]

As the I²C protocol relies on the levels of the data and clock line relative to each other and is dependent on the timing of the level changes for comms to be meaningful, imaginary components of the line impedance, which affect the phase of a signal, present challenges to successful I²C comms. Longer connections between master and slave have increased magnitudes of the imaginary component of the line impedance and, therefore, comms errors over longer connections are more common. In this project, the cable length connecting the

IMU to the MCU is approximately 1.5 m. It was decided to place the $100\ \Omega$ resistors R_3 and R_4 in series with the SCL and SDA lines connected to PF6 and PF7 on the MCU. This was done to increase the resistive (real) component of the cables' impedance and therefore reduce the phase angle of the cable's impedance, allowing for increased comms robustness over a greater distance than the inter-board distances normally intended for I²C comms.

In addition to the SDA and SCL connections between the IMU and MCU, the VDD pins were connected between the boards, as were the GND pins. Finally, the interrupt (INT) pin of the IMU was connected to Port A Pin 0 (PA0 – Pins on the MCU are referenced using this designation from here, where the letters of the acronym represent *Port X*, where *X* can be *A* to *F*, and the number represents the pin number of the port) of the MCU (which was configured as an external interrupt pin) and was raised by the IMU whenever new gyro data was ready to be read from the IMU registers. This occurs at a rate defined in the initialisation of the IMU. Figure 5-65 below shows the MPU-9150 connected to the STM32F051 board.

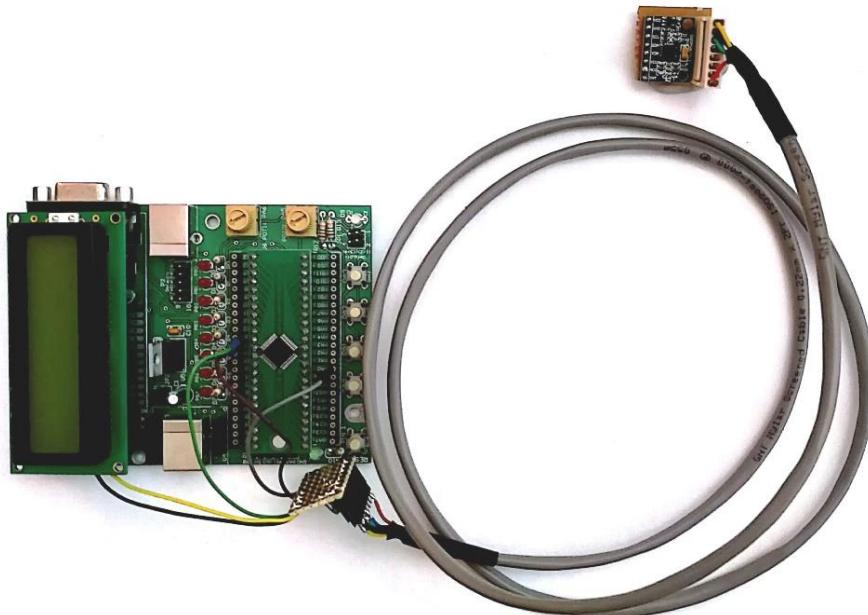


Figure 5-65: MPU-9150 to STM32F051 connection

MCU to Angle Pickoffs Connection

The wipers of the Vishay 357 pots used as angle pickoffs to measure the gimbals' orientation were connected directly to PA5 (yaw pot) and PA6 (pitch pot), of the MCU. The rails of the pots were then initially connected directly to the VDDA and VSSA pins on the MCU. PA5 and PA6 were mapped to two of the channels of the MCU's ADC so that the angular position of the gimbals could be determined by reading the voltage on the pot wipers which varies linearly with angle. However, it was noted on initial testing of the manual positioning control loops that when the gimbals were driven by the motors, large noise spikes were coupled into the wiper line which had not been evident when the gimbals were moved manually. This caused violent jumps in the position of the gimbals as these noise spikes were coupled into the controllers and caused erroneous gimbal actuation. Figure 5-66 below shows

the recorded ADC readings with the large noise spikes as the pitch platform was driven by the motors in a sinusoidal motion to test the noise interference whilst the pot rails were directly connected to the VSSA and VDDA pins of the MCU.

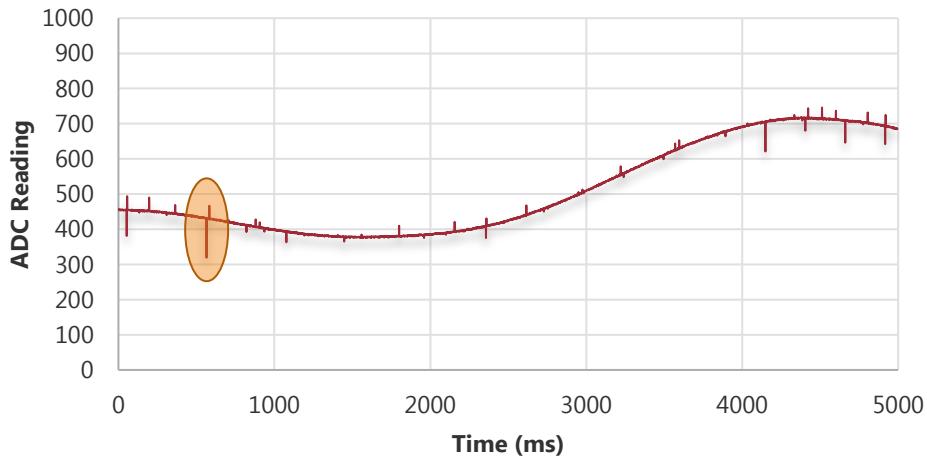


Figure 5-66: ADC readings with pot rails directly connected to VSSA and VDDA

In the figure above, the ADC was set up in 10-bit mode where 1024 integer values were used to represent the full 360° of possible rotation of the pitch platform. Accordingly, each integer value represented a 0.352° rotation of the gimbal. The largest magnitude noise spike was evident 565 ms after the test was begun (indicated by the orange shading). Data points were recorded at 1 ms intervals. The magnitude of the ADC reading at 564 ms and 566 ms was 431 at each point. However, the magnitude of the ADC reading at 565 ms was 319, an integer difference of 112 points, representing an angular error of 39.4° from the expected angular position.

After a long process of attempting to determine the cause of the noise coupling into the wiper line, it was eventually discovered that two power supply decoupling capacitors, recommended for board designs by STMicroelectronics, had been omitted from the design of the STM32F051 development board used. These are shown in Figure 5-67 below, taken from an STMicroelectronics Application Note on ADC performance.

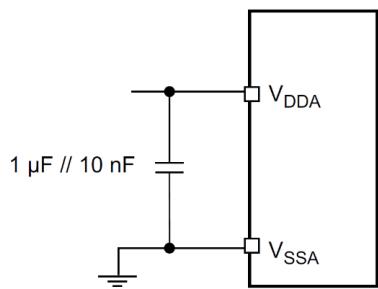


Figure 5-67: Power supply decoupling capacitors recommended by STMicroelectronics for 36, 48, and 64 pin package STM32 microcontrollers such as the STM32F051 [101]

Capacitors C8 and C9 were then soldered across the VSSA and VDDA pins on the MCU, and the sinusoidal drive test above rerun. Figure 5-68, below shows the results of one of these tests with the power supply decoupling capacitors included on the board.

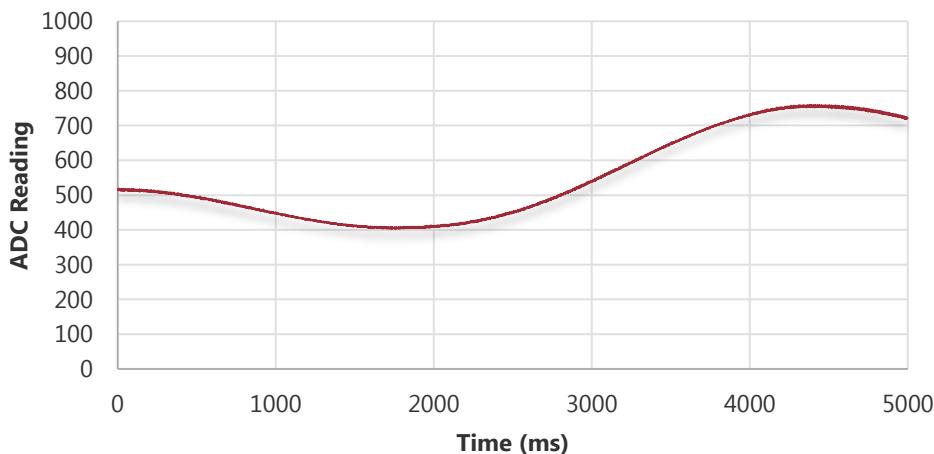


Figure 5-68: ADC readings with pot rails connected to VSSA and VDDA in parallel with C8 and C9

A dramatic improvement in performance was evident upon the inclusion of decoupling capacitors which greatly improved the performance of the manual gimbal positioning loops relying on position feedback from these sensors.

MCU to Motor Driver Connection

For control of the gimbal motors, PB₃-PB₆ were allocated to provide the PWM (speed) and direction signals to the motor driver board. PB₃ provided the direction signal to the yaw motor attached to channel M₁, whilst PB₅ was configured to provide the PWM signal to the yaw motor. PB₄ provided the direction signal to the pitch motor attached to channel M₂, whilst PB₆ was configured to provide the PWM signal to the pitch motor. The 5 V and GND lines of the motor driver were connected to the 5 V USB rail, and the VSS line on the MCU board respectively. The PWR pin was connected to the positive rail of an external power supply set to provide between 12-24 V at various stages of system development and testing.

RPi to MCU Connection

The complete detail of the nature of the connections between the MCU and RPi are given in Section 7.3 which details the development of the target tracker. Here, only the physical connections between the devices and the direction of signals along the lines are detailed.

The VSS line of the MCU was connected to the ground (Pin 39) of the RPi. Pin 11 (GPIO17) of the RPi was configured as an output and connected to the NSRT pin of the MCU. Pin 8 (UART0 TX) of the RPi was connected to PA3 of the MCU which was configured as the RX pin of the second USART peripheral on the MCU. Pin 31 (GPIO06) of the RPi was configured as an output and connected to PA4 of the MCU which was configured as an external interrupt input. Pin 33 (GPIO13) of the RPi was configured as an input and connected to PBo of the MCU which was configured as an output pin. Pin 35 (GPIO19) of the RPi was configured as an input and connected to PB1 of the MCU which was configured as an output pin. Finally, Pin 37 (GPIO26) of the RPi was configured as an input and connected to PB2 of the MCU which was configured as an output pin.

These connections facilitated the communications of target position data between the RPi and MCU.

User Interface to MCU Connection

The laptop running the UI was connected to the MCU via a serial port across either an RS-232 connection or a USB connection. Both connections communicated with USART1 peripheral of the MCU configured on PA9 (TX) and PA10 (RX).

5.4 CHAPTER CONCLUSION

This chapter detailed the process by which all electronic components were selected for use in the system developed in this project. It presented, in detail, the reasons for the selection of specific components over other technologies able to accomplish similar tasks, and justified the choice of gimbal actuators through a rigorous experimental and simulation-based method. In addition to describing the hardware chosen and their specifications, the control architecture used in the project was presented. Within the three-part control structure employed, control and communications tasks were assigned to each of the control computers: Supervisory control tasks to the laptop-based UI, fixed frequency controller algorithms and sensor communications to the MCU, and target tracking and its associated image gathering tasks to the RPi.

Ultimately, the choice of hardware presented in this section was done such that system prime items I_{2.1}-I_{2.2}, I₄, I₅, and I₃ from a hardware perspective were successfully implemented. The implementation of these prime items achieved specifications S8 and S10-S13 directly, whilst contributing to the accomplishment of specifications S₃-S₆ and S₁₄. Unfortunately, S₉ was not achieved due to budget constraints on the system.

6

CONTROLLER DESIGN

6.1 INTRODUCTION

Following the mechanical and the electrical design of the ISP system developed, this chapter describes the design of the various controller algorithms designed for implementation on the control hardware. Namely, these include manual position controllers for the yaw and pitch channels, stabilisation controllers, and finally tracking controllers for the two channels. Together, these control loops facilitate the control of the ISP's gimbals such that its orientation and motion may be controlled to a desired state under various operating conditions.

All controllers developed for the ISP were chosen to be classical controllers of type P or PI with compensation. Although modern and non-linear control methods have been shown to achieve better stabilisation performance, classical controllers were chosen due to the prevalence of their use in the development of stabilised platforms, as stated in Section 2.3.3. Additionally, as this project represented the initial systems development of this ISP, classical controllers were the logical starting point for the development of its control system. All controllers designed in this chapter were developed using the Bode technique and evaluated the system responses under linear and saturated operating conditions. As illustrated previously, by Figure 5-38 of Section 5.2.4, the saturated responses of systems evaluated by this technique are representative only of the operating point at which they are evaluated and therefore excitation signals were chosen to be of magnitudes and frequencies typical of the expected operating environment of the ISP system developed.

Throughout this chapter non-standard terminology has been made used to describe the compensators implemented in the various control loops: The term '*lead compensator*' has been used to describe a compensator with a single zero and no poles which causes a pure phase lead response. The term '*lag compensator*' has been used to describe a compensator with a single pole and no zeroes which causes a pure phase lag. The term '*lead-lag compensator*' has been used to describe a compensator with one zero and one pole which causes both phase lead and phase lag effects across the frequency spectrum. A dominant lead lead-lag compensator has its zero at a lower frequency than its pole and causes phase lead between the frequencies of one tenth the zero frequency and ten times the pole frequency. A dominant lag lead-lag compensator has its pole at a lower frequency than its zero and causes phase lag between the frequencies of one tenth the pole frequency and ten times the zero frequency.

This terminology has been used due to the more intuitive understanding off the phase effect of the compensator associated with the term. [102]

It was decided at this point to make use of the simulation language, Simul_C_EM (Simul_C) for the control system design and simulation needs of the remainder of the project. Simul_C is a C++ based, analytical simulation package suited to classical control design using the Bode technique and time domain simulations which may be observed through several graphing capabilities [102]. Simul_C was developed by Associate Professor Hendrik D. Mouton and is freely available for use from UCT. Simul_C has been noted to run simulations faster than equivalent simulations run using MATLAB Simulink and, in addition, the similarity of C++ to C, the language used to program the STM32Fo MCU on which the control loops designed here were implemented, was beneficial in debugging of system firmware. It allowed line-by-line comparison of simulation code with firmware code to be made and so helped identify errors as either language or implementation errors.

Whilst not a prime item of the system, the manual position controllers are an important aspect of the overall control of the gimbal structure. The section begins with a description of their design before it continues to the development of the stabilisation and tracking loops (prime items I_{3.3} and I_{3.4} from a mathematical simulation perspective after already being described from a hardware perspective in Section 5.2.6.)

6.2 MANUAL POSITION CONTROLLERS

The firmware written for the MCU to control the low-level operation of the ISP system developed is a state machine built on three main program states: The Setup state, Manual state, and Automatic state. This is further detailed in Section 7.2.1, however, the Setup state facilitates correct initialisation of the sensors and hardware, the Automatic state facilitates tracking and stabilisation functionality, and the Manual state enables the orientation of the telescope modeller to be controlled in a servo loop which receives angular position commands from the User Interface. The need for these servo loops arose from the fact that it is unlikely that the ISP will be in an orientation such that the target can be seen on system startup; angular position control is required so that the gimbals may be moved to an orientation where the target is visible in order for the target tracker to begin tracking of the target and control of the gimbals. The controllers designed below facilitate this operation.

6.2.1 POSITION CONTROLLER DEVELOPMENT

As shown below, each gimbal is modelled as a single inertia driven directly by a DC motor controlled by a P controller with a lead-lag compensator.

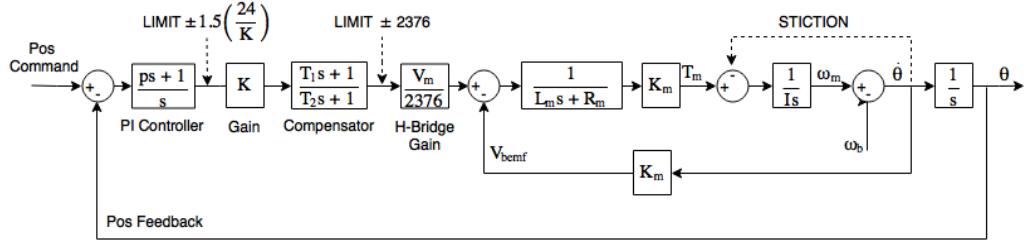


Figure 6-1: Manual position controller model

In the model above, the relative angle, θ , (Pos Feedback) is modelled as being directly compared to the position command. In practice, relative angles are sensed by the angle pickoff pots and read by the ADC of the MCU as a 10-bit digital reading. The relevant sensor scaling required to convert this scalar measurement to a radians equivalent is described later when the firmware implementation of the position control servo loops is detailed in Section 7.2.5. For now, the model assumes a position control command and a relative angle feedback in radians. The limit after the PI controller prevents integrator windup, whilst the second limit prevents the output of the compensator from exceeding the maximum numeric value that can be given to the timer used to generate a PWM signal to control the motor voltage. This limit corresponds to a 99% duty cycle PWM signal being generated; the maximum duty cycle that can be handled by the Quimat Dual Motor Driver used in the system. The H-bridge Gain following this limit models the motor driver and converts the numeric value to the motor voltage. The motor model used for this simulation improves on that used previously in Figure 5-32 by replacing the coefficient of friction term generating the friction torque with the Simul_C STICKION feedback in the model above. This function calculates the frictional moment on the motor shaft as a combination of Coulomb and viscous friction such that the motor friction is given according to the Figure 6-2 below.

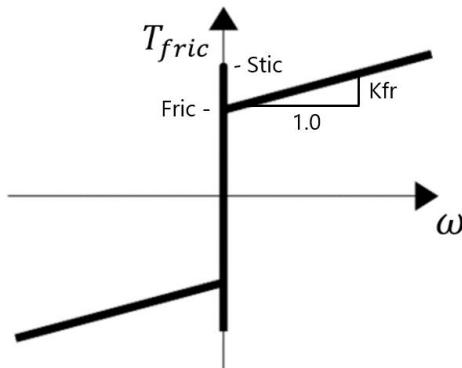


Figure 6-2: Stiction function friction model (Adapted from [103])

Additionally, on testing, it became evident that a PI controller was required to be used in these loops in order to overcome the varying disturbance torque exerted by the camera and IMU connection cables. Table 6-1 below details the parameters used in the simulation results to follow in the next section. The inertial values used are those of I_{yyp} for the pitch channel, and $I_{zzg} + I_{zzp}$ for the yaw channel which is the maximum possible inertia seen by the yaw motor when the telescope modeller is positioned such that $\theta = 0^\circ$. The friction parameters used also represented initial estimates for the ISP system. The Stic_x (where $x = p$ for the pitch

channel and $x = y$ for the yaw channel) terms for the motors above were determined as the result of experimental testing of the gimbals to estimate their static friction properties. The $Fric_x$ and Kfr_x terms here are initial, purely estimated values. The frequencies of the zero and pole of the compensator were chosen such that the zero is at a lower frequency than the pole, giving the compensator a dominant phase lead effect. By comparing the response of the actual working platform to simulations once the ISP had been implemented, as shown in Chapter 8, the friction terms were there adjusted to improve the accuracy of the simulation.

Table 6-1: Manual position loop simulation parameters

Parameter	Pitch Channel	Yaw Channel
p	$\frac{1}{2\pi 0.5}$ s	$\frac{1}{2\pi 0.5}$ s
K	3000	5000
T_1	$\frac{1}{2\pi 0.2}$ s	$\frac{1}{2\pi 0.2}$ s
T_2	$\frac{1}{2\pi 4}$ s	$\frac{1}{2\pi 4}$ s
V_m	24 V	24 V
R_m	1.63 Ω	1.63 Ω
L_m	270 μH	270 μH
K_m	37.7 mNm/A	37.7 mNm/A
$Stic$	18.0 mNm	41.0 mNm
$Fric$	5.4 mNm	24.6 mNm
Kfr	6.13 mNm/(rad/s)	1.75 mNm/(rad/s)
I	0.0164 kgm ²	0.0289 kgm ²

6.2.2 MANUAL POSITION LOOPS SIMULATION RESPONSES

In this section, the frequency response and stability of the loops designed are evaluated. Linear responses in the frequency domain are the result of excitation by a 0.1 rad amplitude sine signal applied to the specified input whilst saturated responses are the result of excitation by a 1.0 rad amplitude sine signal.

Pitch Channel Simulation Responses

The open-loop response shown in Figure 6-3 below represents the linear response of the transfer function from the position error to the position feedback of the pitch channel, whilst the response shown in Figure 6-4 represents the saturated response.

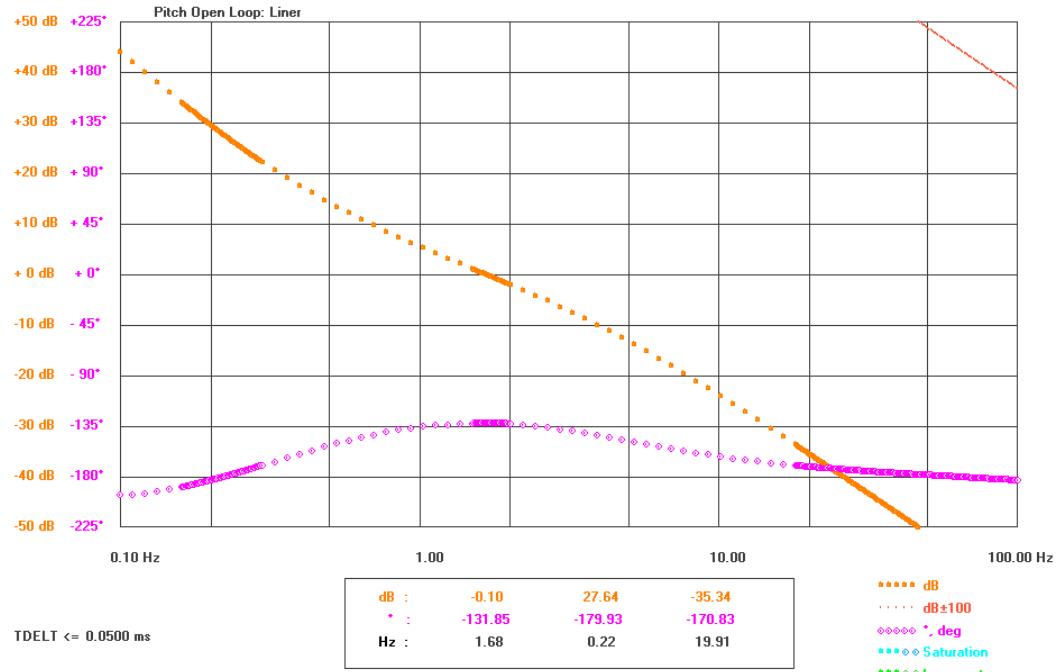


Figure 6-3: Linear open-loop responses of the pitch manual position controller

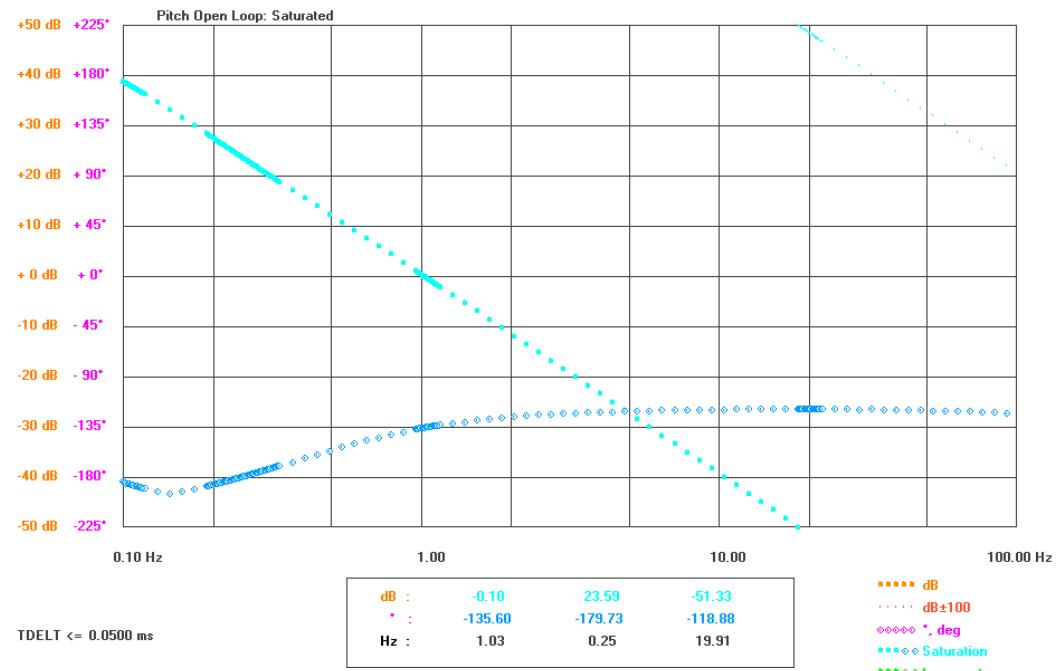


Figure 6-4: Saturated open-loop responses of the pitch manual position controller

In both cases, wide gain and phase margins are evident. A low gain was chosen due to the fact that a relatively slow response with settling times in the order of seconds was desired for these positioning loops which took step commands as inputs and were never required to follow a varying amplitude command signal. Figure 6-5 and Figure 6-6 below show the linear and saturated closed loop responses, respectively.

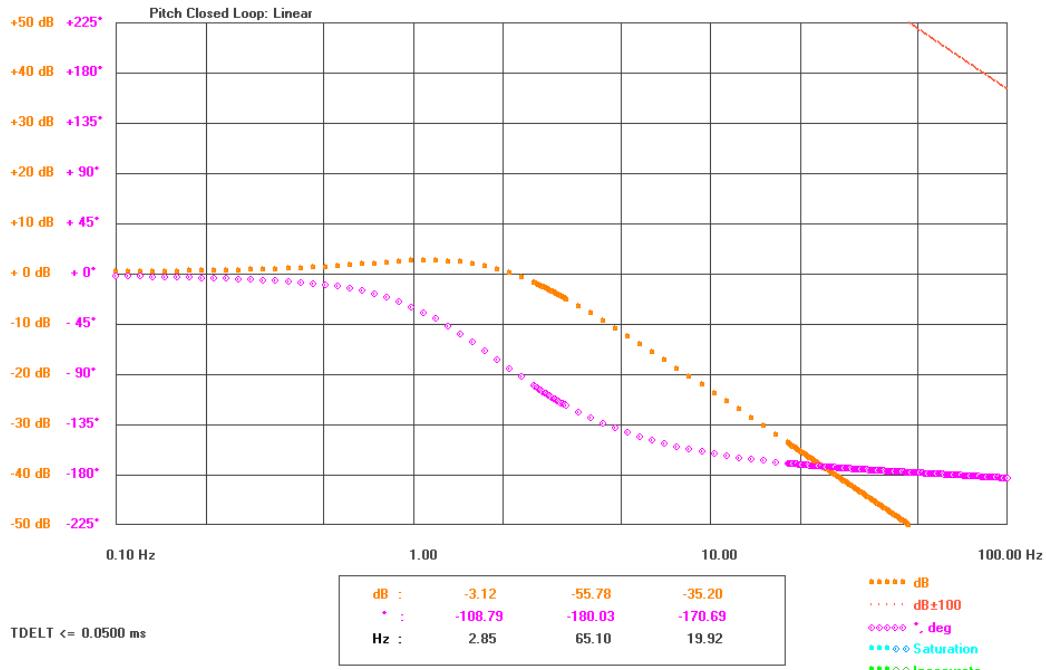


Figure 6-5: Linear closed-loop responses of the pitch manual position controller

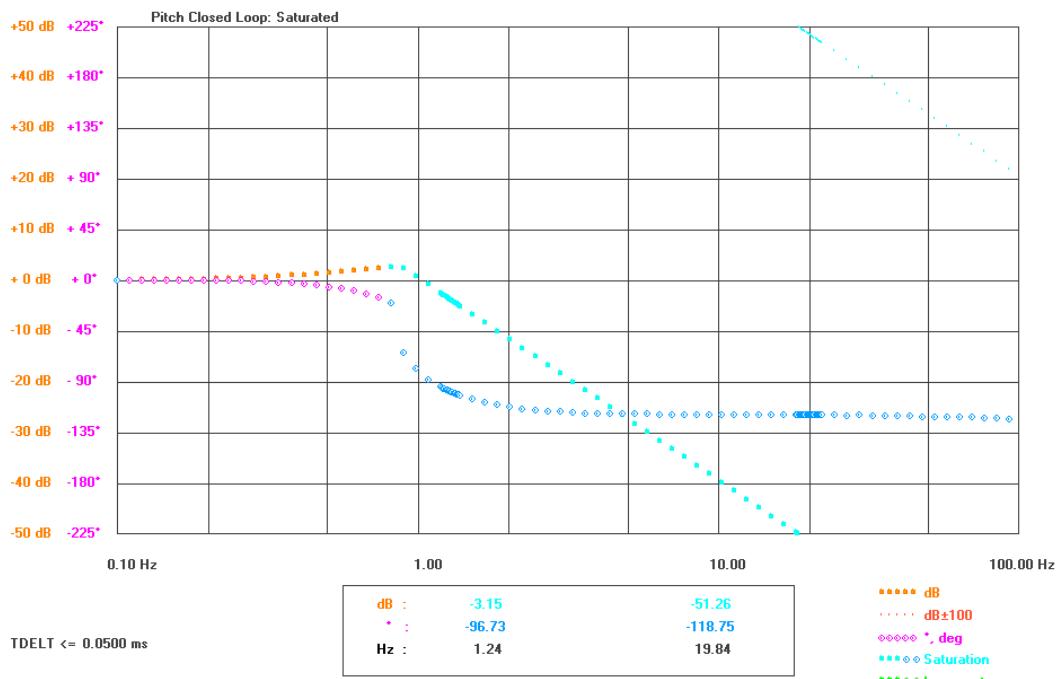


Figure 6-6: Saturated closed-loop responses of the pitch manual position controller

In both figures above, low bandwidths and resonance peaks are evident. The frequencies of the zero of the PI controller, and zero and pole of the lead lag compensator were chosen such that system stability was achieved at low frequencies along with a steep drop-off in gain at frequencies above 3 Hz to negate the effects of ADC wiper noise on the position loop. ADC wiper noise was determined to be at frequencies of approximately 8-20 Hz. The step following response of this loop is shown Figure 6-7 below.

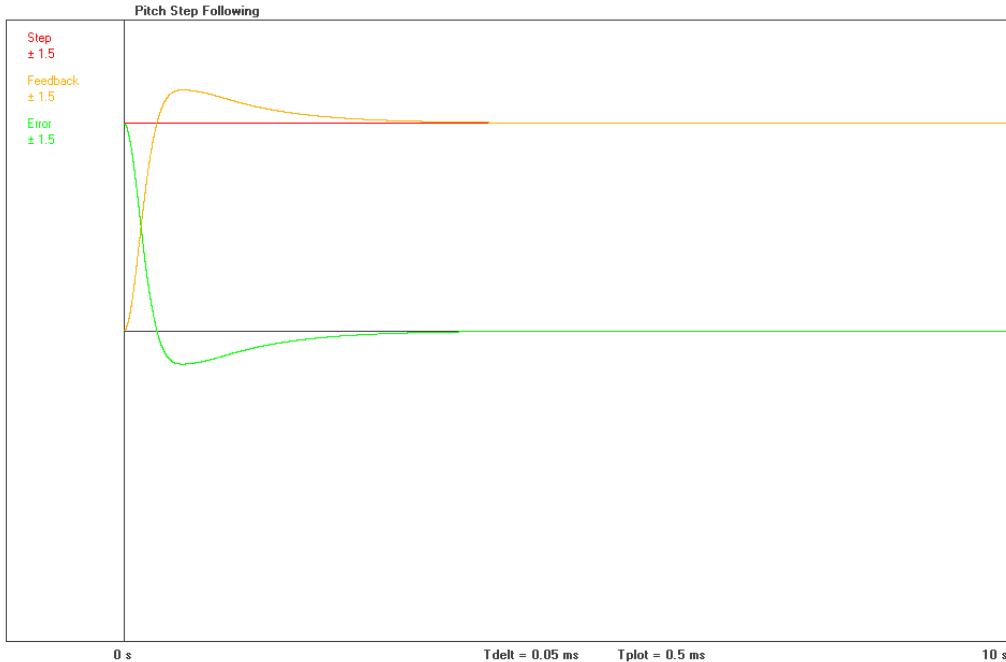


Figure 6-7: Step response of the pitch manual position controller

Overall, a stable loop with low gain was designed to position the pitch platform such that low frequency stability and robustness to ADC noise were achieved. The main parameters of this loop are given in Table 6-2 below.

Table 6-2: Pitch manual position control loop performance parameters

Gain Margin	>50 dB
Phase Margin	44.4 ° (min)
Resonance Peak	2.55 dB (max)
Linear Bandwidth	2.85 Hz
Settling Time	4.08 s

Yaw Channel Simulation Responses

The open-loop responses shown below represent the transfer function from the position error to the position feedback of the yaw channel.

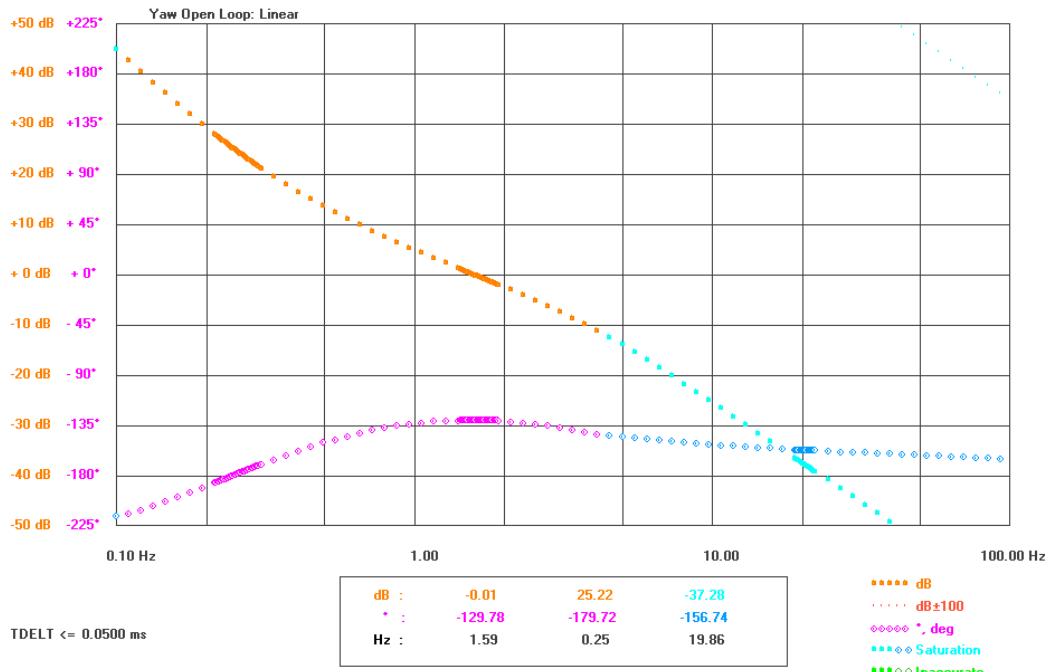


Figure 6-8: Linear open-loop responses of the yaw manual position controller

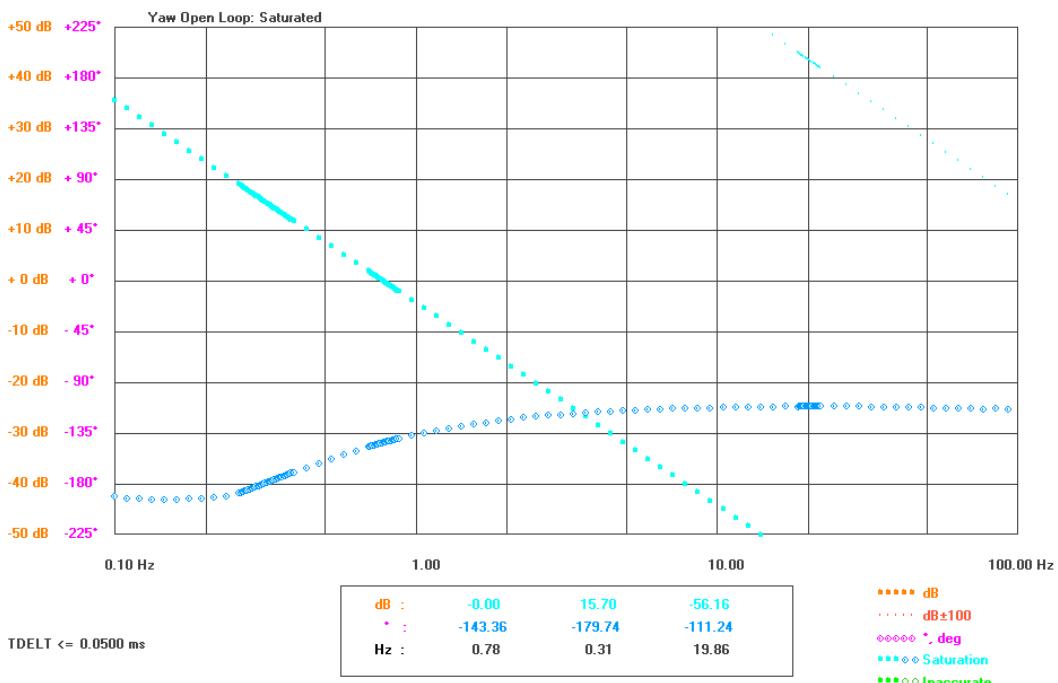


Figure 6-9: Saturated open-loop responses of the yaw manual position controller

The open-loop responses for the yaw channel above show similar responses to those of the pitch channel previously, although the channel begins to saturate at approximately 45 Hz. Closed-loop responses are shown in Figure 6-10 and Figure 6-11 below.

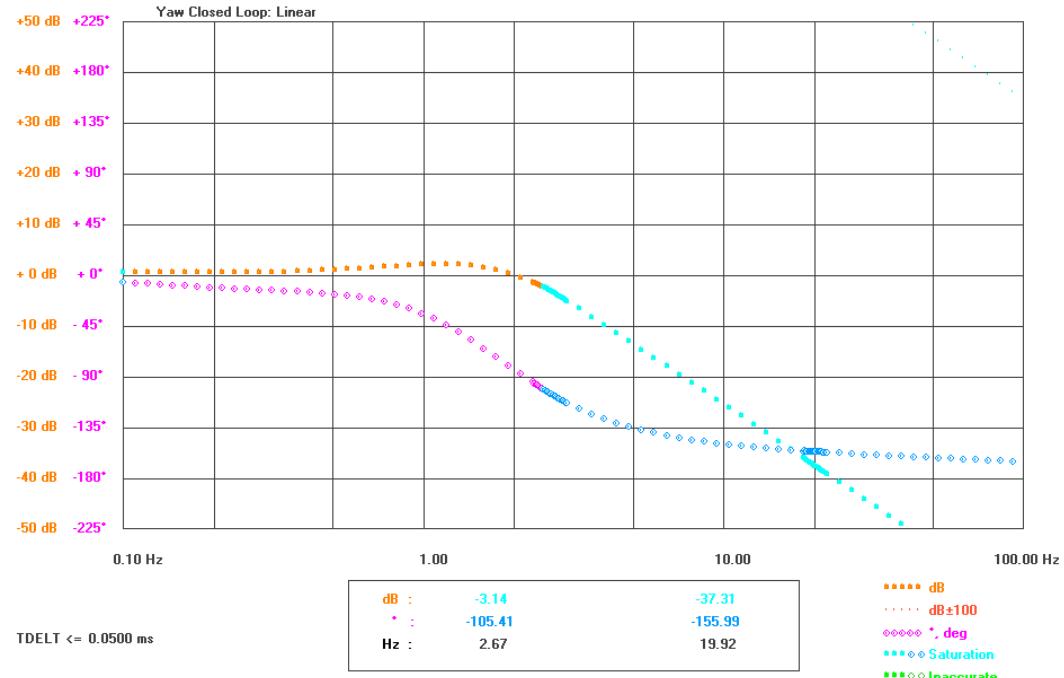


Figure 6-10: Linear closed-loop response of the yaw manual position controller

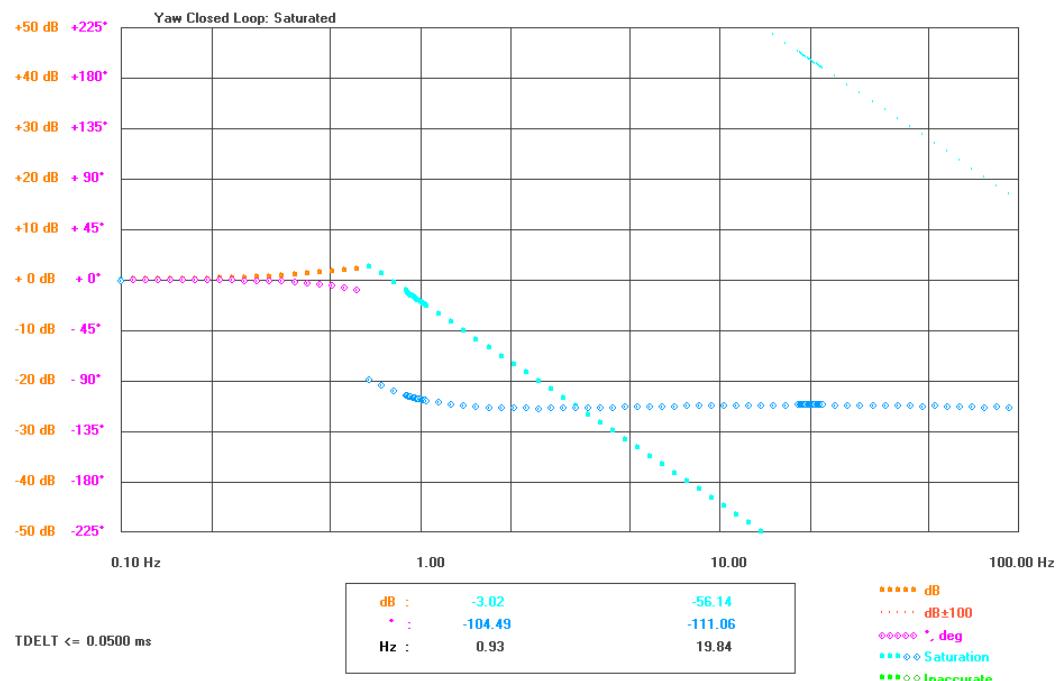


Figure 6-11: Saturated closed-loop response of the yaw manual position controller

As with the open-loop responses, it can be seen that the closed-loop begins to saturate with the 0.1 rad input signal, this time at approximately 25 Hz. However, resonance and bandwidth of the loop for the yaw channel can be seen to be similar to the pitch channel above. Step following is shown by Figure 6-12 below.

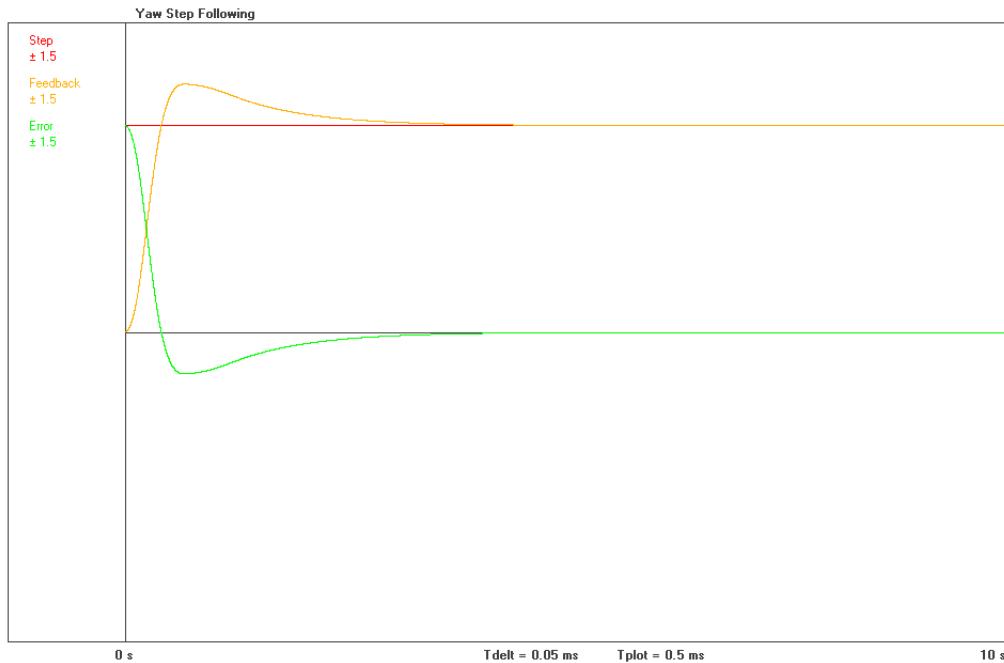


Figure 6-12: Step response of the yaw manual position controller

The main properties, describing the response of this loop are summarised in Table 6-3 below.

Table 6-3: Yaw manual position controller performance parameters

Gain Margin	>50 dB (min)
Phase Margin	36.6 ° (min)
Resonance Peak	2.33 dB (max)
Linear Bandwidth	3.92 Hz
Settling Time	4.37 s

The controllers designed here effectively facilitate the positioning of the gimbals in the Manual state such that the target may be acquired in the FOV of the camera before the Automatic state is entered and the stabilisation and tracking controllers take control of gimbal actuation.

6.3 STABILISATION LOOPS DESIGN (I3.4)

Moving from the design of the manual position controllers, this section details the design and development of the internal stabilisation loop controllers (prime item I3.4) used to control the gimbal rates and attenuate external disturbances incurred to the gimbal structure whilst the system is in the Automatic state. As such, the performance of these loops directly affects LOS jitter, and hence how well specification S6 is met. These loops have higher gain and bandwidth than the outer tracking loops designed to drive them and control the orientation of the ISP.

6.3.1 STABILISATION LOOPS MODEL DEVELOPMENT

To begin the design of the tracking and stabilisation control loops of the ISP a system identification was again developed to build the structure of the initial simulation model. Figure 6-13 below shows the system identification block diagram for the ISP control system.

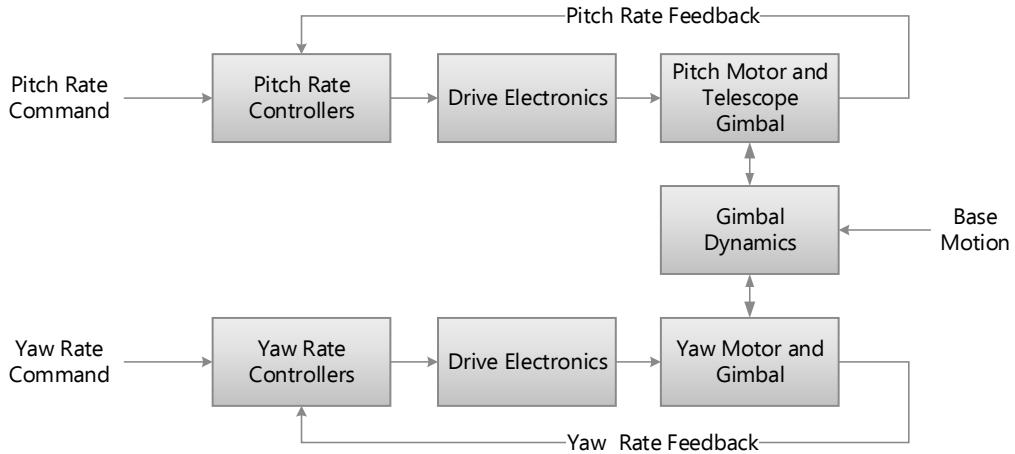


Figure 6-13: ISP stabilisation system identification diagram

The system identification above is representative of the internal stabilisation loop of the motor selection simulation block diagram shown in Figure 5-37. The gimbal dynamics block for the final ISP system took a similar form to that shown in Figure 5-36 and represented the derivations of Section 2.9.2. The controllers designed here were also chosen to be PI controllers cascaded with a gain and lead compensator as before in the manual position controllers and the motor selection simulation. The STICTION function used in the motor model of the previous section was replaced by the STICLIM function which calculates friction in the same manner as the STICTION function but also limits the allowable displacement from the zero position in accordance with the hardware defined limits (see Section 7.2.4). Its implementation is shown in Figure 6-14 below.

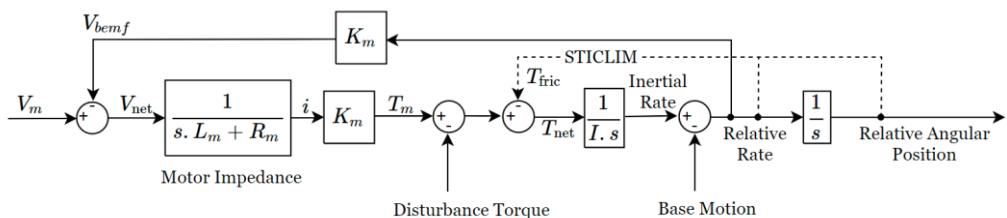


Figure 6-14: Motor model used for the ISP system simulation

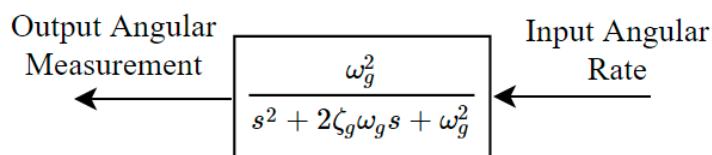
In addition to the parameters used for the motor model in Table 6-1, the relative angular limits imposed on the rotor shafts are given in Table 6-4 below.

Table 6-4: Motor model parameters

Limit_p	+200 °, -20 °
Limit_y	±360 °

As with the motor selection simulation detailed earlier, the control system design was begun with the inner stabilisation loops before moving to the design of the outer tracking loops for each channel. A lengthy process was followed through which the final simulation model and results shown here were obtained. This process was followed for each stabilisation and tracking loop designed. These steps, simply outlined here for the sake of brevity, began with the development of an analogue control model where all blocks were treated as continuous time representations regardless of whether they were, in fact, discrete time, digital components or not. This analogue model was also free from saturation causing blocks or limits and as such, ensured the initial responses observed were those of a linear system. The controllers and compensators implemented in each of the loops were designed first whilst the model was in this analogue, linear configuration. From this point, limits and blocks with non-linear properties were added. These included PWM digital number limits, integrator wind-up limits on the PI controllers, and non-linear friction models amongst others. After this and each subsequent revision, the controller designs were re-evaluated and modified if necessary. The next step involved converting the relevant blocks from their idealised, analogue, continuous time models to more representative, digital, discrete sampling rate models. All blocks that represented an action or effect that was sourced on a digital computer, sensor, or piece of electronics were converted to their digital counterparts and relevant sampling rates were defined for these blocks. Following from the conversion of some blocks from analogue to digital models, time delays due to certain components were added to the model, and relevant scaling factors were incorporated to accurately model certain parts of the system.

An example showing these revisions was in the progression of the model of the gyroscope sensor used to measure inertial rotational rates. The analogue model of each gyro axis, shown in Figure 6-15 below, was simply a second order low pass filter (LPF) at 1000 Hz applied to the relevant inertial rate signal in the model.

**Figure 6-15: Initial gyro model used in the ISP simulation**

Where, $\omega_g = 1000 \text{ Hz} = 6283.19 \text{ rad/s}$, and a damping factor of $\zeta_g = 0.7$ was chosen. However, the MPU9150 is a digital sensor which was configured to have a sampling rate of 500 Hz, a maximum detectable rotational rate of 250 °/s (4.36 rad/s), and a digital LPF applied to its outputs at $\omega_f = 188 \text{ Hz} = 1184.24 \text{ rad/s}$. The outputs of this sensor are in practice, signed 16-bit numbers linearly proportional to the input angular rate. In the first revision of

the model, a limit of ± 4.36 rad/s was applied to the gyro outputs. In the second revision, the analogue model was replaced with a digital representation of the filter which was sampled at 500 Hz. In the final revision of the gyro model, a delay of 1.9 ms was added after the gyro outputs to represent the time taken for the digital LPF at 188 Hz to be performed, and a diminishing scaling factor was introduced to the stabilisation controller gains to account for the gain in scaling the input rate of up to 4.36 (rad/s magnitude) to an output of 32767 (16-bit representation). In addition to these revisions, a gaussian noise with an rms value of 1.5 mrad/s was added to the gyro outputs to model the experimentally determined noise present on the sensor output. This final model is shown in Figure 6-16 below. The same damping factor of $\zeta_f = 0.7$ was chosen.

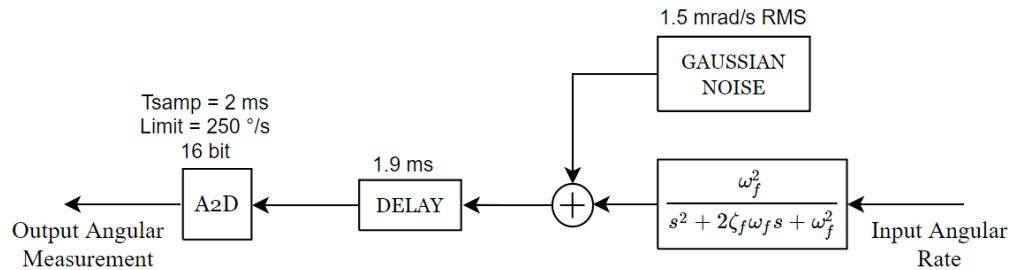


Figure 6-16: Final gyro model used in the ISP simulation

The overall stabilisation loop block diagram for the ISP simulation is shown in Figure 6-17 overleaf. The signals in the block diagram have been numbered for identification and use in the Simul_C simulation package.

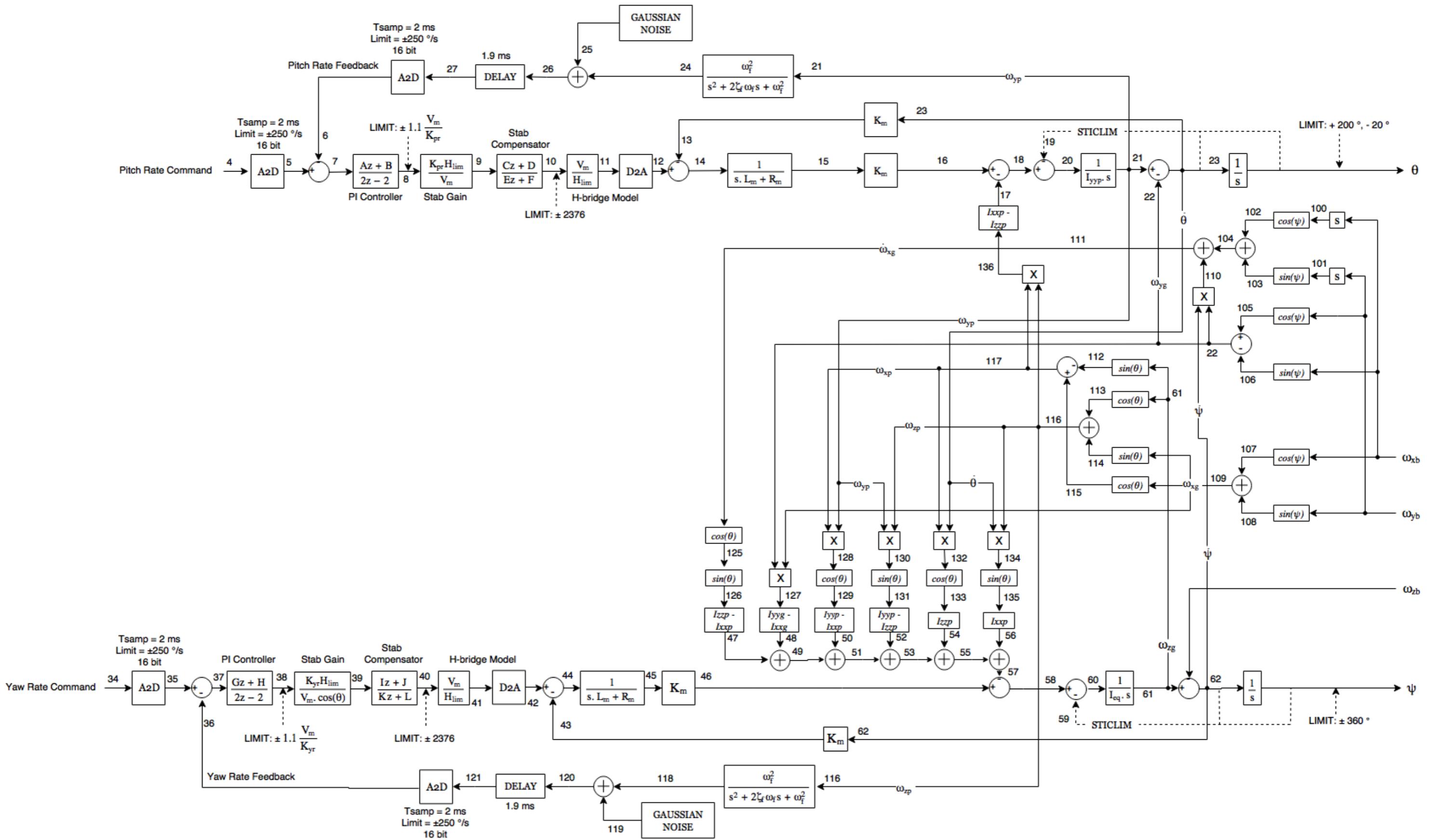


Figure 6-17: Final ISP stabilisation loop block diagram

In the model above, it can be seen that the yaw rate feedback in this model is the ω_{zp} signal rather than the ω_{zg} signal used in the motor selection simulation. Feedback of both signals were trialled on the hardware and it was found that using ω_{zp} produced better stabilisation results than using ω_{zg} as the yaw rate feedback. Initially, it was decided to use ω_{zg} as the feedback in the previous simulation due to the decoupling of ω_{zp} from the yaw gimbal actuator that occurs at pitch angles close to 90°. Using ω_{zg} , which was calculated according to Figure 6-18 below, allowed the yaw gimbal motor to remain coupled to a telescope modeller inertial rate feedback term regardless of pitch angle. However, due to the fact that stabilisation performance at angles away from $\theta = 90^\circ$ was found to be better when using ω_{zp} , it was decided to proceed with the controller design process using this scheme.

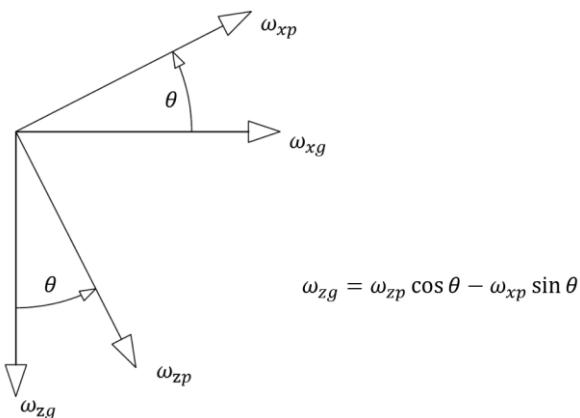


Figure 6-18: Derivation of ω_{zg} from ω_{zp} and ω_{xp}

As can be seen from the model above, ω_{zp} is a function of $\cos(\theta)$. As θ increases towards 90°, less of ω_{zg} is coupled to ω_{zp} until the point where $\theta = 90^\circ$ and the yaw gimbal is completely decoupled from the yaw rate feedback. To compensate for this natural cosine gain in the rate feedback signal a secant(θ) term was added to the forward path of the controller transfer function. However, this scheme did not overcome the decoupling of the feedback from the actuator at $\theta = 90^\circ$. At this point the x_p axis is colinear to the z_g axis but is pointed in the opposite direction. Therefore, to ensure stability on the implemented system, the feedback signal was changed to use $-\omega_{xp}$ when θ was between 85 - 90°.

Table 6-4 previously and Table 6-5 below detail the system parameters used in the simulation. The inertial properties used in this model now represent the SOLIDWORKS estimates from the final mechanical design instead of the best available estimates prior to design completion in the motor selection simulation. Two limits are evident in the forward path of each channel, the first limit of $\pm 1.1 \frac{V_m}{K_x}$ is used to remove the effects of integrator windup in the system, whilst the second limit of ± 2376 is the maximum number that can be used as the output of the controller. The voltage to the motors is provided by an H-bridge amplifier driven by a PWM signal with a duty cycle between 0-99%. The number 2376 is 99% of the full-scale range of the timer which generates this PWM signal on the STM32. H_{lim} is a scaling factor which ensures that a value of ± 2376 at points 10 and 40 in the above model results in a voltage of ± 24 being seen by the motors in the model at points 12 and 42.

Table 6-5: Final ISP stabilisation loop simulation parameters

I_{xg}	0.0267 kgm ²
I_{yg}	0.0159 kgm ²
I_{zg}	0.0123 kgm ²
I_{xp}	0.0048 kgm ²
I_{yp}	0.0164 kgm ²
I_{zp}	0.0166 kgm ²
I_{xzp}	0.0009 kgm ²
I_{zx}	0.0009 kgm ²
K_p	1800
K_y	2550
p_{pr}	$\frac{1}{2\pi 3}$ s
p_{yr}	$\frac{1}{2\pi 3}$ s
T_1	0
T_2	$\frac{1}{2\pi 150}$ s
T_3	0
T_4	$\frac{1}{2\pi 150}$ s
H_{lim}	2400
T_{samp}	2 ms

Table 6-6 below defines the coefficients of the controller and compensator blocks in the previous model.

Table 6-6: Stabilisation loop controller and compensator coefficients

Pitch Channel	Yaw Channel
$A = T_{samp} + 2p_p r$	$G = T_{samp} + 2p_y r$
$B = T_{samp} - 2p_p r$	$H = T_{samp} - 2p_y r$
$C = T_{samp} + 2T_1$	$I = T_{samp} + 2T_3$
$D = T_{samp} - 2T_1$	$J = T_{samp} - 2T_3$
$E = T_{samp} + 2T_2$	$K = T_{samp} + 2T_4$
$F = T_{samp} - 2T_2$	$L = T_{samp} - 2T_4$

6.3.2 STABILISATION LOOPS FREQUENCY DOMAIN SIMULATION RESPONSES

The responses of the yaw and the pitch stabilisation loops in both the frequency and time domains are here presented. The linear response plots below show the behaviour of the relevant loop in response to a varying frequency sine wave of amplitude 0.1 rad/s applied to the rate command input, whilst the saturated response plots show the behaviour of the loop in response to a varying frequency sine wave of amplitude 1.0 rad/s applied to the same input.

Yaw Rate Loop Linear Responses:

The linear open-loop response shown below represents the transfer function from point 37 to point 36 of the model shown in Figure 6-17.

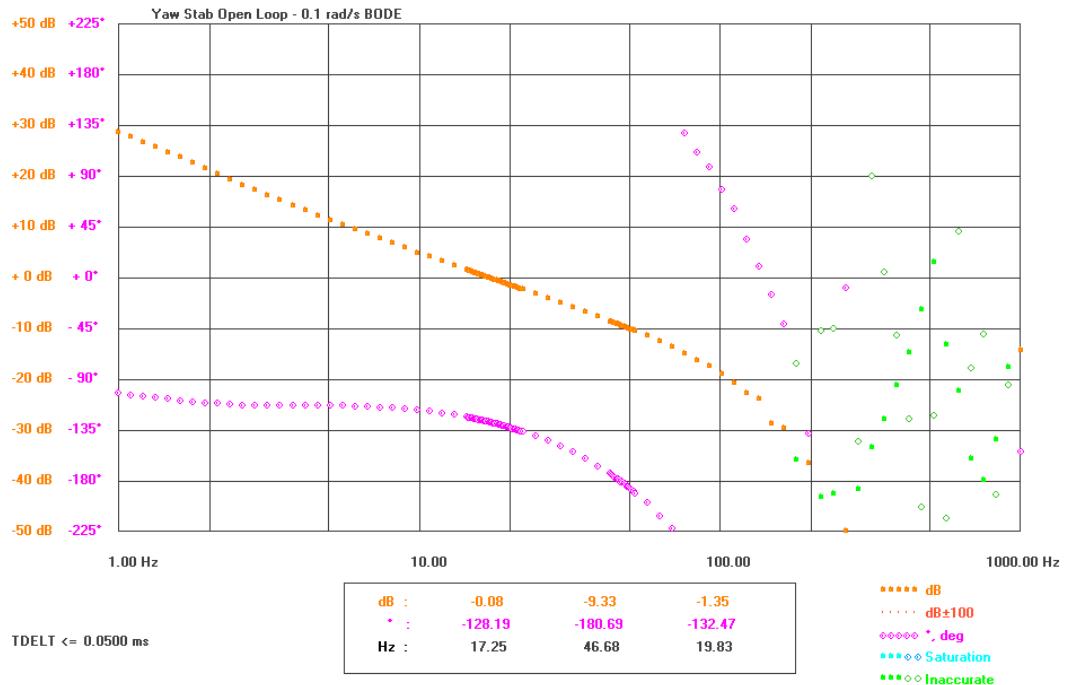


Figure 6-19: Yaw rate open-loop Bode plot - Linear Response

The linear closed-loop response shown below represents the transfer function from point 35 to point 36 of the model shown in Figure 6-17.

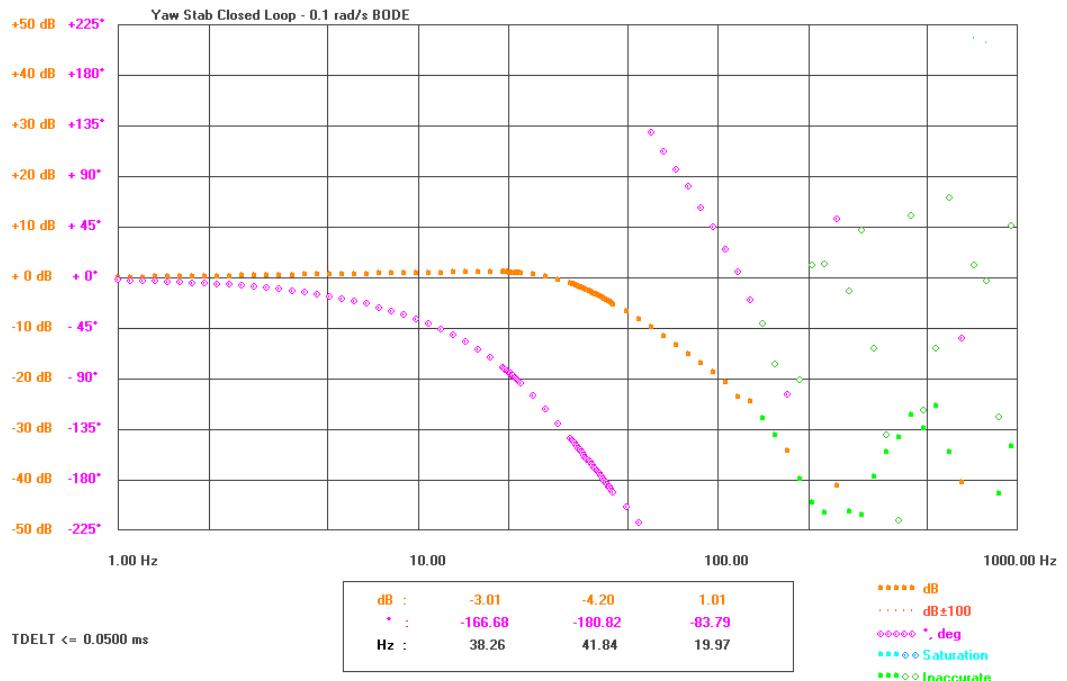


Figure 6-20: Yaw rate closed-loop Bode plot - Linear Response

Yaw Rate Loop Saturated Responses:

The saturated open-loop response shown below represents the transfer function from point 37 to point 36 of the model shown in Figure 6-17.

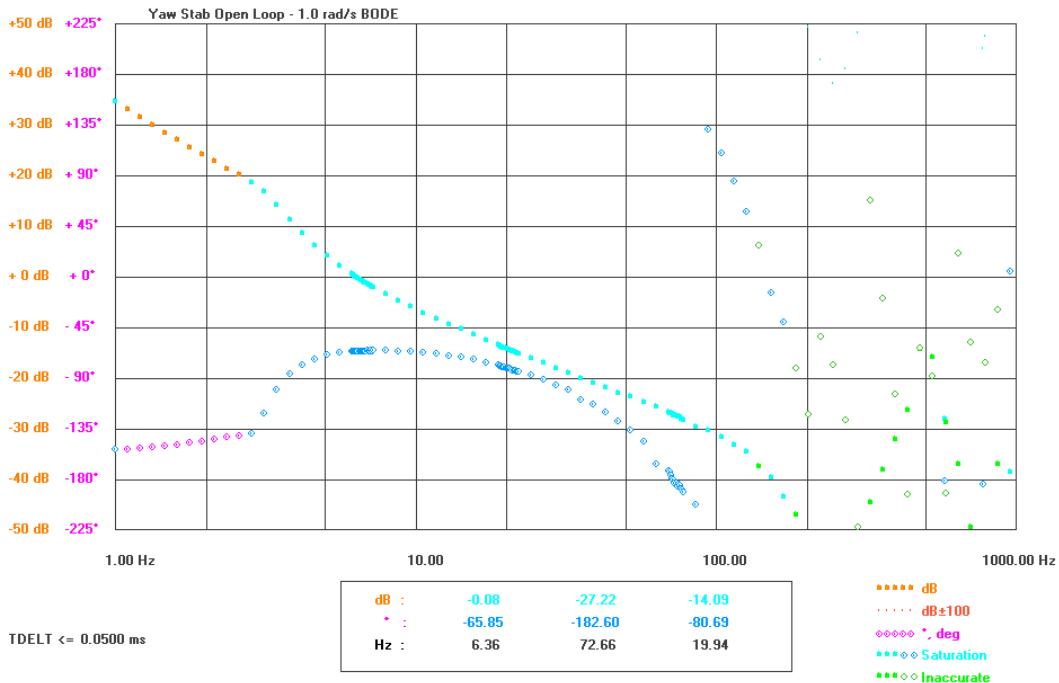


Figure 6-21: Yaw rate open-loop Bode plot - Saturated Response

The saturated closed-loop response shown below represents the transfer function from point 35 to point 36 of the model shown in Figure 6-17.

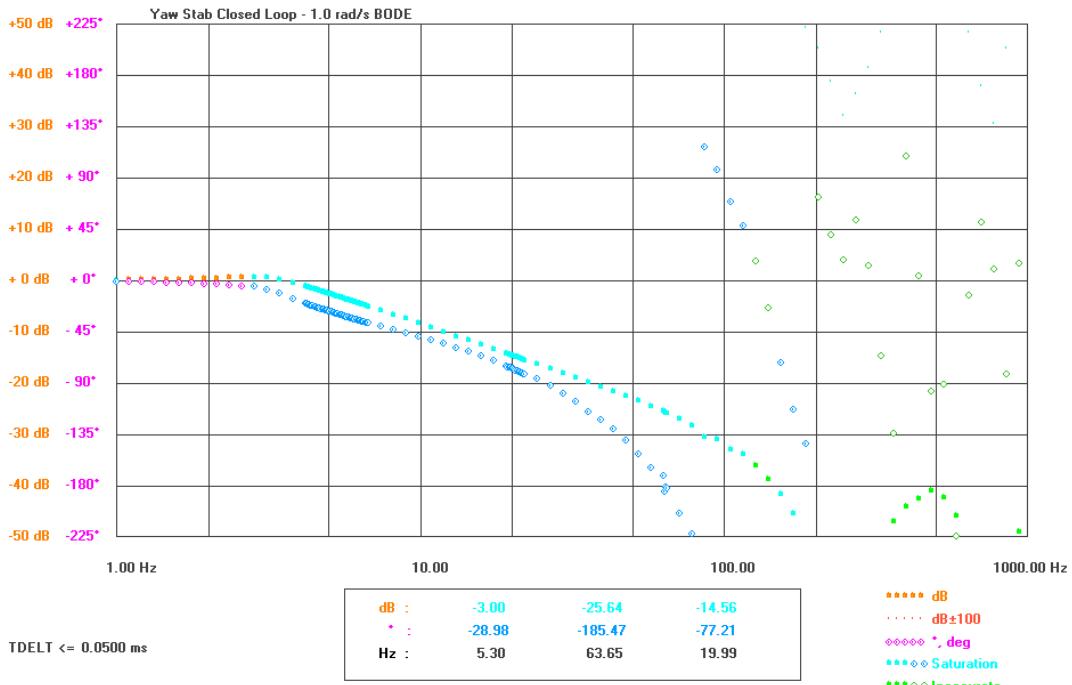


Figure 6-22: Yaw rate closed-loop Bode plot - Saturated Response

The plots above show the stable design of the yaw stabilisation loop for the ISP system. Its main properties are summarised below.

Table 6-7: Yaw rate loop properties

Gain Margin	9.33 dB (min)
Phase Margin	51.81 ° (min)
Resonance Peak	1.22 dB (max)
Linear Bandwidth	38.26 Hz

Pitch Rate Loop Linear Responses:

The linear open-loop response shown below represents the transfer function from point 7 to point 6 of the model shown in Figure 6-17.

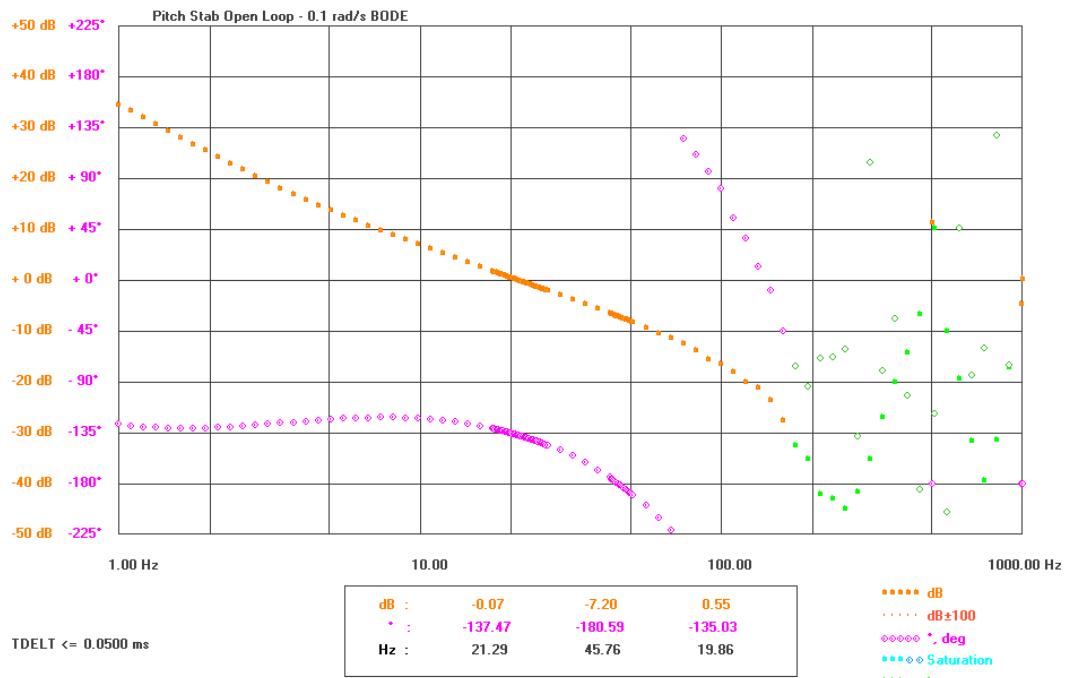


Figure 6-23: Pitch rate open-loop Bode plot - Linear Response

The linear closed-loop response shown below represents the transfer function from point 5 to point 6 of the model shown in Figure 6-17.

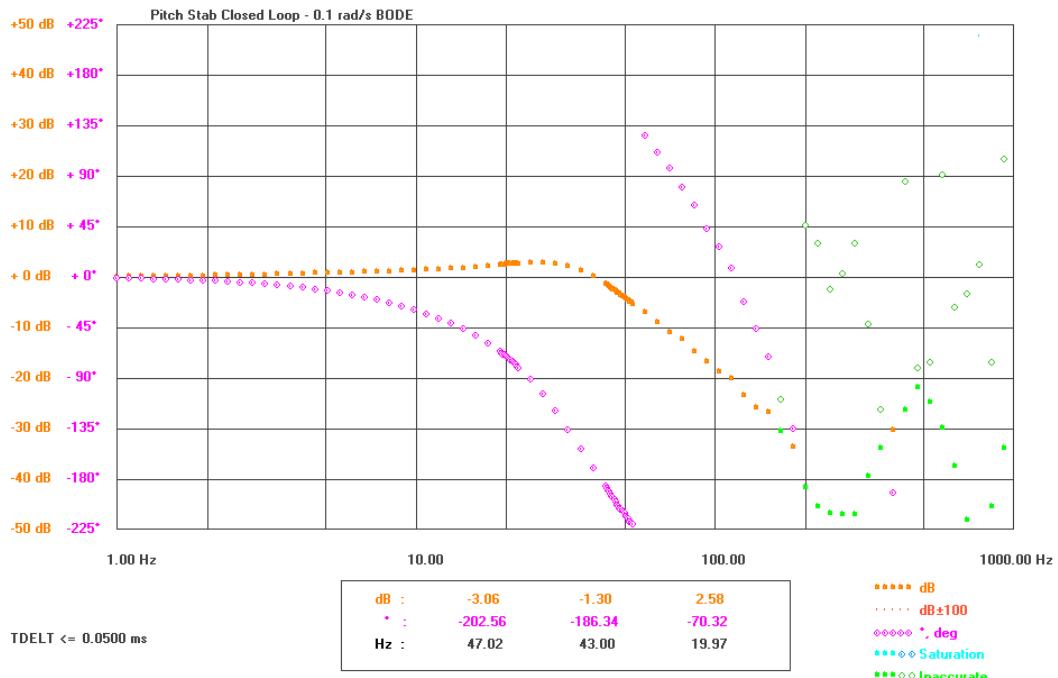


Figure 6-24: Pitch rate closed-loop Bode plot - Linear Response

Pitch Rate Loop Saturated Responses:

The saturated open-loop response shown below represents the transfer function from point 7 to point 6 of the model shown in Figure 6-17.

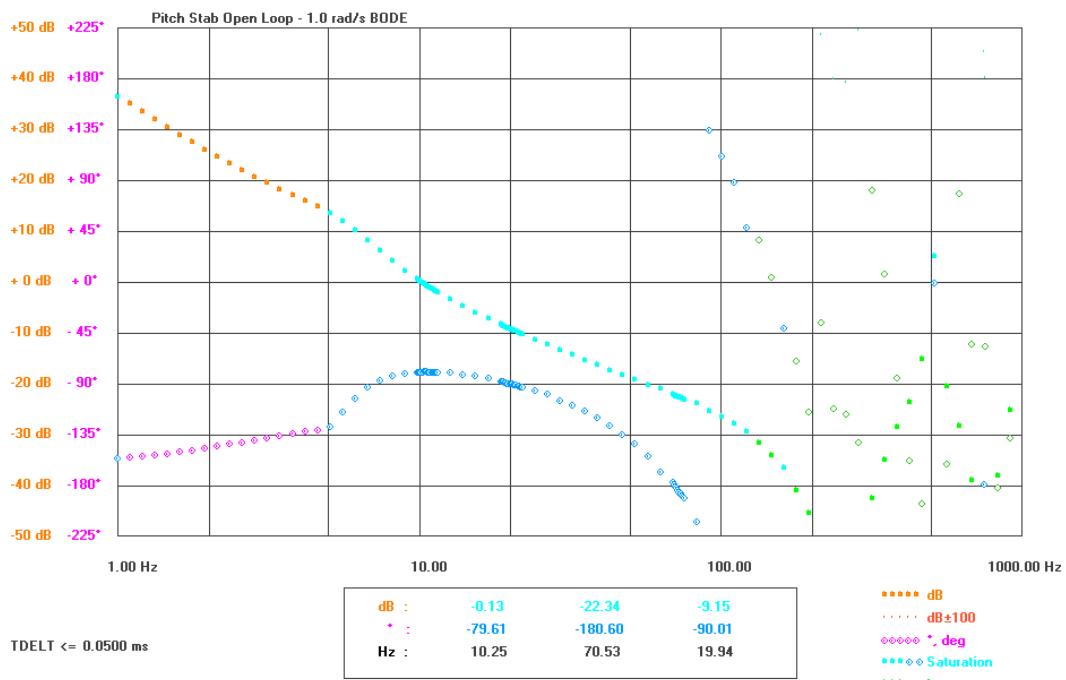


Figure 6-25: Pitch rate open-loop Bode plot - Saturated Response

The saturated closed-loop response shown below represents the transfer function from point 5 to point 6 of the model shown in Figure 6-17.

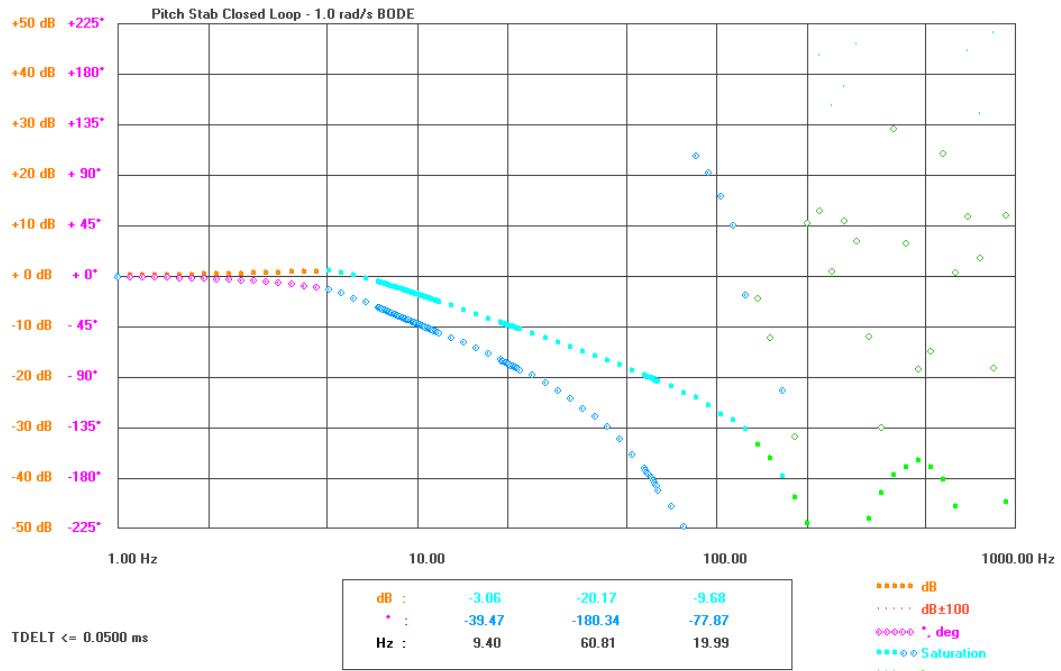


Figure 6-26: Pitch rate closed-loop Bode plot - Saturated Response

The plots above show the stable design of the yaw stabilisation loop for the ISP system. Its main properties are summarised below.

Table 6-8: Pitch rate loop properties

Gain Margin	7.20 dB (min)
Phase Margin	42.53 ° (min)
Resonance Peak	2.78 dB (max)
Linear Bandwidth	47.02 Hz

6.3.3 STABILISATION LOOPS TIME DOMAIN RESPONSES

This subsection shows the time domain response of the controllers, firstly to step inputs to the system, and secondly to base motion disturbances to the ISP host.

Step Response:

The time plot below shows the step response of both the yaw and pitch stabilisation loops in response to a 1.0 rad/s step input on points 34 and 4 respectively.

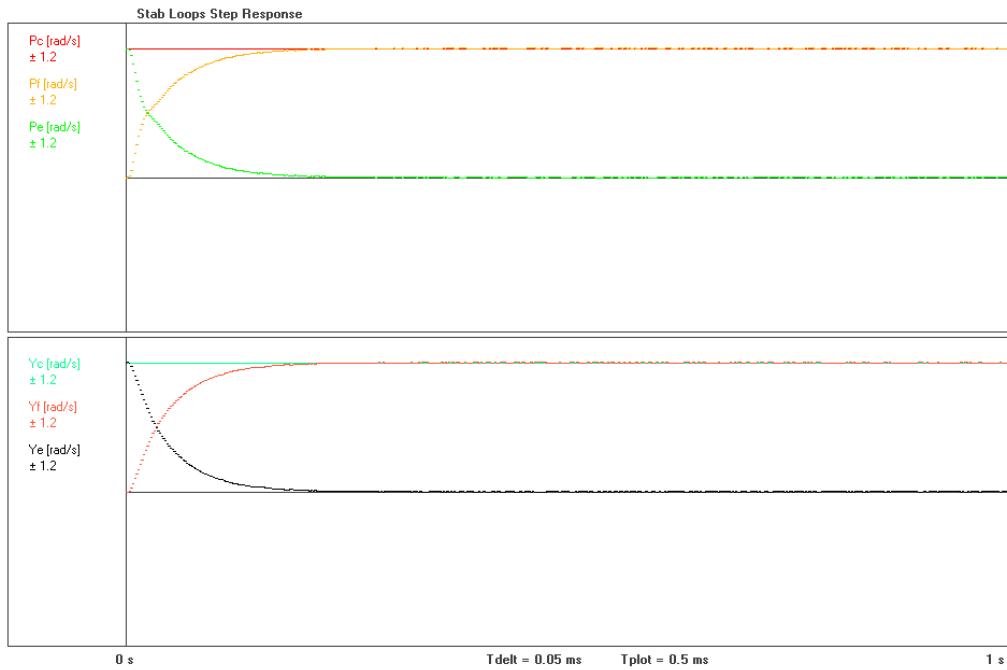


Figure 6-27: Stabilisation loop step responses

It can clearly be seen here that both channels show low settling times, approximately 0.22 s for both channels, and no overshoot on the feedback signal. The pitch channel shows a time constant of 0.041 s, whilst the yaw channel's time constant is at 0.046 s. Additionally, due to the integrator in the PI controllers used, both loops settle with no constant error.

Base Motion Effect:

The time plots below show the effect of base motion on the simulation when the ISP is oriented in its home position ($\psi = \theta = 0^\circ$). Frequency swept sine waves of various amplitudes were applied successively to each base axis between at frequencies varying between 0.1 – 5.0 Hz over a 13 s period. This frequency range was chosen as it covers the range of the dominant disturbances found in the expected operating environment (see Figure 5-24 to Figure 5-27). During this simulation period the inertial rate of each gimbal about their axis of control was monitored as well as motor voltages for both the yaw and pitch motors. Figure 6-28 below shows the effect of a large amplitude base motion at frequencies between 1.0 – 5.0 Hz on the ISP when it is oriented in its home position.

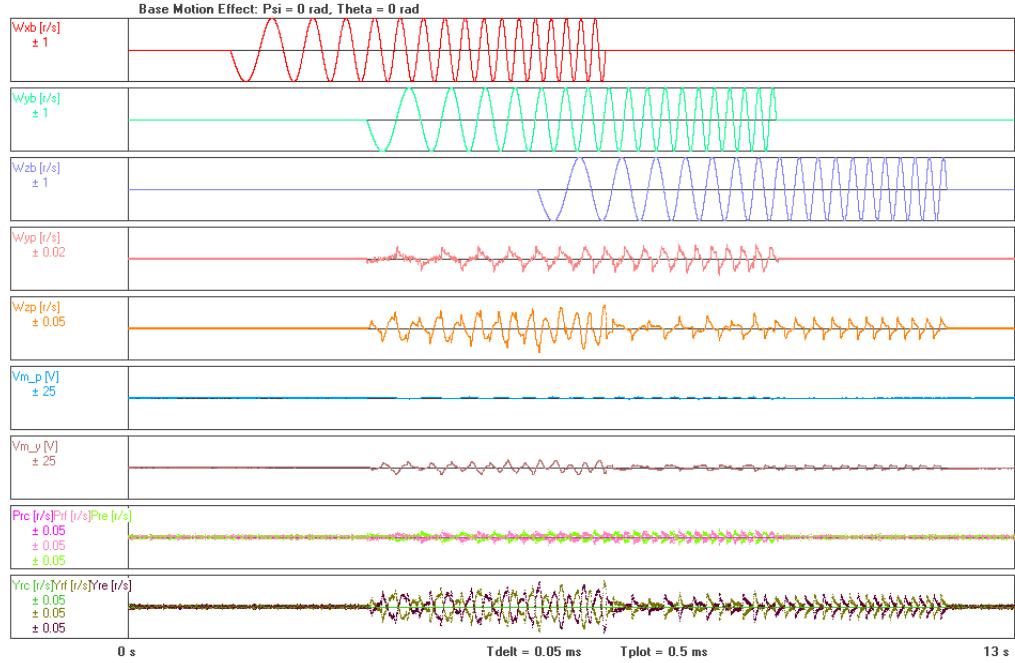


Figure 6-28: 1.0 rad/s base motion effects when $\psi = \theta = 0^\circ$

It can clearly be seen from the above figure that the controllers designed are capable of attenuating large disturbance inputs and that motor voltages do not saturate to their 24 V limit during this simulation. The inertial rates of the telescope modeller, ω_{yp} and ω_{zp} remain less than approximately 0.008 and 0.035 rad/s respectively. Figure 6-29 below shows the simulation response to base motion signals at amplitudes and frequencies between 0.1 – 0.5 Hz, representative of the peaks of the simulated base motion signal shown in Figure 5-28 to Figure 5-30.

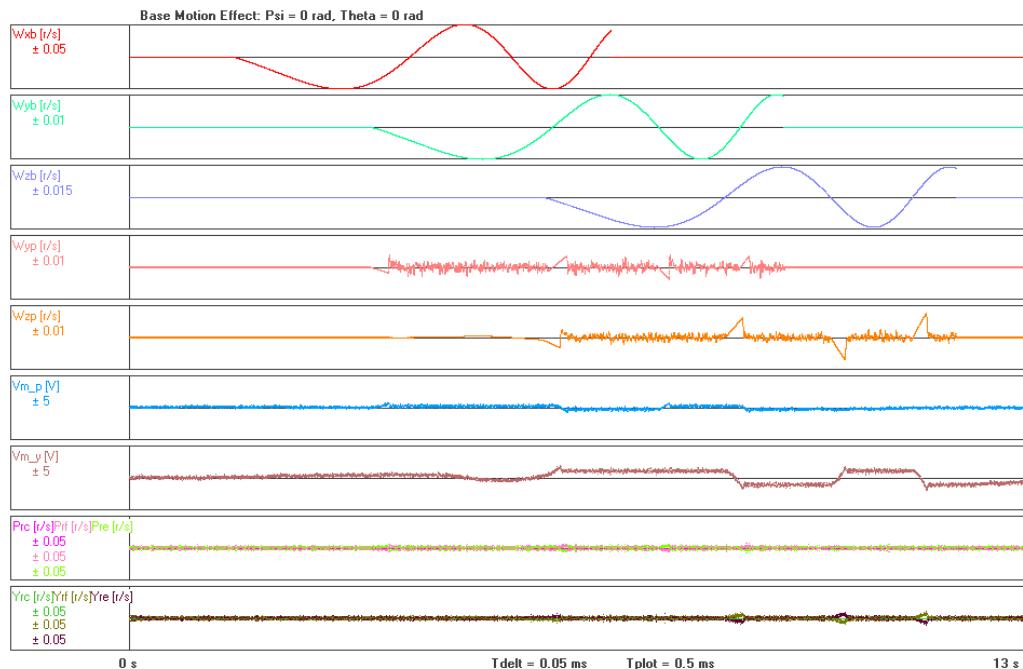


Figure 6-29: Simulated base motion signal peak effects when $\psi = \theta = 0^\circ$

It can be seen from the figure above that, again, the motor voltages remain low indicating no saturation of the system and the inertial rates ω_{yp} and ω_{zp} remain less than 0.004 and 0.008 rad/s respectively. However, it can also be seen that as the amplitude of the base motion input decreases between Figure 6-28 and Figure 6-29, the performance of the stabilisation controllers decrease. Inertial rates of the telescope modeller have not been attenuated as strongly in the second test as they were in the first. The next subsection describes the determination of the expected base motion isolation properties of the system.

BASE MOTION AND TORQUE REJECTION OF THE STABILISATION LOOPS

Base Motion Isolation:

In both the previous figures showing the effects of base motion on the inertial rates of the telescope modeller, base motion isolation (BMI) is defined from an input axis to an output axis at a such that:

$$\text{Base Motion Isolation} = 20 \log \left| \frac{\text{Amplitude } \omega_{np}}{\text{Amplitude } \omega_{nb}} \right| , \text{ where } n \in \{x, y, z\}$$

Therefore, for the first test, with large amplitude base motion signals, BMI for the pitch channel, ω_{yb} to ω_{yp} , is approximately -41.9 dB, and for the yaw channel, ω_{zb} to ω_{zp} , is approximately -29.11 dB. For the second test, with much smaller base motion signals, the BMI of the pitch channel is only approximately -8.0 dB, and for the yaw channel is only approximately -4.9 dB, showing far reduced performance from the performance with greater amplitude signals at higher frequencies. These isolation approximations were calculated at the peaks of the ω_{yp} and ω_{zp} signal in Figure 6-29. These peaks are the result of inter-gimbal stiction which couples the base motion into the telescope inertial rates until it can overcome by the stabilisation controllers. Looking at sections of the curves where the gimbals do not become stationary when changing direction and are therefore not affected by stiction, BMI increases to approximately -14.2 dB and -15.2 dB for the pitch and yaw channels respectively.

Figure 6-29 above (and Figure 6-52 in Section 6.4.2), shows the strong performance limiting effects of gimbal frictional disturbances on the stabilisation system. In this figure gimbal friction has the dominant effect on limiting the inertial rate control of the ISP for small amplitude base motion signals. Further effects of base motion and gimbal friction on the system whilst in the worst-case orientation of $\psi = -45^\circ, \theta = 45^\circ$ are shown in Section 6.4.2 after the design of the tracking loops necessary to control the ISP's orientation.

It can also be seen from the ω_{zp} curve of Figure 6-28 that base motion isolation is clearly affected by disturbances about other axes which couple into the telescope inertial rates due to the kinematic and geometric coupling relationships shown Section 2.9.2. Therefore, to obtain a more accurate estimate of the base motion isolation for the yaw and pitch channels independent of disturbances about other axes, a frequency domain evaluation of the performance of each channel was performed using a Bode plot which input a varying frequency sine wave about the relevant axis of the base, and measured the output at the relevant inertial rate signal. Initially, as shown in Figure 6-30 below, the yaw channel of the

system was evaluated first using a 1.0 rad/s amplitude sine signal, before an evaluation was performed using a 0.014 rad/s sine signal, shown in Figure 6-31 below.

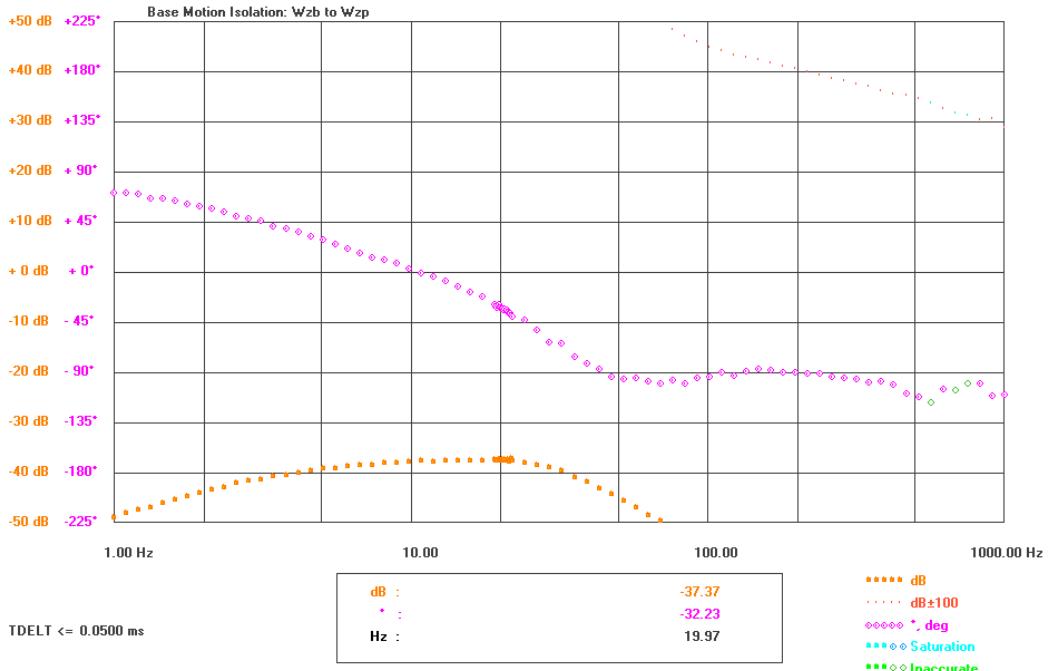


Figure 6-30: Yaw base motion isolation Bode plot with a 1.0 rad/s amplitude signal

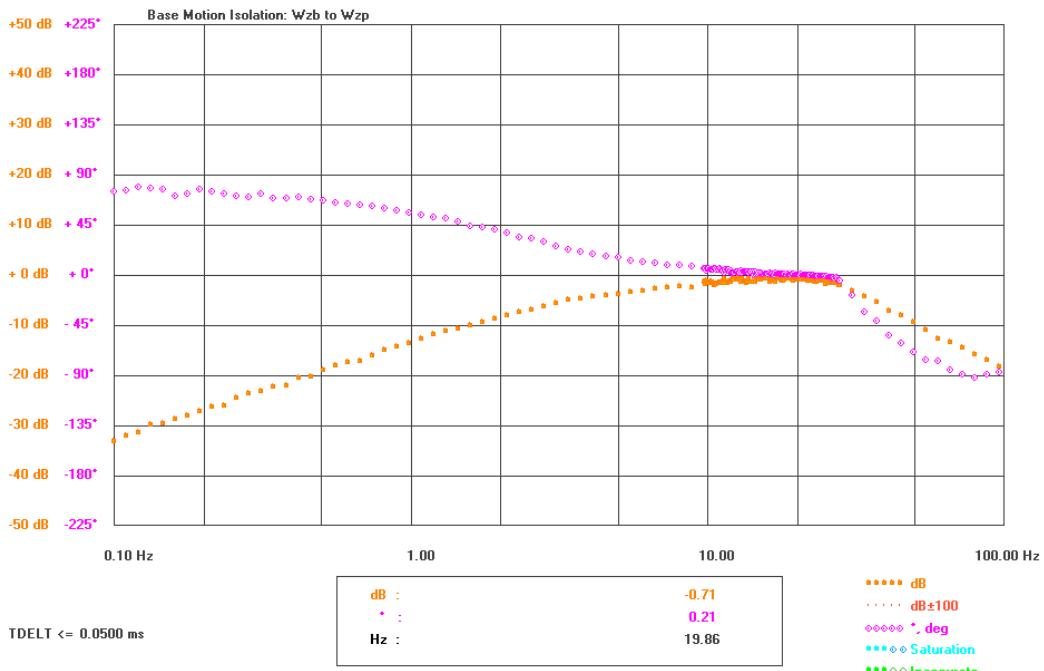


Figure 6-31: Yaw base motion isolation Bode plot with a 0.014 rad/s amplitude signal

The figures above confirm that attenuation performance decreases with decreasing amplitude input signal; the BMI of the yaw channel in response to a 1.0 rad/s amplitude signal

at 1 Hz was -48.5 dB, whilst for the 0.014 rad/s input reduced to -32.8 dB. These tests were then repeated for the pitch channel with results shown in Figure 6-32 and Figure 6-33 below.

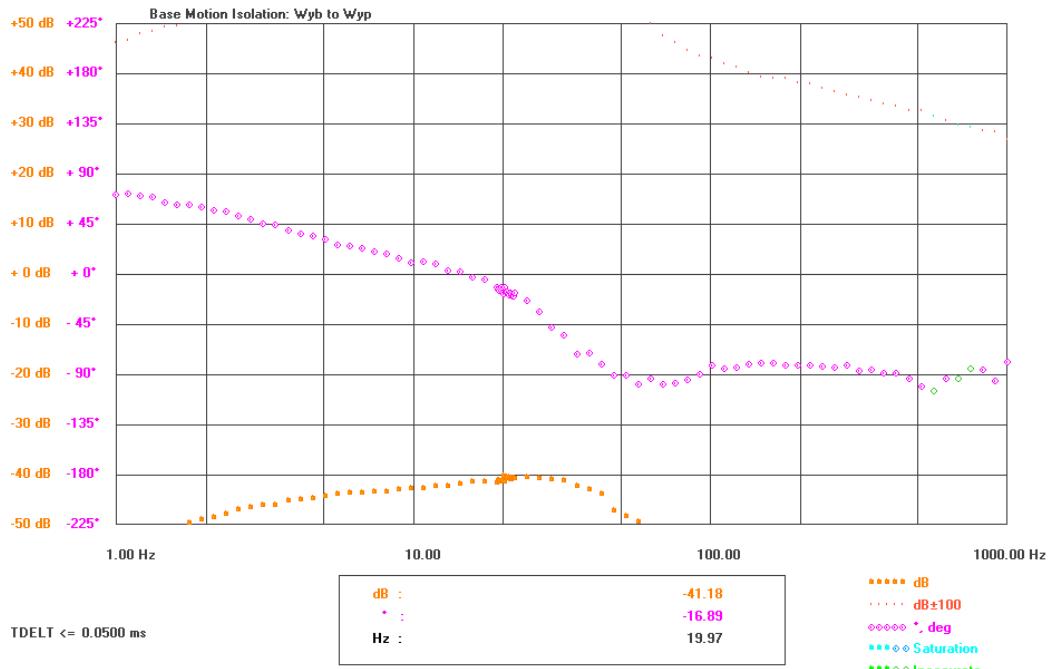


Figure 6-32: Pitch base motion isolation Bode plot with a 1.0 rad/s amplitude signal

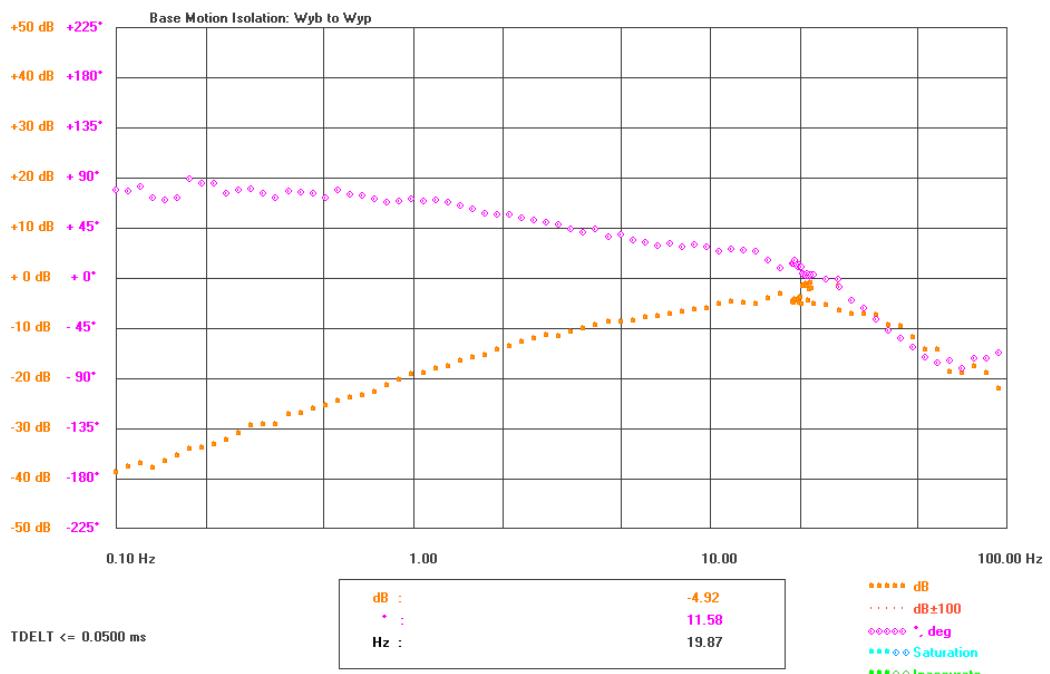


Figure 6-33: Pitch base motion isolation Bode plot with a 0.01 rad/s amplitude signal

In the figures above, the BMI of the pitch channel in response to a 1.0 rad/s amplitude signal at 1 Hz was less than -50 dB, whilst for the 0.01 rad/s input reduced to -38.1 dB.

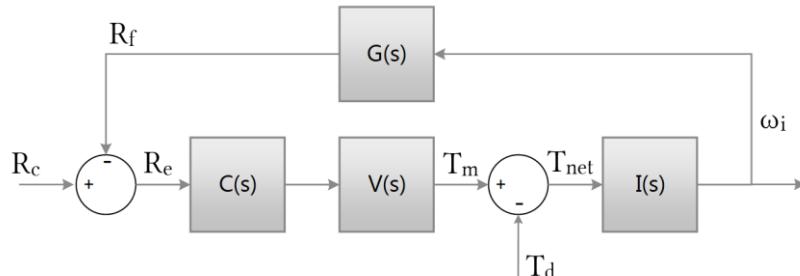
Table 6-9 below summarises the expected base motion isolation properties of the ISP when it is in its home position under the influence of these signals.

Table 6-9: System base motion isolation estimation

Channel	Frequency (Hz)	Base Motion Isolation (dB)
Yaw	1.0	-48.5
	0.1	-32.8
Pitch	1.0	<-50
	0.1	-38.1

Torque Rejection:

The previous method for evaluating the disturbance attenuation properties of the stabilisation controllers was based on the magnitude of the reduction of amplitude of a base motion rate signal to the corresponding inertial rate signal. However, these inertial rate signals are dependent on the relative angles of the gimbals and therefore, the BMI ratio will vary depending on gimbal orientation. Defining a torque rejection ratio independent of angle provides a convenient measure of attenuation performance of the controllers. The method followed here is described in [21]. The stabilisation loop for each channel may be represented by the simplified block diagram shown in Figure 6-34 below.



Where, R_c = Rate Command, R_f = Rate Feedback, R_e = Rate Error, T_m = Motor Torque, T_d = Disturbance Torque, T_{net} = Net Torque, and ω_i = Inertial Rate.

Figure 6-34: Simplified single channel stabilisation loop

In the figure above, $C(s)$ represents the transfer function of the stabilisation controller and compensators, $V(s)$ represents the transfer function of the electronics comprising the motor driver and DC motor, $I(s)$ represents the gimbal inertia transfer function and $G(s)$ represent the transfer function of the gyro sensor. Torque rejection may be defined as the transfer function from the disturbance torque to the output inertial rate given below.

$$\text{Torque Rejection} = \left| \frac{\omega_i}{T_d} \right| = \left| \frac{I(s)}{1 + C(s)V(s)I(s)G(s)} \right|$$

This transfer function is difficult to evaluate on the actual hardware and therefore may be approximated by the following:

$$\left| \frac{R_e}{R_c} \right| = \left| \frac{1}{1 + C(s)V(s)I(s)G(s)} \right| \approx \left| \frac{\omega_i}{T_d} \right|$$

The above approximation holds at low frequencies if $I(s)$ is assumed to be a rigid body. Using the above method, Figure 6-35 and Figure 6-36 below were plotted for the ISP system to estimate the torque rejection properties of the yaw channel at 1.0 Hz for 1.0 rad/s amplitude input signals, and 0.1 Hz for 0.014 rad/s amplitude input signals.

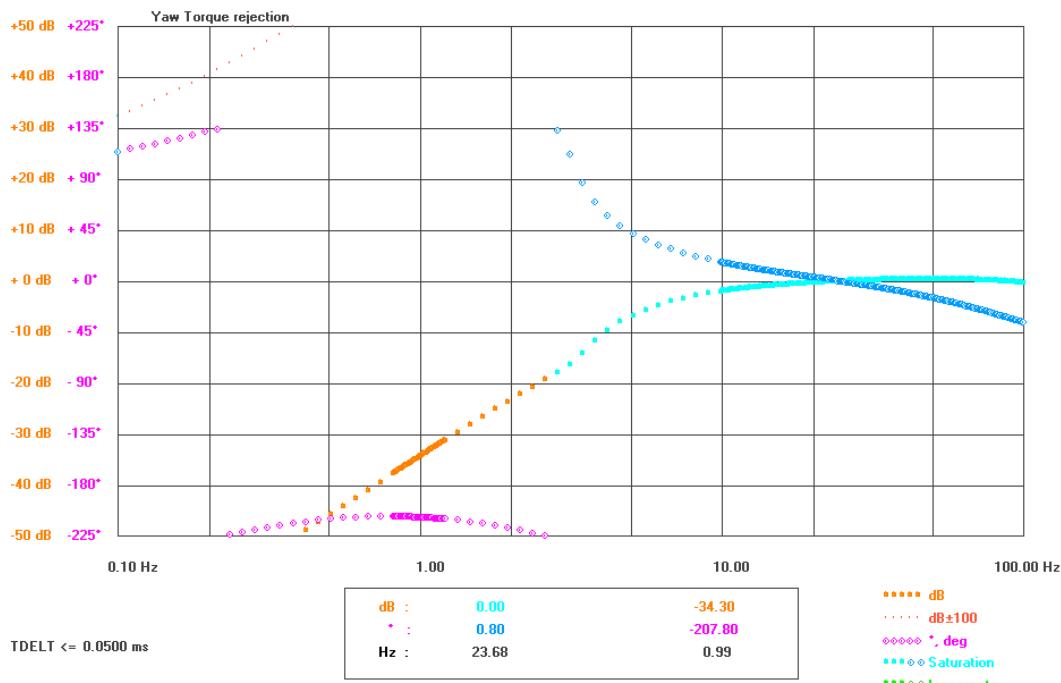


Figure 6-35: Yaw torque rejection- Yaw rate command to rate error (1.0 rad/s)

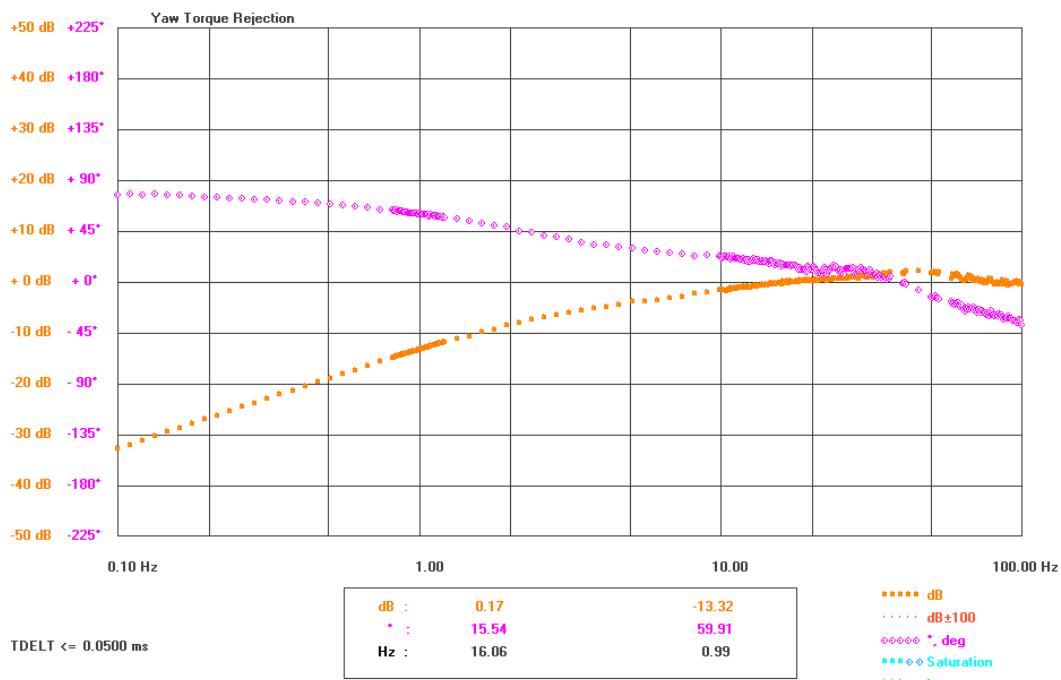


Figure 6-36: Yaw torque rejection- Yaw rate command to rate error (0.014 rad/s)

Figure 6-37 and Figure 6-38 below estimate the torque rejection properties of the pitch channel at 1.0 Hz for 1.0 rad/s amplitude input signals, and 0.01 Hz for 0.01 rad/s amplitude input signals.

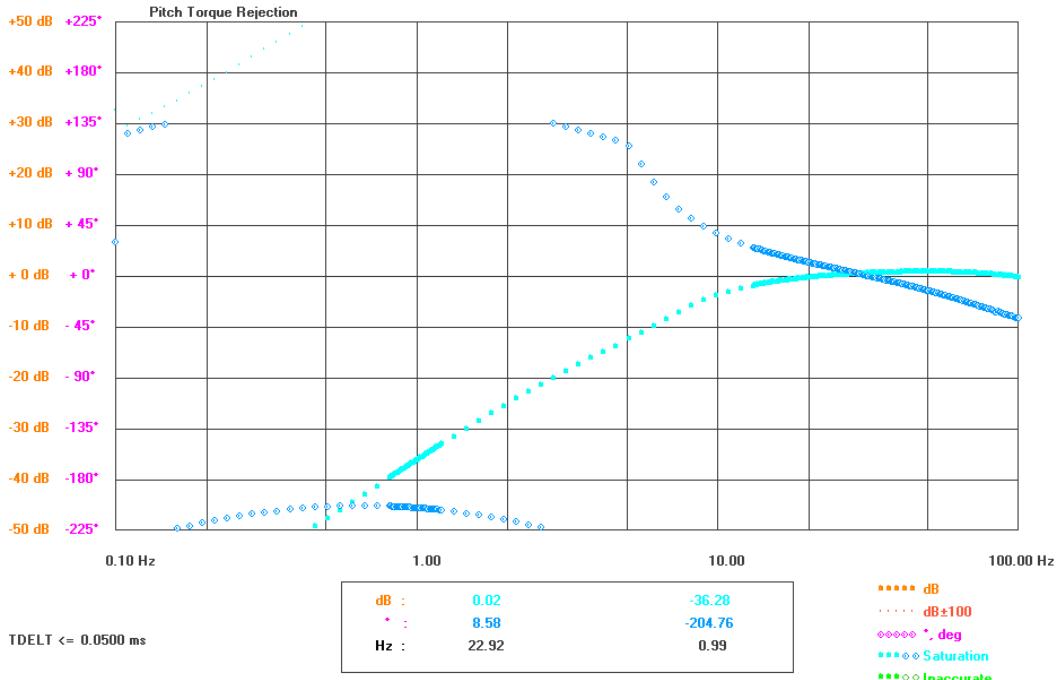


Figure 6-37: Pitch torque rejection- Pitch rate command to rate error (1.0 rad/s)

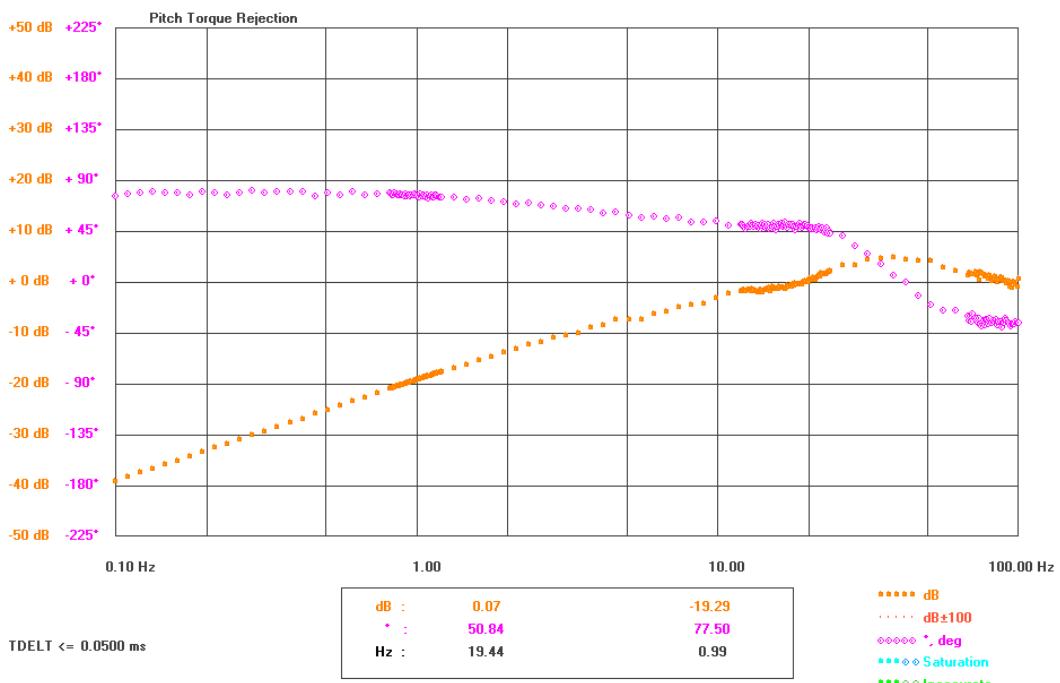


Figure 6-38: Pitch torque rejection- Pitch rate command to rate error (0.01 rad/s)

Table 6-10 below summarises the performance of each channel.

Table 6-10: Approximated torque rejection properties of the ISP stabilisation loops

Channel	Torque Rejection 1.0 rad/s at 1 Hz	Torque Rejection 0.014 (0.01 - Pitch) rad/s at 0.1 Hz
Yaw	-34.30 dB	-32.3 dB
Pitch	-36.28 dB	-38.8 dB

The figures in Table 6-9 and Table 6-10 above show that the loops designed estimate a torque rejection performance of this system which is consistent with other research projects reviewed in Section 2.3.3.

6.4 TRACKING LOOPS DESIGN (I3.3)

Once the stabilisation loops had been designed such that they were stable, the tracking loops driving them were designed. These facilitated the control of the telescope modeller's orientation in the simulation and represented prime item I3.3 of the system. Figure 6-39 below shows the development of the system identification diagram to include the tracking loops driving the stabilisation loops.

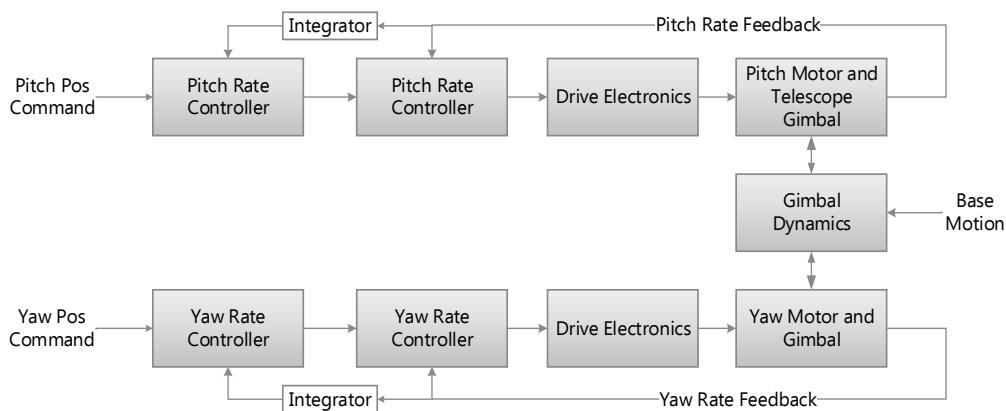


Figure 6-39: System identification block diagram for the ISP control system

As with the motor selection simulation, integrators were added to the rate feedback signals to create position feedback signals on position controller could operate. These controllers took the same form as those of Figure 78 previously and were placed such that they drove the stabilisation loops according to the cascade control structure described by Figure 5-35. The overall block diagram showing ISP simulation in this configuration is shown in Figure 6-40 overleaf. The development of this block diagram proceeded along similar lines of revision to that of the stabilisation loop, accordingly, the model shown represents that of the final, digital system.

In addition to the stabilisation loop parameters listed in Table 6-4 through Table 6-10 previously, Table 6-11 below defines the coefficients of the compensators used in the tracking loops in the block diagram overleaf, whilst Table 6-12 further details these parameters.

Table 6-11: Stabilisation loop controller and compensator coefficients

Pitch Channel	Yaw Channel
$M = T_{samp} + 2T_a$	$G = T_{samp} + 2T_c$
$N = T_{samp} - 2T_a$	$H = T_{samp} - 2T_c$
$O = T_{samp} + 2T_b$	$I = T_{samp} + 2T_d$
$P = T_{samp} - 2T_b$	$J = T_{samp} - 2T_d$

Table 6-12: Tracking loop control parameters

K_{pt}	6.0
K_{yt}	6.0
T_a	0
T_b	$\frac{1}{2\pi 10}$ s
T_c	0
T_d	$\frac{1}{2\pi 10}$ s

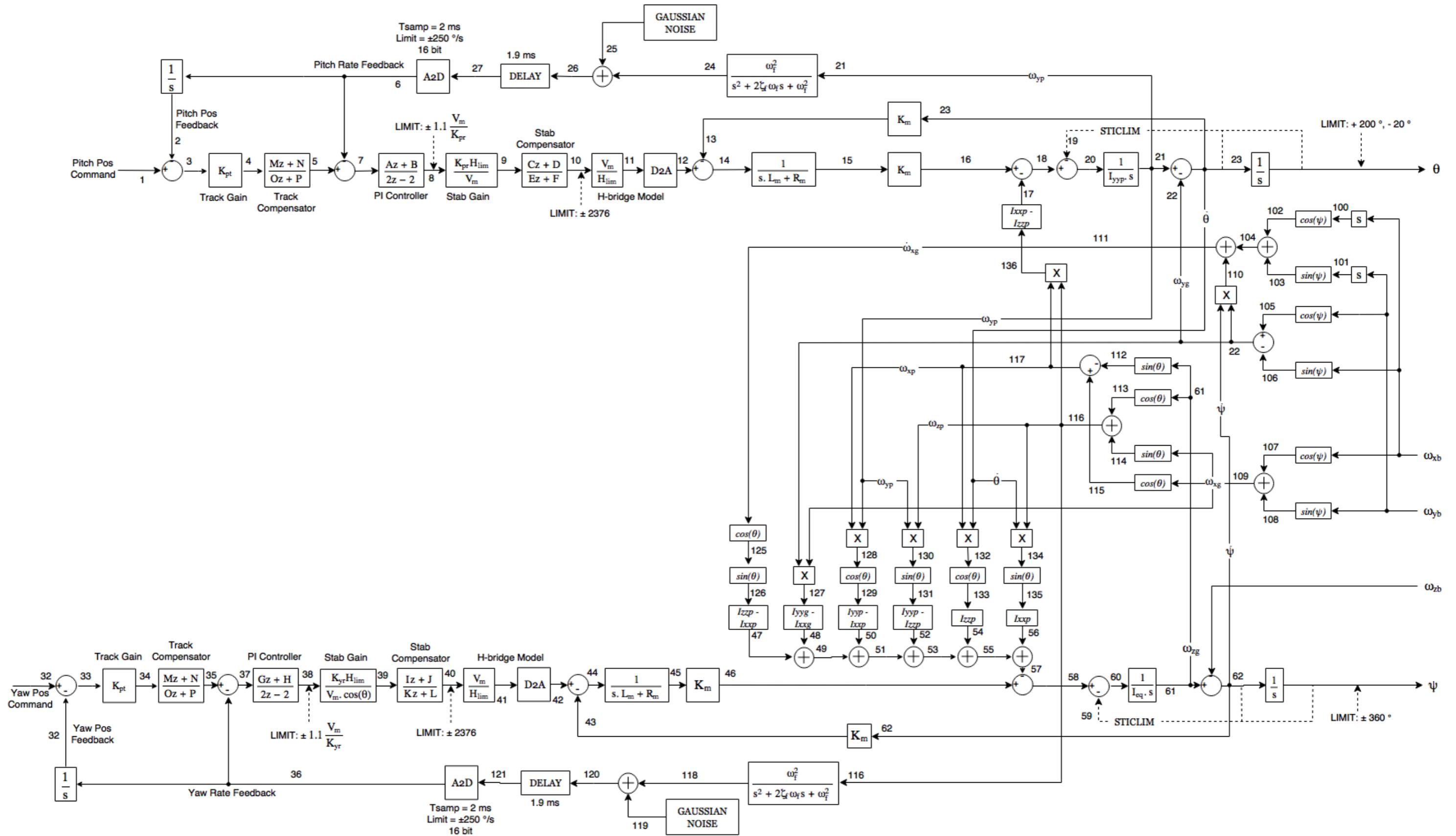


Figure 6-40: ISP model with tracking loops included around the stabilisation loops

6.4.1 TRACKING LOOP FREQUENCY DOMAIN SIMULATION RESPONSES

The responses of the yaw and the pitch tracking loops in both the frequency and time domains are here presented. The linear response plots below show the behaviour of the relevant loop in response to a varying frequency sine wave of amplitude 0.01 rad applied to the position command input, whilst the saturated response plots show the behaviour of the loop in response to a varying frequency sine wave of amplitude 0.163 rad applied to the same input. This value was chosen due to it being half of the angle of view of the full frame visible through the camera system, and therefore the maximum position error possible on the system when a target is visible.

Yaw Tracking Loop Linear Responses:

The linear open-loop response shown below represents the transfer function from point 33 to point 32 of the model shown in Figure 6-40.

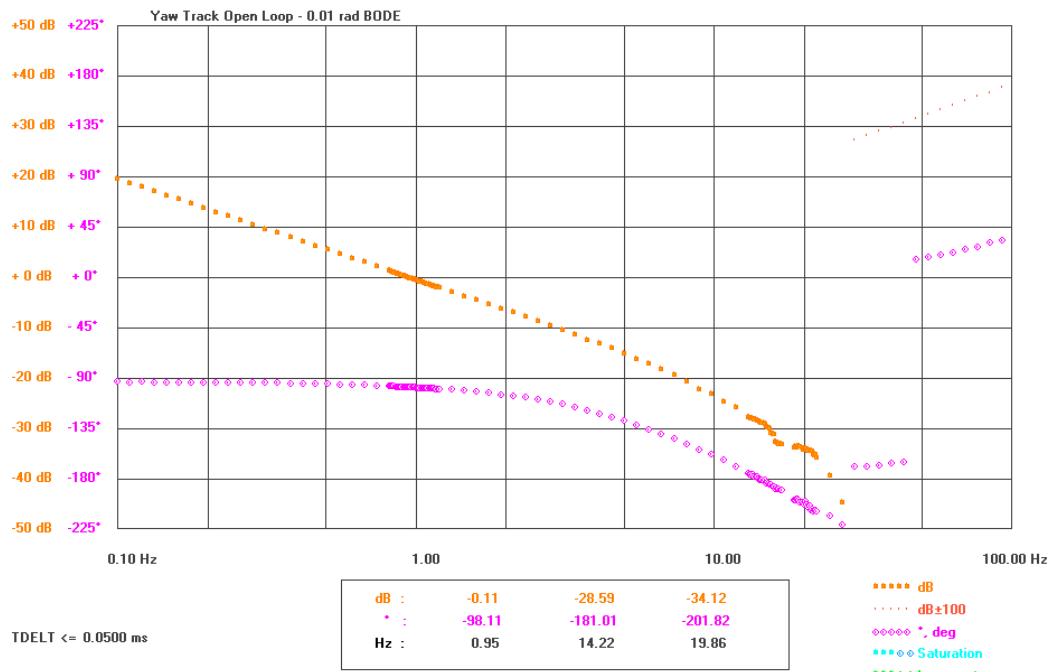


Figure 6-41: Yaw track open-loop Bode plot - Linear Response

The linear closed-loop response shown overleaf represents the transfer function from point 31 to point 32 of the model shown in Figure 6-40.

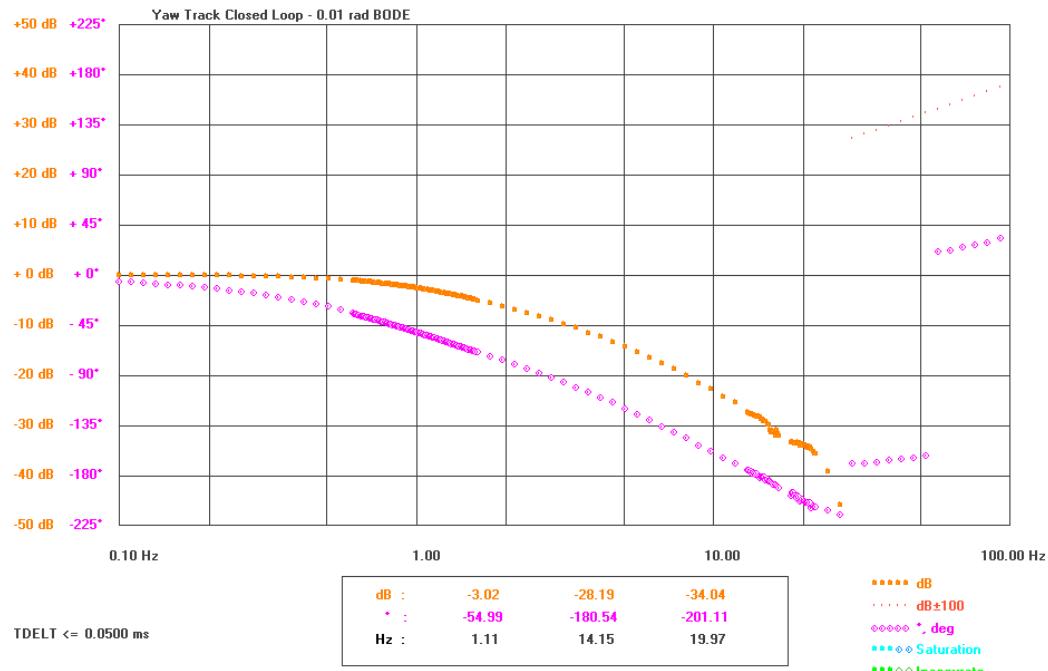


Figure 6-42: Yaw track closed-loop Bode plot - Linear Response

Yaw Tracking Loop Saturated Responses:

The saturated open-loop response shown below represents the transfer function from point 33 to point 32 of the model shown in Figure 6-40.

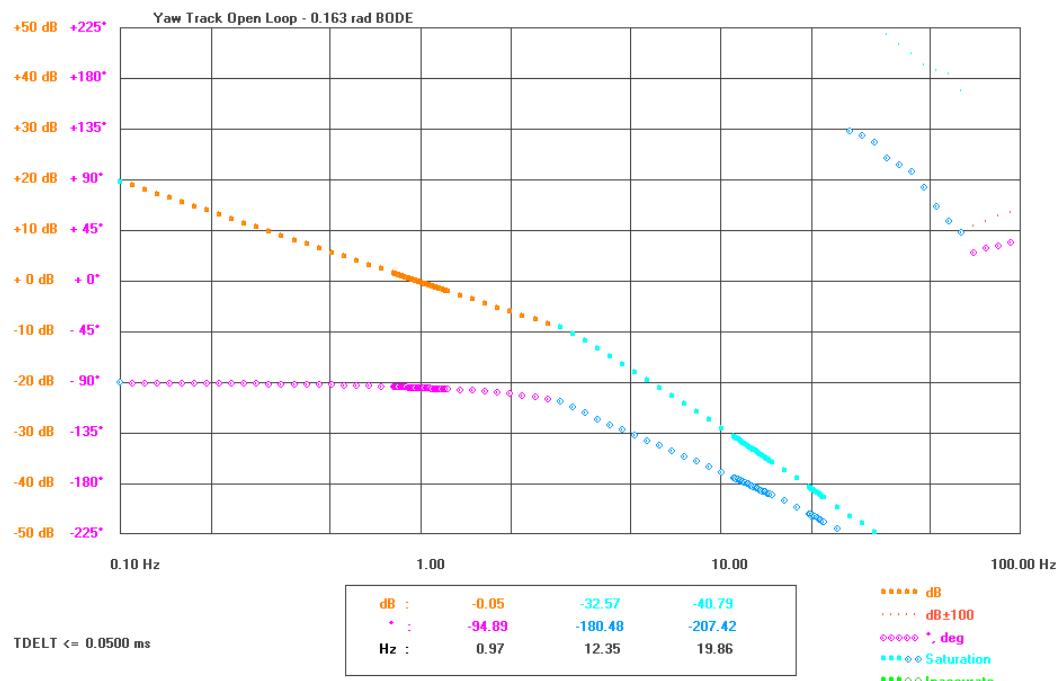


Figure 6-43: Yaw track open-loop Bode plot - Saturated Response

The saturated closed-loop response shown below represents the transfer function from point 31 to point 32 of the model shown in Figure 6-40.

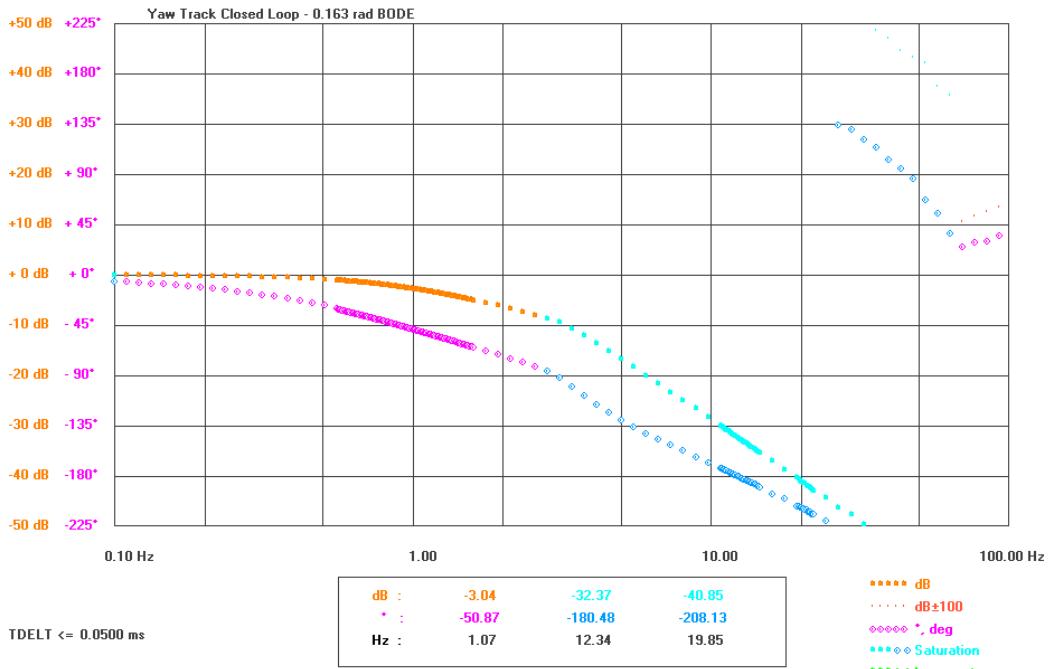


Figure 6-44: Yaw track closed-loop Bode plot - Saturated Response

The figures above show the stable design of the tracking loop controllers and compensators for the yaw channel of the ISP. Its main properties are summarised below.

Table 6-13: Yaw position loop properties

Gain Margin	25.67 dB (min)
Phase Margin	84.04 ° (min)
Resonance Peak	-
Linear Bandwidth	1.14 Hz (max)

The low bandwidth of the tracking loop designed here failed to meet the marginal requirement of 5 Hz developed in the system specification process. However, as celestial bodies move at rates predominantly far slower than even 1 Hz, it was deemed sufficient for the project.

Pitch Tracking Loop Linear Responses:

The linear open-loop response shown below represents the transfer function from point 3 to point 2 of the model shown in Figure 6-40

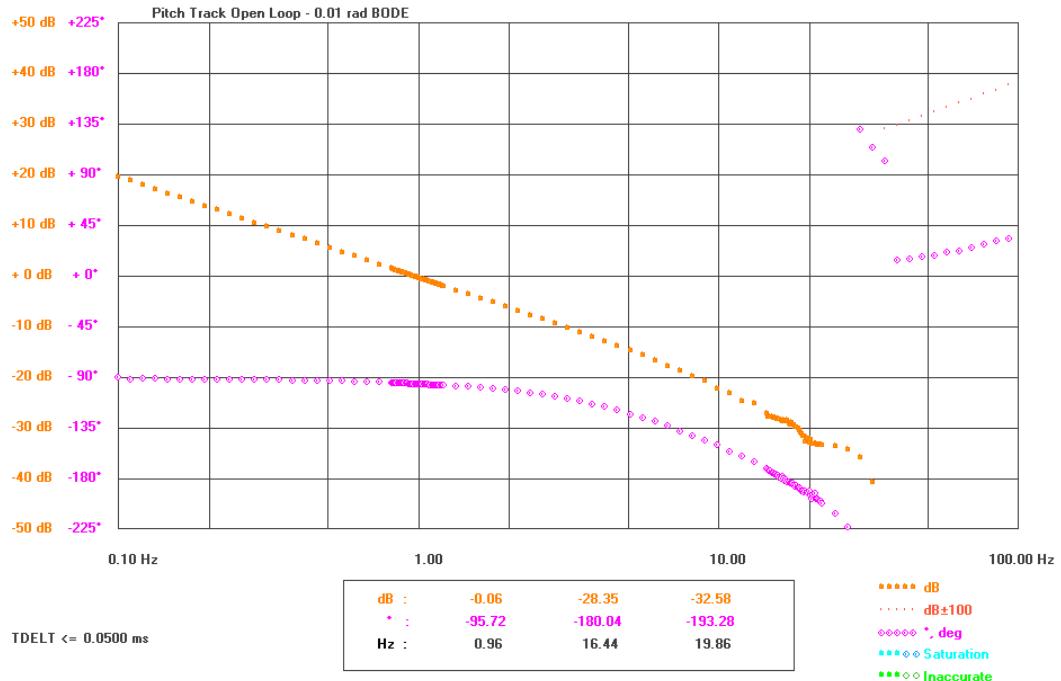


Figure 6-45: Pitch track open-loop Bode plot - Linear Response

The linear closed-loop response shown below represents the transfer function from point 1 to point 2 of the model shown in Figure 6-40.

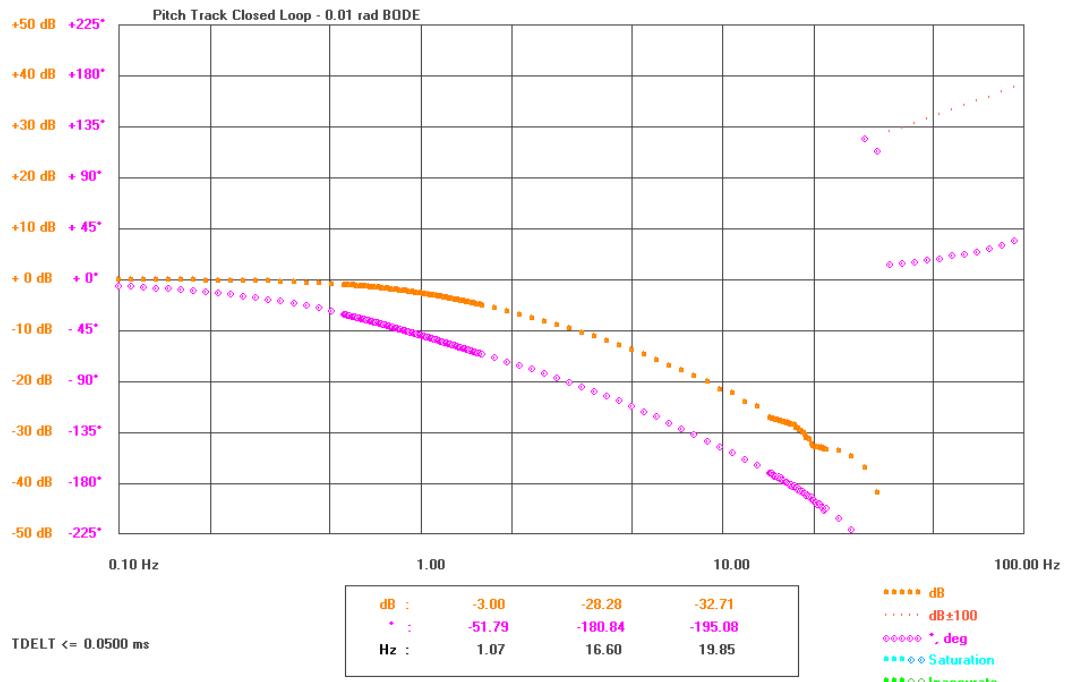


Figure 6-46: Pitch track closed-loop Bode plot - Linear Response

Pitch Tracking Loop Saturated Responses:

The saturated open-loop response shown below represents the transfer function from point 3 to point 2 of the model shown in Figure 6-40.

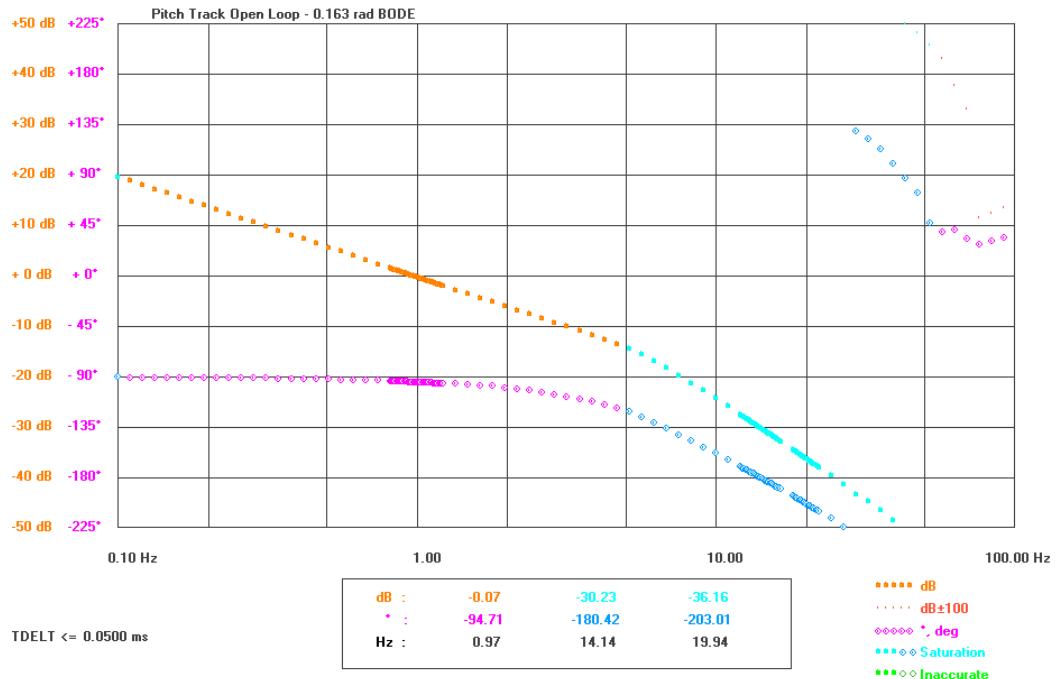


Figure 6-47: Pitch track open-loop Bode plot - Saturated Response

The saturated closed-loop response shown below represents the transfer function from point 1 to point 2 of the model shown in Figure 6-40.

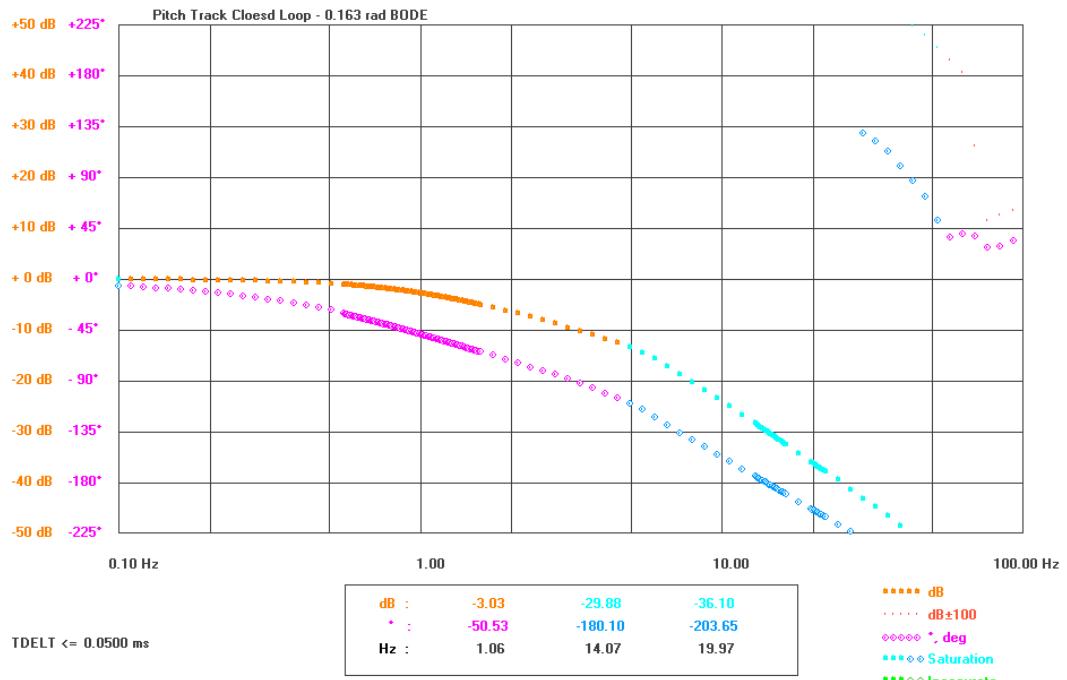


Figure 6-48: Pitch track closed-loop Bode plot - Saturated Response

The figures above show the stable design of the tracking loop controllers and compensators for the yaw channel of the ISP. Its main properties are summarised below.

Table 6-14: Pitch position loop properties

Gain Margin	24.22 dB (min)
Phase Margin	82.84 ° (min)
Resonance Peak	-
Linear Bandwidth	1.12 Hz (max)

6.4.2 TIME DOMAIN RESPONSES OF THE TRACKING LOOPS

Step Response:

The figure below shows the time domain response of the pitch and yaw tracking loops in response to a 0.163 rad step input applied at points 2200 and 2230 respectively.

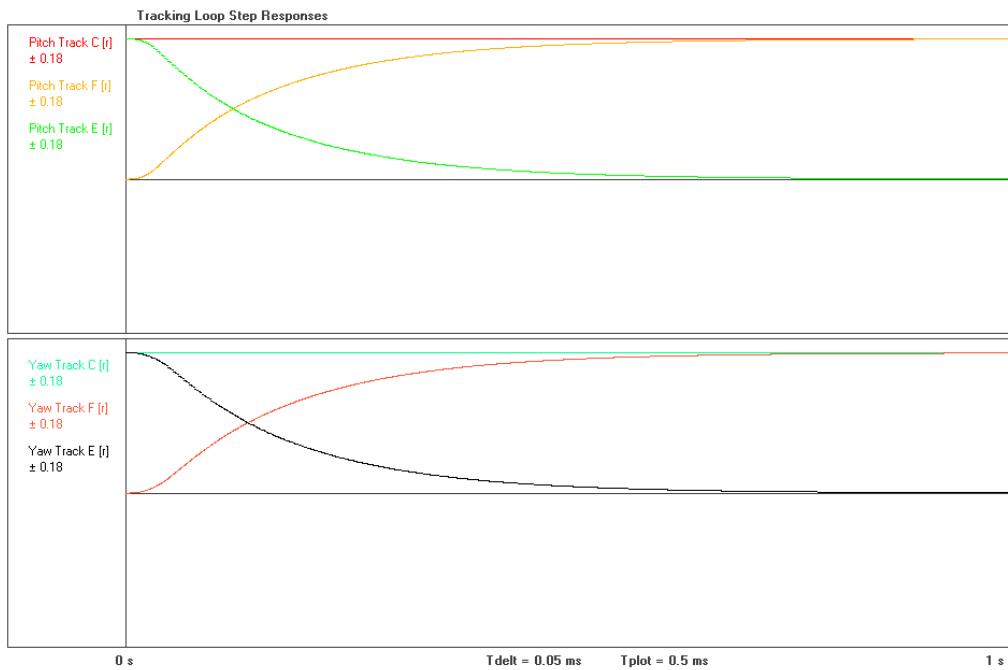


Figure 6-49: Tracking loops step following response

It can be seen clearly from the step response plots above that the control loops designed are stable and show no resonance. The pitch loop has a time constant of 0.17 s and a settling time of 0.91 s, whilst the yaw channel has a time constant of 0.19 s and a settling time of 0.95 s. Both the yaw and the pitch loops have settling times of between 0.8 - 0.9 s

Base Motion Effects:

In the previous section describing the design of the stabilisation controllers, the effects of base motion on the inertial rates of the telescope modeller were considered when the ISP was in its home position. Here, now that tracking controller have been designed to orient the

gimbals, these effects are reconsidered with the system in its worst-case position of $\psi = -45^\circ, \theta = 45^\circ$. Figure 6-50 below is analogous to Figure 6-28 of the previous section. It shows the time domain response of the system under a large 1.0 rad/s base motion signal with a frequency varying between 1-5 Hz.

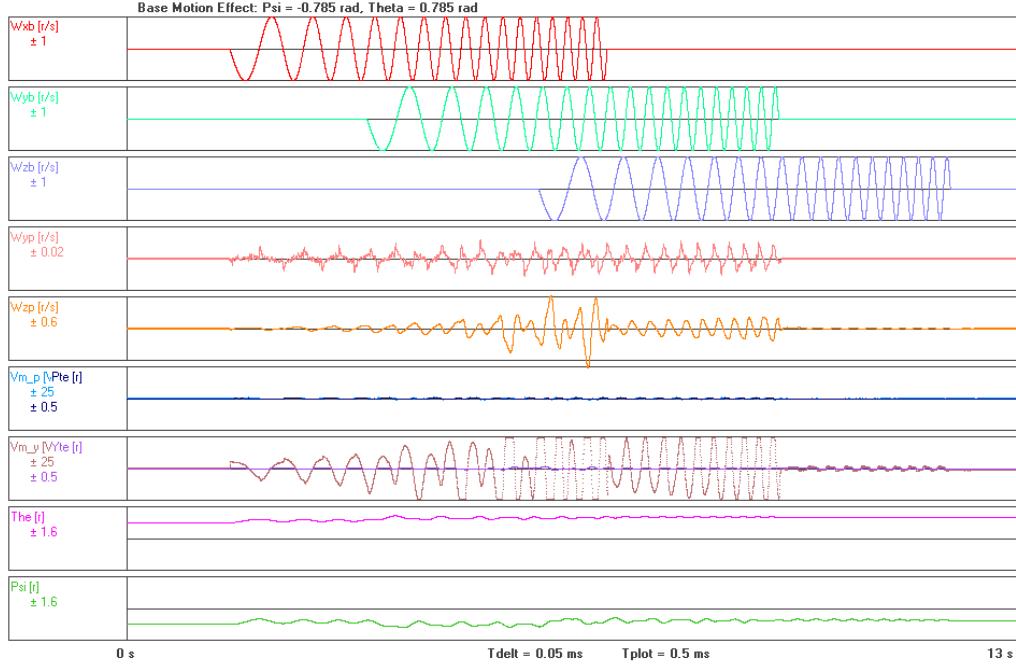


Figure 6-50: 1.0 rad/s base motion effect in the worst-case position

Here it can be seen that pitch controller performs similarly to previously, with the peak amplitude of ω_{yp} remaining at approximately 0.01 rad/s in response to the base motion. However, the yaw stabilisation controller now saturates under the large base motion disturbance, as can be seen by the yaw motor voltage limiting at 24 V in the seventh curve. The inertial rate, ω_{zp} , reaches to more than 60% of the magnitude of the input base motion (a base motion isolation of only approximately -4.4 dB) when base motion is evident about all three orthogonal axes. The controller responds better when base motion is constrained to the x_g and y_g axes, or the y_g and z_g axes, and best when disturbances are only about the z_g axis. Figure 6-51 below shows the effect of reducing the amplitude of the base motion signals above to 0.25 rad/s.

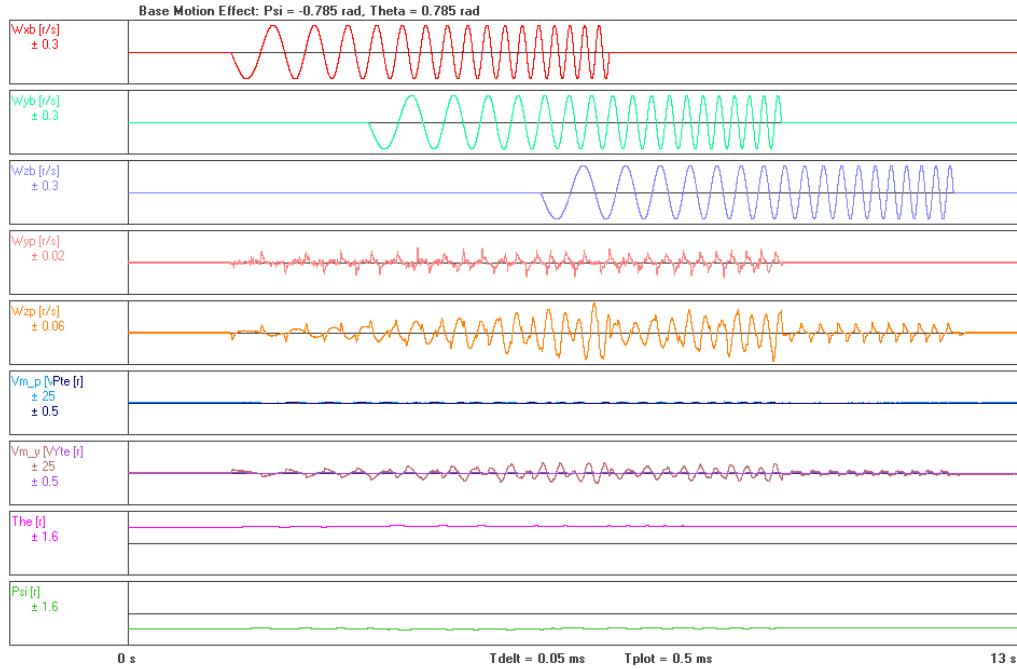


Figure 6-51: 0.25 rad/s base motion effect in the worst-case position

The reduction in amplitude of the base motion signal meant that the yaw stabilisation controller no longer saturates and that the amplitude of ω_{zp} now only reaches 24 % of the magnitude of the input signals. This improves the base motion isolation to approximately -12.4 dB from the previous test. Figure 6-52 below shows the system response to the dominant peaks from the simulated base motion signal developed for the motor selection simulation.

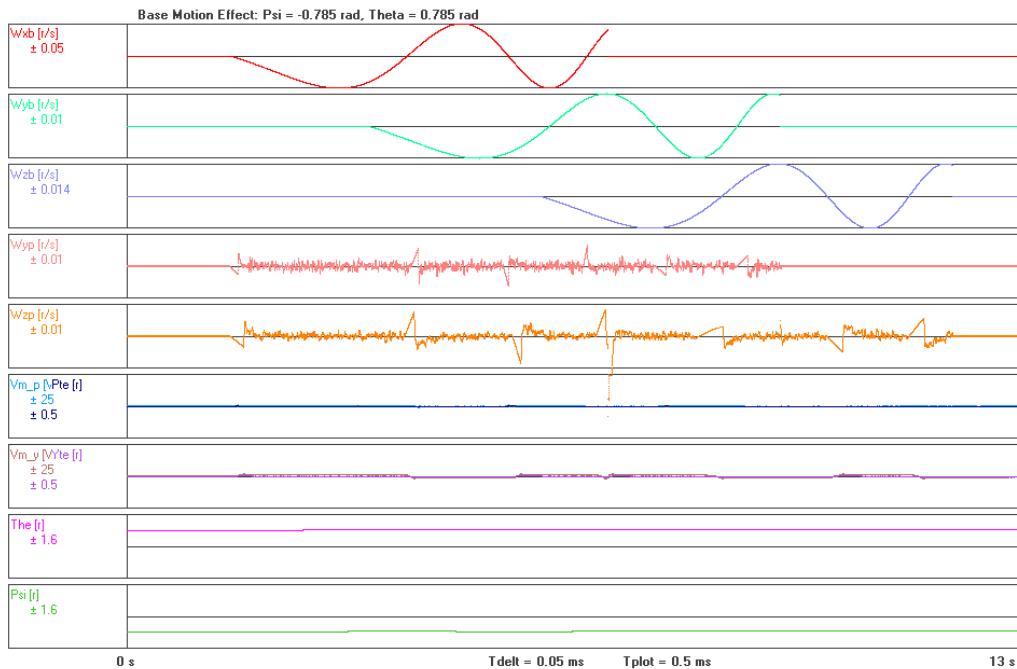


Figure 6-52: Base motion effect of the peaks of the simulated base motion signal at 0.1-0.2 Hz in the worst-case position

At this point it can be seen that the stab controllers are capable of attenuating base motion disturbances about the y_b and z_b axes at approximately -5.0 dB and -4.5 dB respectively at the stiction peaks on the inertial rate signals. Attenuation when the gimbals are already moving improves to approximately -15.4 dB and -18.3 dB about the same respective axes.

These results, coupled with those of Section 6.3.3, suggest that for base motion signals that do not cause the motors to saturate, the motors themselves are able to provide enough torque for the stabilisation loops to achieve typical performance for controllers designed using classical control methods. However, the gimbal stiction present on the mechanical assembly severely limits the achievable performance for low frequency, low amplitude signals. In addition, it was also seen that in the worst-case position, high amplitude base motion signals cause the yaw motor to saturate and disturbance rejection performance to severely degrade. As these high amplitude signals are not expected to be found in the operating environment of this ISP, this does not pose a problem for this project. However, if future work involves a change to a harsher operating environment it is suggested that another rigorous evaluation of the environment disturbances and simulation process be followed to determine whether the Faulhaber 3257024CR motor remains suitable for use as the yaw gimbal actuator.

6.5 TRACKING LOOP MODEL INCLUDING THE TARGET TRACKER

The target tracker system is required to locate the target on the FOV of the camera sensor and determine its angular position in terms of the LOS of the camera. The previous system model relied on target position commands being manually given to the control system; this revision includes the relevant mathematical model required to calculate the yaw and pitch tracking errors from the inertial position of the target and the current inertial orientation and rates of the ISP's gimbals. Figure 6-53 below shows the system identification diagram of the system with the Target Tracker included in the model.

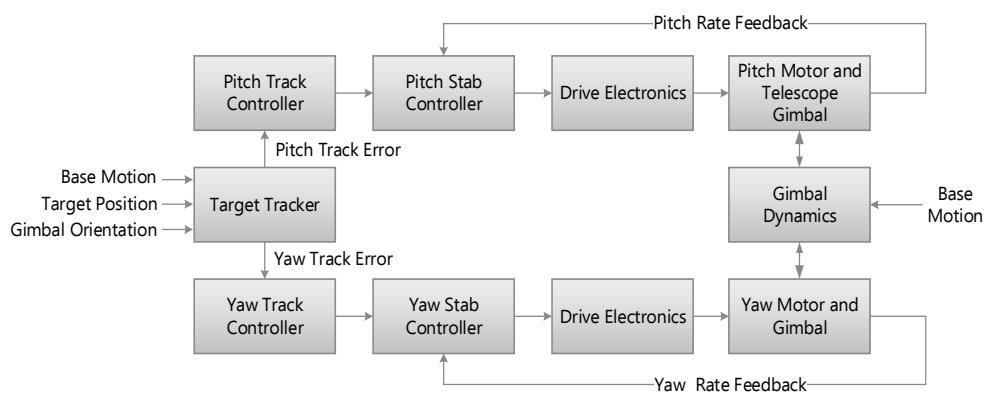


Figure 6-53: System Identification Diagram of the model with the Target Tracker included

It can be seen from the figure above that the tracking errors on which the tracking controllers act are now developed by the target tracker block. In practice this achieved determining the pixel location of the target centroid in the camera FOV and comparing it to

the centre of the FOV to find the pixel position error. This pixel error is then converted to an angle error on which the tracking controllers act. This is further detailed in Sections 7.3 and 7.2.7, however, at this point, it is sufficient to view the target tracker as block which determines the angle errors of the pitch and yaw tracking loops from the inertial position of the target, the inertial orientation of the ISP gimbals, and the angular rates of the ISP host vehicle. The section below describes the derivation of the relative geometry mathematics required to determine these angular errors in the system simulation.

6.5.1 DERIVATION OF THE SYSTEM RELATIVE GEOMETRY

The inertial orientation of a body in space can be represented by the three Euler rotations. Consider the host vehicle onto which the ISP base is affixed, its orientation can be described by these rotations. If this body is represented by a three-axis gimbal system with axes $\{x_i, y_i, z_i\}$ as shown by Figure 6-54 below, then the angles formed by moving the axis are first ψ_i , then θ_i , then ϕ_i to give the ISP system base-bound, $\{x_b, y_b, z_b\}$ axis defined in Section 2.9.1.

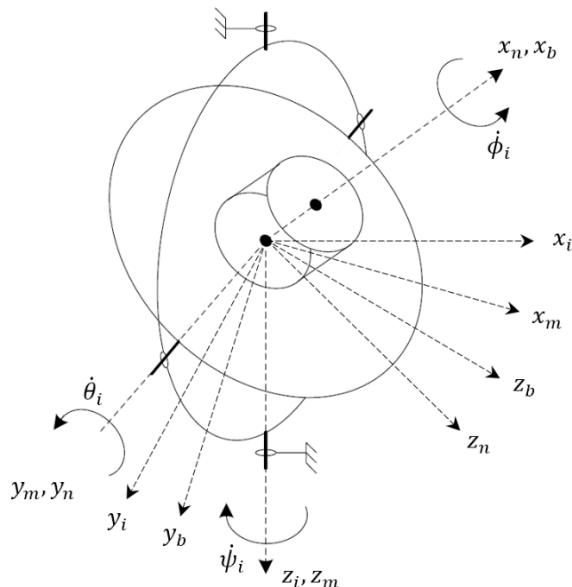


Figure 6-54: Host vehicle modelled as a three-axis gimbal (adapted from [104])

In the figure above, ψ_i is defined as the counter-clockwise angle between the x_i and the x_m axes, θ_i is defined as the counter-clockwise angle between the z_m and the z_n axes, and ϕ_i is defined as the counter-clockwise angle between the y_n and the y_b axes. The angular rates of these gimbals are given from inner-most to outer-most by:

$$\begin{bmatrix} \omega_{xb} \\ \omega_{yb} \\ \omega_{zb} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi_i & \sin \phi_i \\ 0 & -\sin \phi_i & \cos \phi_i \end{bmatrix} \cdot \begin{bmatrix} \omega_{xn} \\ \omega_{yn} \\ \omega_{zn} \end{bmatrix} + \begin{bmatrix} \dot{\phi}_i \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} \omega_{xn} \\ \omega_{yn} \\ \omega_{zn} \end{bmatrix} = \begin{bmatrix} \cos \theta_i & 0 & -\sin \theta_i \\ 0 & 1 & 0 \\ \sin \theta_i & 0 & \cos \theta_i \end{bmatrix} \cdot \begin{bmatrix} \omega_{xm} \\ \omega_{ym} \\ \omega_{zm} \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{\theta}_i \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} \omega_{xm} \\ \omega_{ym} \\ \omega_{zm} \end{bmatrix} = \begin{bmatrix} \cos \psi_i & \sin \psi_i & 0 \\ -\sin \psi_i & \cos \psi_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \omega_{xi} \\ \omega_{yi} \\ \omega_{zi} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dot{\psi}_i \end{bmatrix}$$

As $\begin{bmatrix} \omega_{xi} \\ \omega_{yi} \\ \omega_{zi} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$ by definition,

$$\begin{bmatrix} \omega_{xm} \\ \omega_{ym} \\ \omega_{zm} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \dot{\psi}_i \end{bmatrix}$$

$$\begin{aligned} \therefore \begin{bmatrix} \omega_{xb} \\ \omega_{yb} \\ \omega_{zb} \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi_i & \sin \phi_i \\ 0 & -\sin \phi_i & \cos \phi_i \end{bmatrix} \left\{ \begin{bmatrix} \cos \theta_i & 0 & -\sin \theta_i \\ 0 & 1 & 0 \\ \sin \theta_i & 0 & \cos \theta_i \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ \dot{\psi}_i \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{\theta}_i \\ 0 \end{bmatrix} \right\} + \begin{bmatrix} \dot{\phi}_i \\ 0 \\ 0 \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi_i & \sin \phi_i \\ 0 & -\sin \phi_i & \cos \phi_i \end{bmatrix} \cdot \begin{bmatrix} -\dot{\psi}_i \sin \theta_i \\ \dot{\theta}_i \\ \dot{\psi}_i \cos \theta_i \end{bmatrix} + \begin{bmatrix} \dot{\phi}_i \\ 0 \\ 0 \end{bmatrix} \end{aligned}$$

$$\begin{bmatrix} \omega_{xb} \\ \omega_{yb} \\ \omega_{zb} \end{bmatrix} = \begin{bmatrix} -\dot{\psi}_i \sin \theta_i + \dot{\phi}_i \\ \dot{\theta}_i \cos \phi_i + \dot{\psi}_i \cos \theta_i \sin \phi_i \\ -\dot{\theta}_i \sin \phi_i + \dot{\psi}_i \cos \theta_i \cos \phi_i \end{bmatrix} \quad (a)$$

$$= \begin{bmatrix} -\dot{\psi}_i \sin \theta_i + \dot{\phi}_i \\ \dot{\theta}_i \cos \phi_i + \dot{\psi}_i \cos \theta_i \sin \phi_i \\ \dot{\psi}_i \cos \theta_i \cos \phi_i \end{bmatrix} \quad (b)$$

$$= \begin{bmatrix} -\dot{\psi}_i \sin \theta_i + \dot{\phi}_i \\ \dot{\theta}_i \cos \phi_i + \dot{\psi}_i \cos \theta_i \sin \phi_i \\ -\dot{\theta}_i \sin \phi_i + \dot{\psi}_i \cos \theta_i \cos \phi_i \end{bmatrix} \quad (c)$$

Algebraic manipulation:

$$(b) \sin \phi_i + (c) \cos \phi_i: \quad \omega_{yb} \sin \phi_i + \omega_{zb} \cos \phi_i = \dot{\psi}_i \cos \theta_i \quad (d)$$

$$(b) \cos \phi_i - (c) \sin \phi_i: \quad \omega_{yb} \cos \phi_i - \omega_{zb} \sin \phi_i = \dot{\theta}_i \quad (e)$$

Substituting (d) into (a):

$$\omega_{zb} = \phi_i - \tan \theta_i (\omega_{yb} \sin \phi_i + \omega_{zb} \cos \phi_i)$$

$$\begin{aligned} \therefore \begin{bmatrix} \dot{\psi}_i \\ \dot{\theta}_i \\ \dot{\phi}_i \end{bmatrix} &= \begin{bmatrix} 0 & \sec \theta_i \sin \phi_i & \sec \theta_i \cos \phi_i \\ 0 & \cos \phi_i & -\sin \phi_i \\ 1 & \tan \theta_i \sin \phi_i & \tan \theta_i \cos \phi_i \end{bmatrix} \cdot \begin{bmatrix} \omega_{xb} \\ \omega_{yb} \\ \omega_{zb} \end{bmatrix} \\ &= \begin{bmatrix} \psi_i \\ \theta_i \\ \phi_i \end{bmatrix} = \frac{1}{s} \begin{bmatrix} \dot{\psi}_i \\ \dot{\theta}_i \\ \dot{\phi}_i \end{bmatrix} \end{aligned}$$

If the target has an inertial position:

$$\text{Inertial Target Position} = \begin{bmatrix} X_{targ} \\ Y_{targ} \\ Z_{targ} \end{bmatrix}$$

And \vec{B} is defined as the vector which describes the target position in the FOV of the camera affixed to the telescope modeller and aligned with its axes such that the centre of its FOC is along the x_p axis, then:

$$\vec{B} = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix} \cdot \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi_i & \sin \phi_i \\ 0 & -\sin \phi_i & \cos \phi_i \end{bmatrix}.$$

$$\begin{bmatrix} \cos \theta_i & 0 & -\sin \theta_i \\ 0 & 1 & 0 \\ \sin \theta_i & 0 & \cos \theta_i \end{bmatrix} \cdot \begin{bmatrix} \cos \psi_i & \sin \psi_i & 0 \\ -\sin \psi_i & \cos \psi_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_{targ} \\ Y_{targ} \\ Z_{targ} \end{bmatrix}$$

The pitch and yaw gimbal position/tracking loop error signals are therefore given by:

$$P_{te} = -\tan^{-1}\left(\frac{B_3}{B_1}\right), \quad Y_{te} = \tan^{-1}\left(\frac{B_2}{B_1}\right)$$

These results are included in the final system simulation model shown in Figure 6-55 overleaf. Also included in the model shown is a delay of 95 ms on tracking error outputs from the relative geometry block. This delay models the processing delay of the target tracker which is capable of processing a minimum of 10.5 frames per second (see Section 7.3.2).

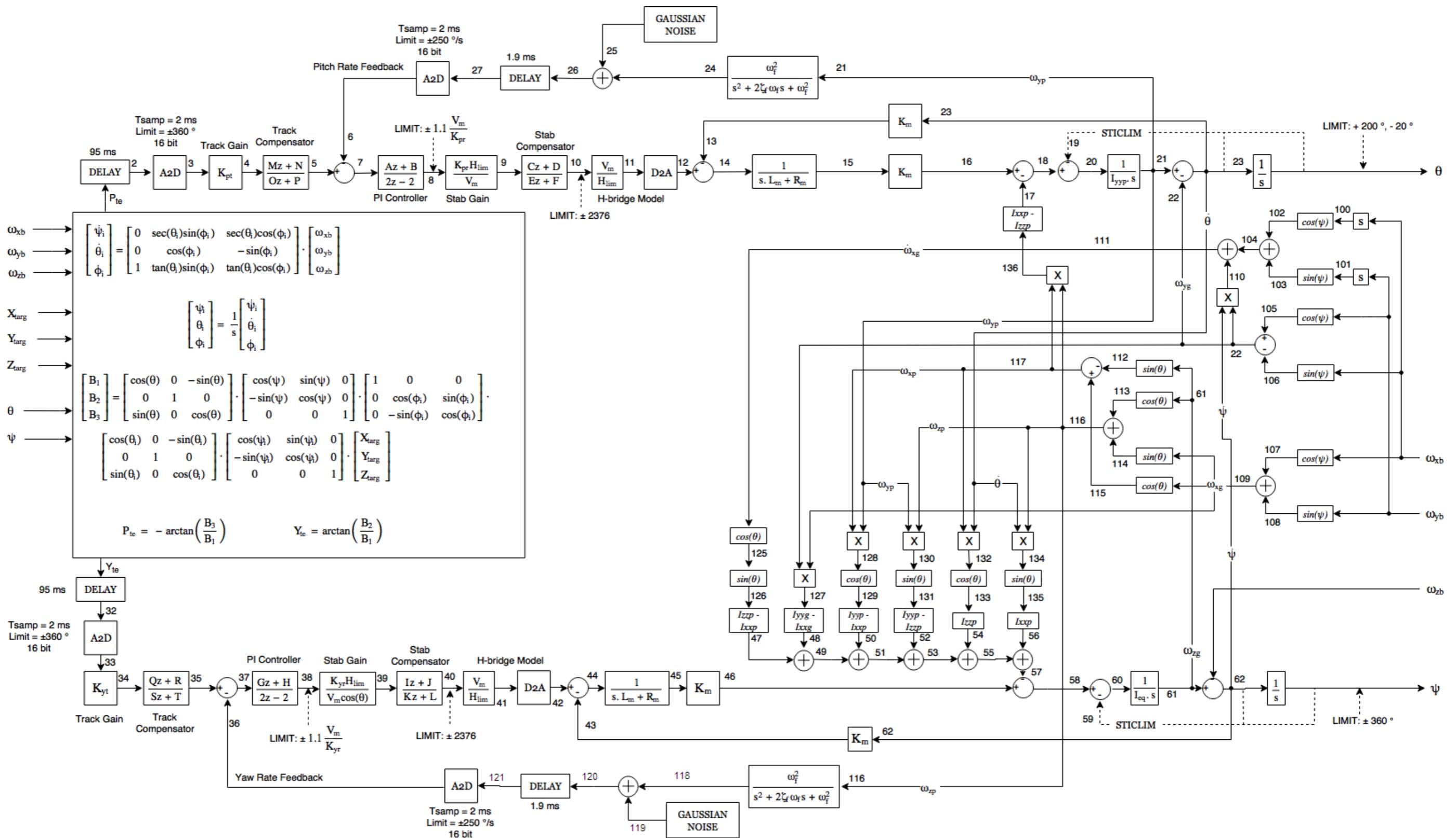


Figure 6-55: Final ISP simulation block diagram

6.5.2 TESTING OF THE SIMULATION WITH RELATIVE GEOMETRY ADDED

In order to verify the relative geometry model included in the latest revision of the system simulation, a step response in the time domain and base motion effect plots of the same form as those of the previous section were simulated.

Step Response:

The figure below shows the step response of the ISP to the gimbal positions, $\theta = 45^\circ, \psi = -45^\circ$. This was done by setting the target position to $\{x_i, y_i, z_i\} = \{1000, -1000, -1414.2\}$.

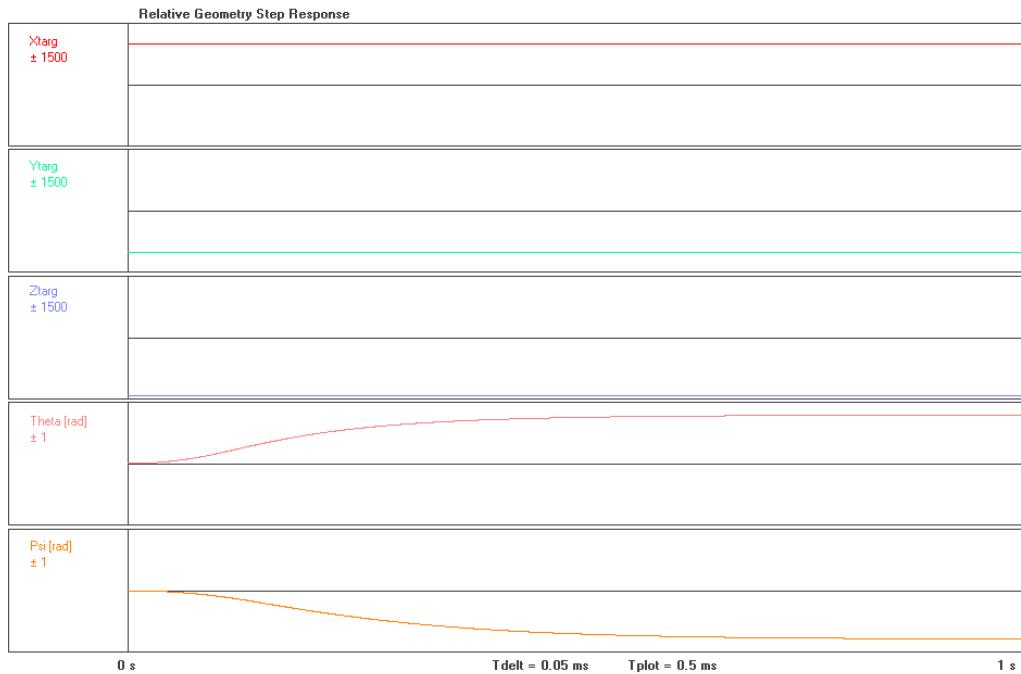


Figure 6-56: Tracking step response using a target and relative geometry

The step response above shows successful tracking of the target with the relative geometry model.

Base Motion Effects:

The base motion tests of Section 6.4.2 were rerun using the revised model, such that Figure 6-57 below represents the system response to 1.0 rad/s amplitude base motions between 1.0 – 5.0 Hz whilst the ISP is oriented in its worst-case position.

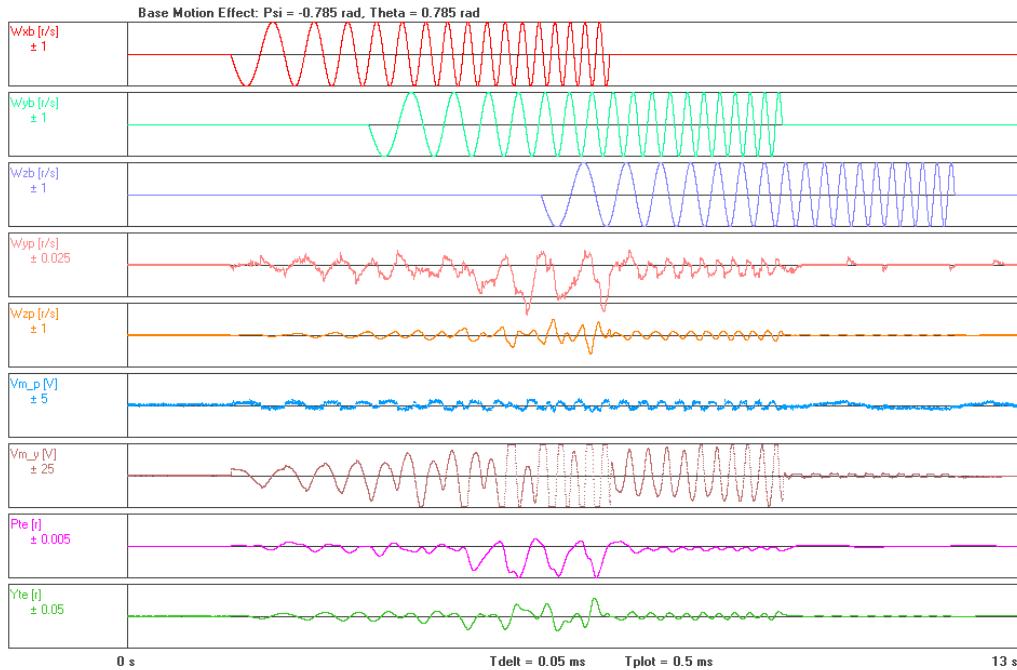


Figure 6-57: 1.0 rad/s base motion effect with the relative geometry model

Although the responses of the system here are not identical to those of the analogous Figure 6-50, they are of the same approximate magnitudes and shapes. The small differences that exist can largely be accounted for by the addition of the 95 ms delay which has been included in this simulation revision to model the time taken by the target tracker to identify and locate the target, which exacerbates the effects of saturation evident in response to large base motion signals. In the plot above, the pitch and yaw track error signals were plotted in the final two curves. These signals are the output of the target tracker and represent system jitter in a circumstance like this where the target is stationary. The system specifications of Appendix A defined maximum jitter allowances for the final system in specification S6; under dynamic vehicle conditions, jitter was to be less than 2 mrad and less than 0.5 mrad under stationary host conditions. In the figure above, it can be seen that the ISP is not capable of achieving these specifications under large base motions but underperforms when saturated by a factor of approximately 12.5. Continuing to compare the responses between tracking methods, Figure 6-58 below shows the responses of the model with the amplitude of the base motion signals reduced to 0.25 rad/s across the same frequency range, whilst Figure 6-59 shows the effect of a base motions representative of the peaks of the simulated base motion signal.

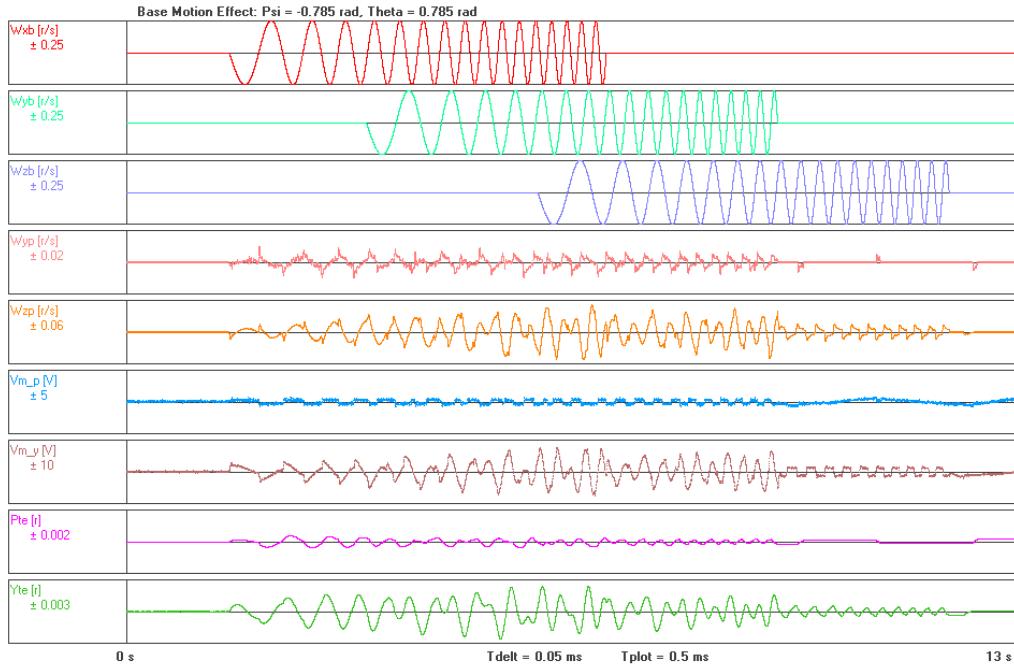


Figure 6-58: 0.25 rad/s base motion effect with the relative geometry model

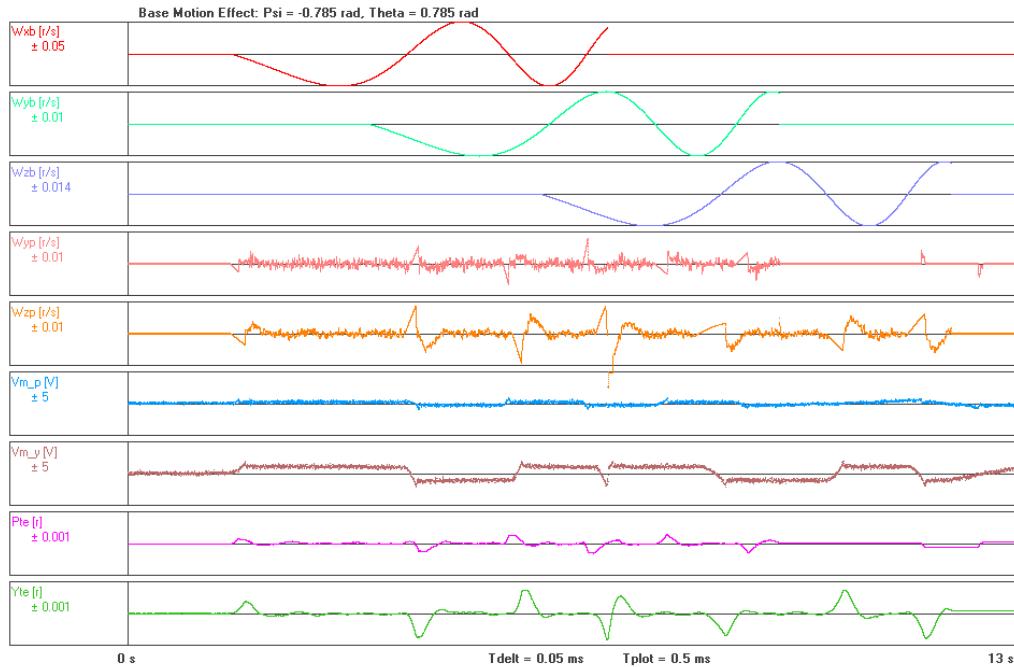


Figure 6-59: Base motion effect of peak simulation signal in the worst-case position with relative geometry

With the base motion magnitudes reduced to 0.25 rad/s, and those of the peaks of the simulated base motion signal, the simulation response using the relative geometry block matches that of the initial method very well (see Figure 6-51 and Figure 6-52) with the inertial rates being almost identical even with the inclusion of the 95 ms delay. The jitter performance of the system under linear conditions with smaller base motion disturbances is also much improved from the previous test. Jitter now matches the specification for the ISP's

perform well under dynamic conditions and falls to less than 3 mrad for 0.25 rad/s base motions and less than 1 mrad for base motions representative of the peaks of the simulated base motion signal. These results also indicate that the relative geometry model included here performs as expected and facilitates the tracking of a target whose position is defined in the inertial axis system.

The final base motion effect investigated using the model was that of the simulated base motion signal itself. This signal models the disturbances expected from the operating environment defined for the ISP in this project, a moving vehicle. This signal was developed according to the method described in the subsection, “Experimental Determination of Vehicular Base Motions” of Section 5.2.4, where peak signals from several base motion test measurements were added to a Gauss noise to create simulated signals which were representative of the peak and RMS values of the test data signals. When used in the motor selection simulation, these signals were read from a .csv file into the simulation, however, Simul_C_EM did not have this functionality and so the signals were created directly in the simulation as a combination of sine waves and Gauss noise functions. These base motions are shown in the first three curves of Figure 6-60 below.

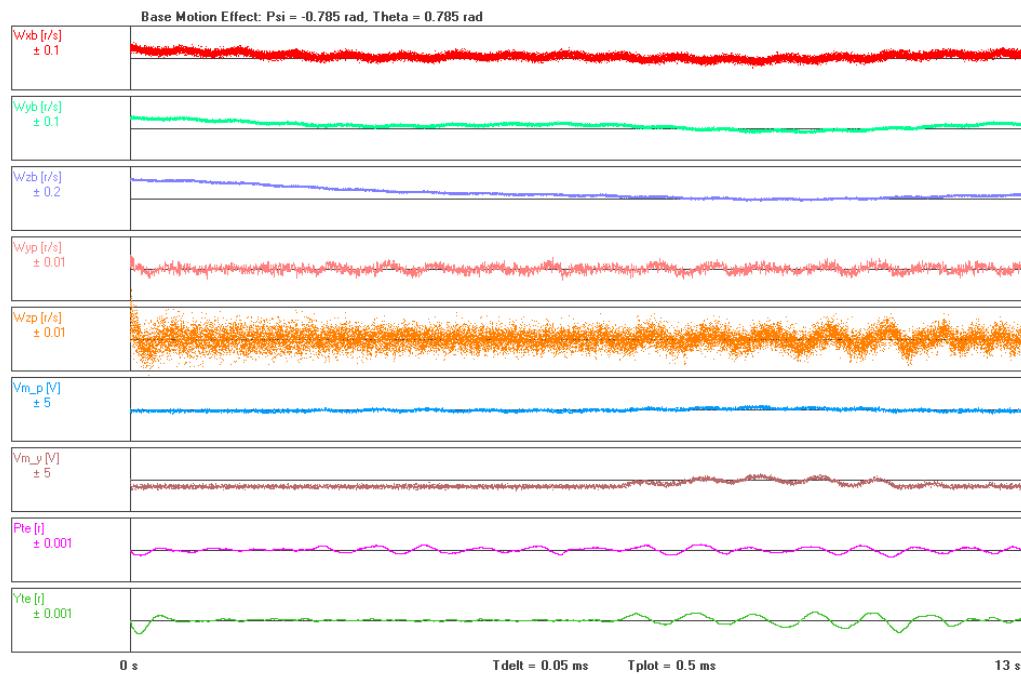


Figure 6-60: Base motion effect of the simulated base motion signal on the ISP in the worst-case position

It can be seen from the above simulation result that the ISP system performs well under the influence of the simulated base motion signal with jitter being constrained to less than 0.4 mrad for both channels. Repeating the last test with the ISP in the home position shows that similar jitter performance is achieved. This is shown in Figure 6-61 below.

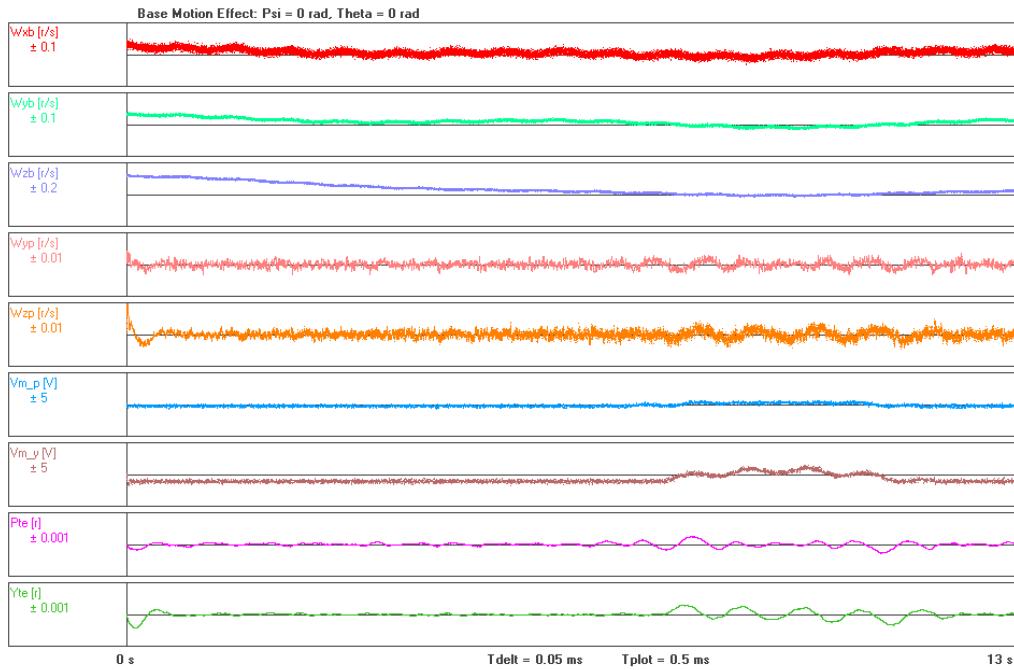


Figure 6-61: Base motion effect of the simulated base motion signal on the ISP in the home position

Whilst jitter performance is similar across both orientations, it can be seen than disturbance attenuation about the z_p axis is improved in the home position, as has been observed across all testing of the base motion effects on the ISP.

6.6 CHAPTER CONCLUSION

This chapter detailed the design of the various control loops required for the successful implementation of the ISP system. To facilitate this, a complete system simulation model was written in Simul_C. The final version of this model may be found in Appendix C.

Firstly, the manual position controllers were designed. These loops were tasked with facilitating control of the orientation of the ISP gimbals such that the target may be initially acquired by the target tracker.

Second, the stabilisation loops (prime item I3.4) were designed such that both loops had bandwidths greater than 38 Hz and resonance of less than 3.0 dB. These loops made use of compensated PI controllers to ensure adequate low-frequency control action. Torque rejection is estimated to be up to -34 dB for the yaw channel, and -39 dB for the pitch channel at frequencies up 1 Hz, whilst jitter on the telescope platform is expected to meet the specification S6 and be less than 2 mrad under the expected operating conditions of the system.

Finally, the tracking loops (prime item I3.3) driving the stabilisation loops were designed. These made use of compensated P controllers, and achieved bandwidths of approximately 1

Hz and showed no resonance. The low bandwidth of the tracking loops was deemed acceptable due to the slow motion of celestial bodies which move at frequencies far lower than 1 Hz. In addition, a mathematical model for the target tracker (prime item I3.2) was developed to complete the system simulation model. The next chapter describes the implementation of these controllers and their associated support functions in software and firmware.

7

SOFTWARE AND FIRMWARE IMPLEMENTATION

7.1 INTRODUCTION

The design and implementation section of this report concludes here with a description of the software and firmware developed for the various systems of the project. The section begins by describing the firmware written for the STM32 MCU which was tasked with reading the sensors introduced in Chapter 5, running the control loops designed in Chapter 6, and managing the comms between the STM32, RPi and the PC based UI. It then moves to detail the implementation of the target tracker on the RPi computer and concludes by detailing this User Interface.

7.2 STM32 FIRMWARE

The firmware developed for the STM32 MCU is the most important control program developed in the project. It handles all comms and control tasks and manages the overall system state and timing. This section details the firmware developed for the MCU. The firmware was written in C using a combination of register-level code and code written using the STM32Fo Standard Peripheral Library (SPL) written by STMicroelectronics. An overall description of the code is given before detailed function descriptions are given where necessary. In all cases, the firmware descriptions given here are at a functional level (unless hardware level detail is required) using flowcharts whilst the actual firmware may be found in Appendix C.

7.2.1 OVERALL DESCRIPTION OF FIRMWARE

The firmware written for the project made use of many of the available peripherals and pins on the STM32 development board described previously. The peripherals and pins used and their functional assignment is detailed by Table 7-1 below.

Table 7-1: Functional assignment of the STM32 peripherals

Peripheral	Pin Allocation (STM32 – External)	Functional Assignment
ADC	PA5 – Yaw PA6 – Pitch	Two ADC channels were used to read the wiper voltage of the potentiometers which measured the relative angles of the yaw gimbal and pitch platform. The ADC on the STM32 may be configured to 8,10, or 12-bit mode. For this application, it was set up to 10-bit mode so that a resolution of greater than 1 bit per degree or rotation of the gimbals was evident.
EXTI	PA0 – MPU9150 INT Pin	The MPU9150 IMU was set up to generate a rising edge on its INT pin when new data was ready to be read from the device. This was handled using an external interrupt (EXTI) input assigned to a rising edge on PA0.
	PA4 – RPi Pin 31	The Target Tracker software raises Pin 31 on the RPi (GPIO6) when new the new target position has been acquired and is ready to be sent to the STM32 via USART comms. This flag is handled by a rising edge external interrupt on PA4.
GPIOA	PA12&15 - LCD	Assigned as outputs to the LCD screen.
GPIOB	PB0-2 – RPi comms flags	These three pins on Port B are used as flags to manage the comms between the RPi and STM32. Further detail on their operation is given in Section 7.3.2.
	PB5 – Yaw direction PB6 – Pitch direction	Pins PB5&6 are set as outputs used to control the direction of rotation of the yaw and pitch motors.
	PB8&9 – LCD	Assigned as outputs to the LCD screen.
GPIOC	PB14&15 – LCD	Assigned as outputs to the LCD screen.
I2C2	PF6 – SCL line PF7 – SDA line	The IMU communicates with the STM32 via an I ² C interface at 400 kHz on lines PF6 and PF7.
TIM1	-	The function of Timer 1 is dependent on the system state: In the Start-up state, the timer generates an overflow interrupt after 50 ms. It is initialised immediately after the IMU is configured and is used to create a 50 ms delay during which the system does no other operations to allow time for the IMU to initialise correctly [72]. In the Manual state, the timer generates an overflow interrupt at 1 kHz to provide timing for the running of the yaw and pitch manual position control loops. Timer 1 is disabled in the Automatic state.
TIM2	PB3 – PWM Yaw	Timer 2 generates a PWM signal on PB3 to control the speed of the yaw motor.
TIM3	PB4 – PWM Pitch	Timer 3 generates a PWM signal on PB4 to control the speed of the pitch motor.

USART1	PA9 – TX PA10 – RX	The USART1 peripheral was assigned to all comms between the STM32 and the host PC UI.
USART2	PA3 – RX	The USART2 peripheral was used to receive comms from the RPi. PA3, the RX pin of USART2 was connected to Pin 8, the TX pin of the RPi. Comms between the devices was unidirectional, from the RPi to the STM32, and so, the TX pin of the STM32 and the RX pin of the RPi were left unconnected.

As previously indicated, the firmware written for the STM32 was a state machine consisting of three main program states; the Setup, Manual, and Automatic states. The peripherals detailed above are those made use of at any point in the runtime of the firmware but they are not all used in each system state.

The Setup state is the reset state of the MCU, it runs for a very short period and in it, all peripherals are initialised and the IMU is configured. An overflow interrupt 50 ms after initialisation is created by Timer 1 is used to implement a system delay to allow time for the gyros to start-up correctly. The interrupt handler of the timer in this state sets a flag to indicate that sufficient time has passed for correct start-up of the gyro and that the main program can continue. The handler then disables the timer, preventing it from generating another interrupt after the next 50 ms, and switches the system state to Manual. In the Setup state PA12&15, PB8&9, and PC14&15 are used as general-purpose outputs to control the LCD. These pins remain used for this function throughout the runtime of the firmware regardless of system state.

The Manual state is the first of two main functional states in which the program operates for the remainder of the runtime of the system. In correct operation, it is automatically entered once the gyro start-up delay is complete. This state allows the gimbal orientation to be controlled manually from position commands sent from the UI. As such, it makes use of the USART1 peripheral to facilitate serial comms between the UI and the STM32. It also uses Timer 1 set to generate overflow interrupts at 1 kHz to time the manual position control servo loops. These loops require the ADC peripherals used to provide angular position feedback of the gimbals' position and they require the use of Timer 2 and 3 to generate the PWM signals used to control motor speed. They also make use of PB5 and PB6, set-up as outputs to control the direction of the motors. In the Manual state, EXTI interrupts and I²C comms are disabled because neither inertial rate data or target position data are required for the intended operation of the system in this state.

The Automatic state is the second of the main program states used by the system. In this state, the ISP runs the stabilisation and tracking loops and transmits system runtime data back to the UI. It is initiated by a command from the UI whilst the system is in the Manual state. It is also ended by a command from the UI; either a stop command which initiates a shutdown of the system or a directive to revert to the Manual state. Timer 1 is not used in this state, but except for this Timer, all other peripherals used in the Manual state are also used in the Automatic state. EXTI interrupts from both lines are used in this state as the

control loops run in here rely on target and inertial rate data from the relevant systems. New data of both forms is indicated by EXTI interrupts on PAo and PA6. USART₂ and PBo-₂ are used to facilitate and manage the serial comms between the RPi and the STM₃₂, and the I²C peripheral is used to communicate with the IMU.

Figure 7-1 below describes the overall function of the firmware. Several sub-processes are used in the flowchart, and those that are numbered are detailed in the subsections that follow.

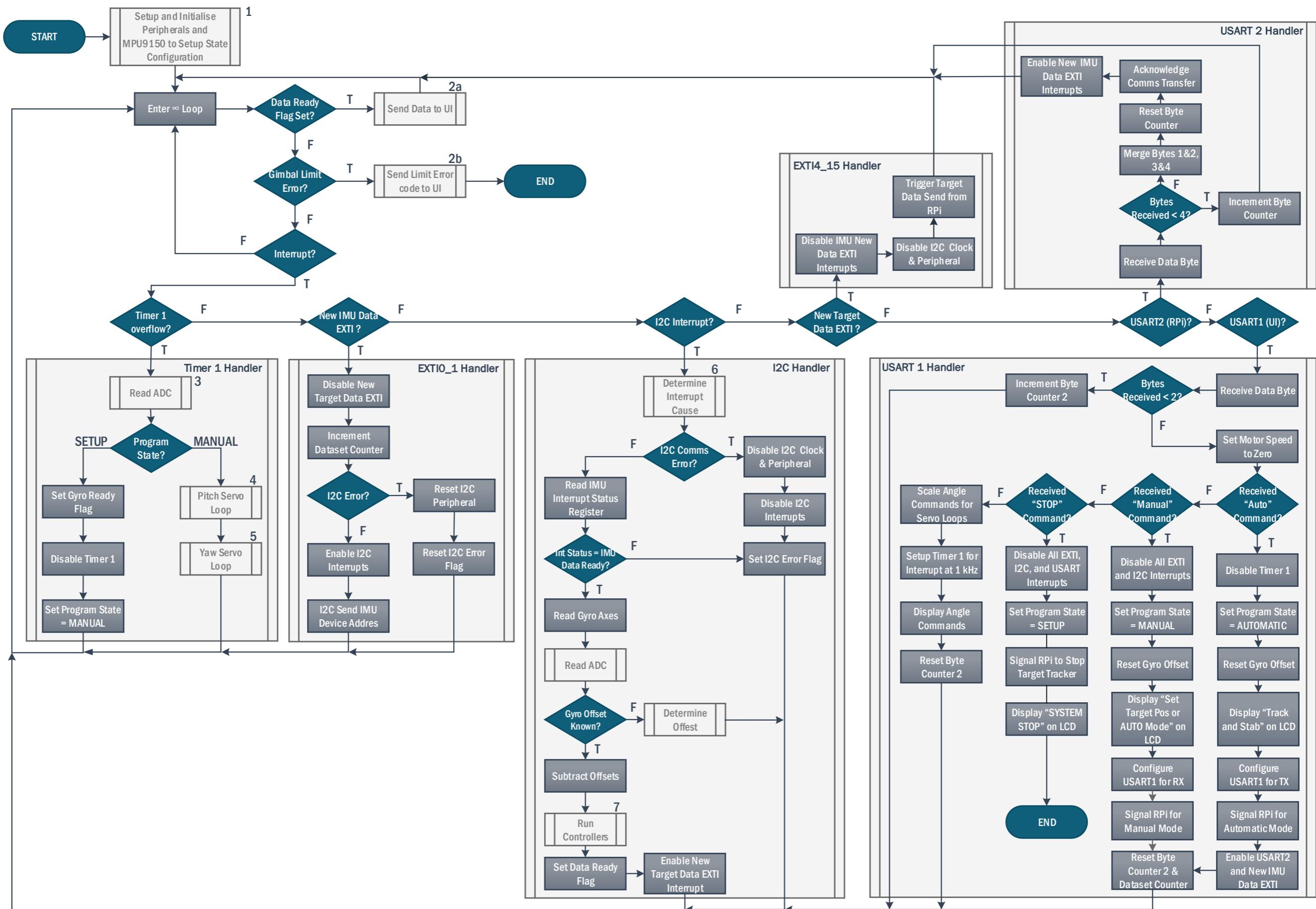


Figure 7-1: Overall Description of the STM32 Firmware

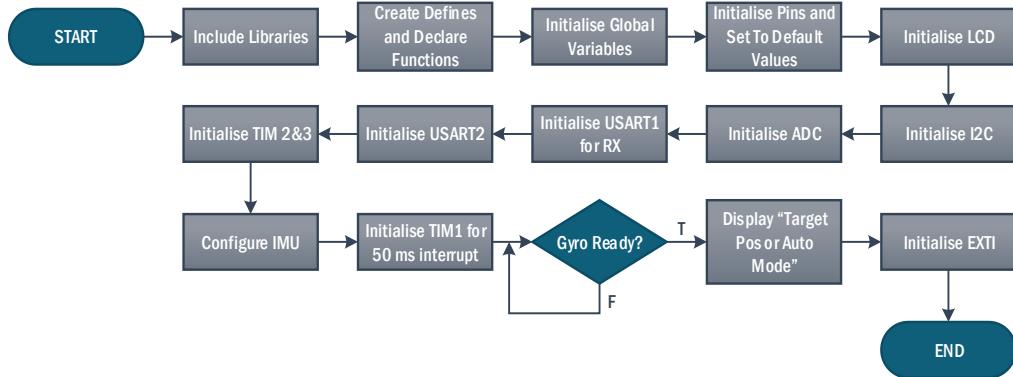
From the figure above, it can be seen that the system makes heavy use of an event-driven program structure, with the only synchronous task in the infinite while loop being to send system runtime data or a limit error code to the UI. This structure arose naturally out of the fact that the main control feedback data for both the tracking and the stabilisation loops is provided from external systems which raise flags when new data is available; rate data from the IMU at a fixed frequency of 500 Hz, and target position data from the RPi at a varying frequency between 10.5 – 15 Hz. Running the tracking and stabilisation loops from an untimed infinite loop, or an interrupt service routine (ISR) triggered by a timer overflow introduced the possibility of additional delays in action on new data. It was therefore decided to time the controller algorithms using the external interrupt generated by the MPU9150 INT pin which is raised high each time new data is ready to be read from the IMU. This occurs at a programmed rate of 500 Hz. The general functional sequence of events in the above flowchart for the Automatic state is, therefore:

1. EXTI interrupt on PAo indicating new gyro data is ready.
2. Read gyro data from the IMU.
3. Read ADC to determine gimbal positions. If they are out of bounds, stop the motors and shut down the system.
4. Run the pitch and yaw tracking and stabilisation control loops.
5. If new target data is available, receive target data packet.
6. Send system runtime data to the UI.

At any point during the above sequence, the STM32 may receive a supervisory command from the UI which changes the system state and breaks the above sequence of operation. The compiled code size of the firmware above was 32491 bytes and therefore only just fit within the 32 KB limit for the STM32F0.

7.2.2 SUBPROCESS I: SETUP AND INITIALISATION

The first subprocess encountered in the main firmware is that which sets up and initialises the various peripherals and sensors used in the project. This subprocess is further detailed in Figure 7-2 below.

**Figure 7-2: Setup and Initialisation subprocess**

The subprocess first includes the library files for the LCD, creates the system definitions, declares functions and defines the global variables used in the program. It then initialises all pins used for general I/O tasks and sets them to their default values, except for those assigned to the LCD which are setup in the Initialise LCD function.

The I²C peripheral is then setup for comms at 400 kHz on PF6&7 with a digital filter of 5 clock cycles to allow settling of the SDA and SCL signal levels. At this point, the peripheral is configured to generate I²C interrupt requests in response to various possible I²C events, but these requests are not yet enabled to actually cause an interrupt at this point. These interrupt requesting events are arbitration loss and bus errors, transfer complete flags, not acknowledge signals (NACK), RX, and TX events. These interrupt events are used in the Automatic state but are not required in the Setup state where comms with the IMU are managed through synchronous, flag polling methods. Hence, they remain disabled at the NVIC for the Setup state. In general, for an interrupt event to be generated by a peripheral on the STM32Fo, the peripheral must be configured to generate an interrupt in response to a given condition, and the NVIC must be configured to enable the interrupt to run the appropriate ISR in response to the event. The I²C peripheral at this point is configured to generate interrupts in response to these events, but the NVIC has not yet allowed the associated ISRs to run subsequently.

The ADC is setup in 10-bit mode, the USART1 baud rate is set to 115200 bps (the maximum supported by the LabVIEW UI) with even parity and one stop bit whilst the USART2 baud rate is set to 230400 bps with even parity and one stop bit. Timers 2 and 3 are setup to generate edge aligned PWM signals with a frequency of 20 kHz.

The IMU is configured such that its full-scale range of rate measurement is $\pm 250^\circ/\text{s}$, and generates an interrupt on the INT pin every 1 ms when new data from the x, y, and z gyro axes is ready to be read. Additionally, its onboard LPF which acts on this data is set to a cut-off frequency of 188 Hz.

7.2.3 SUBPROCESS 2: STM32 TO UI DATA TRANSFER

The second subprocess of Figure 7-1 regards the function used to send data to the UI from the STM32 via a serial over USB connection controlled by the USART1 peripheral. The function, described in Figure 7-3 below is called under two circumstances; when the Inertial Data Ready flag is set (a flag which indicates that new inertial data has been read and processed by the MCU) and the CPU is not doing any other tasks, and when a limit error condition has been detected indicating that the gimbals are out of their allowed angular ranges and that the system must be shut down to prevent damage.

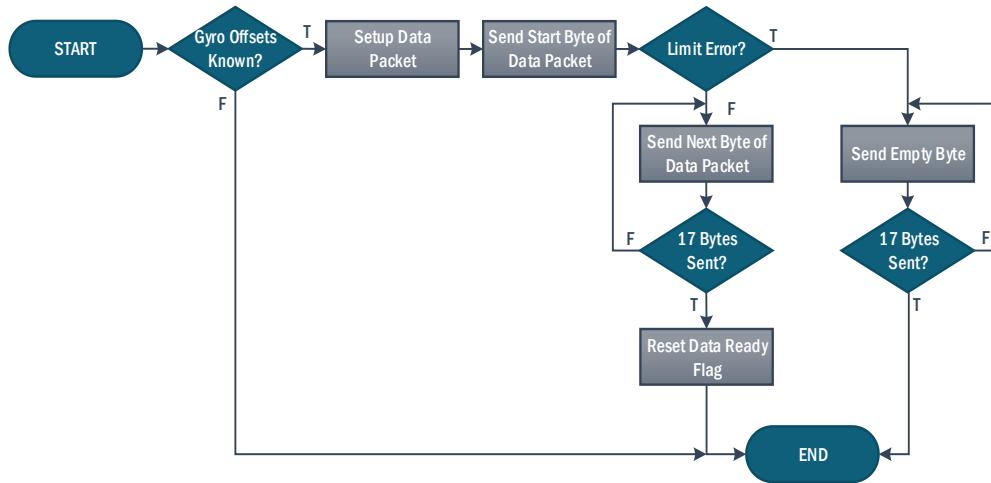


Figure 7-3: STM32 to UI data transfer function

The function sends data only once the offsets of the gyros are known. For the first two seconds of Automatic operation, the gyros are sampled and their outputs are averaged to determine their offsets whilst the gimbals are stationary. After this, the function will transfer data to the UI in the form of a data packet of 17 bytes preceded by a start of packet identifier byte. Once all 17 bytes of this packet have been sent the function ends. This data packet is structured according to Table 7-2 below.

Table 7-2: STM32 to UI data packet structure

Byte	Parameter
1	ω_{xp} High Byte
2	ω_{xp} Low Byte
3	ω_{yp} High Byte
4	ω_{yp} Low Byte
5	ω_{zp} High Byte
6	ω_{zp} Low Byte
7	Yaw Angle Low Byte
8	Pitch Angle Low Byte
9	Yaw/Pitch High Bits
10	X Target Position High Byte

11	X Target Position Low Byte
12	Y Target Position High Byte
13	Y Target Position Low Byte
14	Dataset Counter HH
15	Dataset Counter HL
16	Dataset Counter LH
17	Dataset Counter LL

In the table above, most byte parameters are labelled “High” or “Low” byte. This is due to most datatypes being used on the MCU being at least 16-bit numbers. The USART peripheral is configured for 8-bit word lengths and therefore, to send data it is required to split the variables into individual bytes of the eight most significant (High), and eight least significant (Low) bits. The yaw and pitch angles contain 10-bits of precision each and therefore require only three bytes in total to represent the 20 bits in total. The eight least significant bits of each measurement are represented by Byte 7 and 8, whilst Byte 9 contains, from left to right, two zeroes, the two most significant bits of the 10-bit yaw measurement, two zeroes, and finally, the two most significant bits from the pitch measurement. The Dataset Counter is a 32-bit number with an initial value of zero which is incremented each time the New IMU Data EXTI interrupt occurs. As this takes place at a fixed rate of 500 Hz, it is used to provide a timestamp for each data packet sent to the UI. This timestamp represents the time elapsed since the initiation of the Automatic state. As it is represented by a 32-bit number it is required to be broken into four bytes to be sent to the UI. These individual bytes are reconstructed by the UI to provide system runtime data to the operator. “HH” therefore represents the most significant byte of this number, “HL” the second most significant byte, “LH” the second least significant byte, and “LL” the least significant byte.

In the case of a Limit Error, the data packet is replaced by a series of 17 empty bytes sent to the UI. This understood by the UI as the error code for an out of bounds condition being met which causes the User Interface to return an error message stating this error to the user and a shutdown of the UI.

7.2.4 SUBPROCESS 3: READING OF THE ADC

As stated in Section 6.2.2, the ADC lines were subject to noise. The function which reads the ADC is also tasked with performing a moving average calculation on the readings to help compensate for this noise, as well as with determining whether the system is beyond its limits. The pseudo code below describes the operation of this function:

```

Yaw Previous = Yaw Current
Read Yaw Channel
Read Pitch Channel

```

```

Perform moving average calculation on Yaw
Perform moving average calculation on Pitch

Yaw Diff = Yaw Current – Yaw Previous

If Program State is Automatic

    if Yaw Diff > 200

        Increment Negative Crossing Counter
        if Positive Crossing Counter > 0

            Decrement Positive Crossing Counter

    else if Yaw Diff < -200

        Increment Positive Crossing Counter
        if Negative Crossing Counter > 0

            Decrement Negative Crossing Counter

    if Positive or Negative Crossing Counter > 1

        Run Limit Error Handler

    else if 310° < pitch angle < 50°

        Run Limit Error Handler

```

The function above computes the moving average (MA) on the current (i) yaw and pitch readings according to the following algorithm [105]:

$$MA_{[i]} = \frac{\left(MA_{[i-1]}^* + X_{[i]} - \frac{MA_{[i-1]}^*}{N} \right)}{N}$$

Where N is the effective number of data points over which the moving average is calculated ($N = 16$ for this average), and $MA_{[x]}^*$ is the moving average of the x th term multiplied by N .

The limits for the gimbals are defined such that the pitch platform may not go within 50° of the vertical down position from either direction, and the yaw gimbal may not cross the zero position twice in a row from the same direction. This limits the yaw gimbal to a maximum of 720° of allowable rotation. The pots chosen were single turn, continuous rotation pots, therefore at the $0/360^\circ$ position, the pot wiper may almost instantaneously change from $0V$ to $3.3V$ (or 0 to 1024) on the ADC output. This position was defined as the zero position and aligned according to the definitions of Figure 2-23. Therefore, if the difference between the current and previous yaw readings is sufficiently large, a zero crossing may be identified. Testing has revealed that a scalar value of 200 for this difference is a sufficiently large cut off to accurately identify a crossing. The direction of the crossing is determined by the sign of the difference. The logic above counts the number of crossings in each direction and runs the Limit Error handler if two in a row in the same direction occur.

This handler disables ETXI interrupts, switches the motors off, and calls the data transfer function to send the Limit Error code to the UI.

7.2.5 SUBPROCESSES 4 AND 5: MANUAL POSITION CONTROL

The pitch and yaw servo loops contained in the Timer 1 handler above are the functions in which the control loops designed in Section 6.2 are implemented. For these loops and all others implemented on the SMT32, compensator, controller, and other transfer functions with non-zero orders of s or z were implemented using difference equations. Functions were also multiplied out as far as possible to reduce the computational load on the CPU.

For the manual position control loops, the PI controller and compensator were first converted to the z-plane using the bilinear transform:

$$s = \frac{2}{T_{\text{samp}}} \cdot \frac{z - 1}{z + 1}$$

Therefore, for a system with sampling time, T_{samp} , the PI controller, with input $E(s)$ and output $P(s)$, is given by:

$$\frac{P(s)}{E(s)} = \frac{ps + 1}{s} \quad \equiv \quad \frac{P(z)}{E(z)} = \frac{Az + B}{Cz + D}$$

where,

$$A = T_{\text{samp}} + 2p$$

$$B = T_{\text{samp}} - 2p$$

$$C = 2$$

$$D = -2$$

And the compensator transfer function is given by:

$$\frac{Y(s)}{X(s)} = \frac{T_1 s + 1}{T_2 s + 1} \quad \equiv \quad \frac{Y(z)}{X(z)} = \frac{Mz + N}{Oz + P}$$

where,

$$M = T_{\text{samp}} + 2T_1$$

$$N = T_{\text{samp}} - 2T_1$$

$$O = T_{\text{samp}} + 2T_2$$

$$P = T_{\text{samp}} - 2T_2$$

The difference equations for these z-plane transfer functions were then determined by cross multiplication and expansion as follows.

For the PI controller:

$$P(z)Cz + P(z)D = E(z)Az + E(z)B$$

$$P(z) = \frac{E(z)A + E(z)Bz^{-1} - P(z)Dz^{-1}}{C}$$

and as, z^{-1} represents a delay of T_{samp} in a discrete time system, the output of the PI controller is, therefore, given as:

$$P = \frac{AE + BE_p - DP_p}{C}$$

where the subscript p denotes the previous value of the term. Likewise, the compensator is given by:

$$Y(z)Oz + Y(z)P = X(z)Mz + X(z)N$$

$$Y(z) = \frac{X(z)M + X(z)Nz^{-1} - Y(z)Pz^{-1}}{O}$$

$$Y = \frac{MX + NX_p - PY_p}{O}$$

In addition to the conversion of the s-plane representations of the transfer functions to difference equations, scaling of the controller gain was required to account for the position sensor gain introduced to the system by the ADC readings. The 10-bit numbers representing the angular position of the gimbals were used as the feedback terms rather than an angle measurement in radians. This was done to reduce the computational requirements of the loops by removing the division required to scale the reading to a radians value. To account for this sensor gain in the feedback path, the gain terms of each channel were scaled down by this factor on implementation to ensure no change was made to the open loop design of the system. This scaling factor applied to the gain term was:

$$\text{Scaling Factor} = \frac{1}{\text{Sensor Gain}} = \frac{1}{\left(\frac{1024}{2\pi}\right)} = 0.0061$$

The final parameters for these controllers as implemented on the STM32 are given in Table 7-3 below and are the result of multiplying out the expressions given in Figure 6-1 and Table 6-1:

Table 7-3: Implemented servo loop control parameters

Parameter	Pitch Channel	Yaw Channel
A	0.6376	0.6376
B	-0.6356	-0.6356
C	2	2
D	-2	-2
Integrator Windup Limit	±193.61	±116.17
K	18.41	30.68
M	1.5925	1.5925
N	-1.5906	-1.5906

O	0.0806	0.0806
P	-0.0786	-0.0786

The implementation of these manual position controllers, which describe the servo loop subprocesses 4 and 5, is described in Figure 7-4 below.

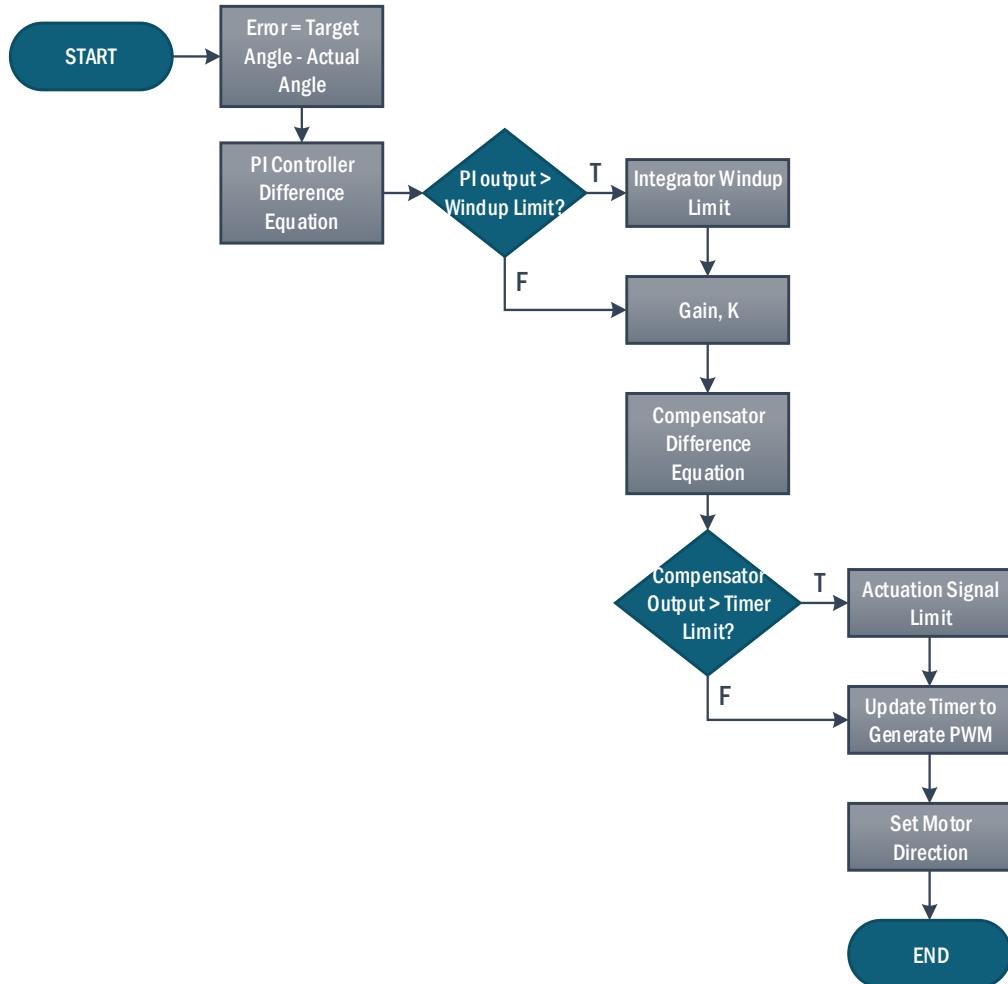


Figure 7-4: Gimbal positioning servo loop implementation

7.2.6 SUBPROCESS 6: I²C INTERRUPT CAUSE DETERMINATION

Once the program moves from the Manual to the Automatic state, the I²C peripheral used no longer used in a synchronous polling mode. Instead, the interrupts configured in the setup state are now enabled and comms handled by the peripheral are performed in an event-driven structure. In order for the correct action to be taken by the I²C ISR, the cause of the interrupt must first be determined. This is done according to the flowchart below.

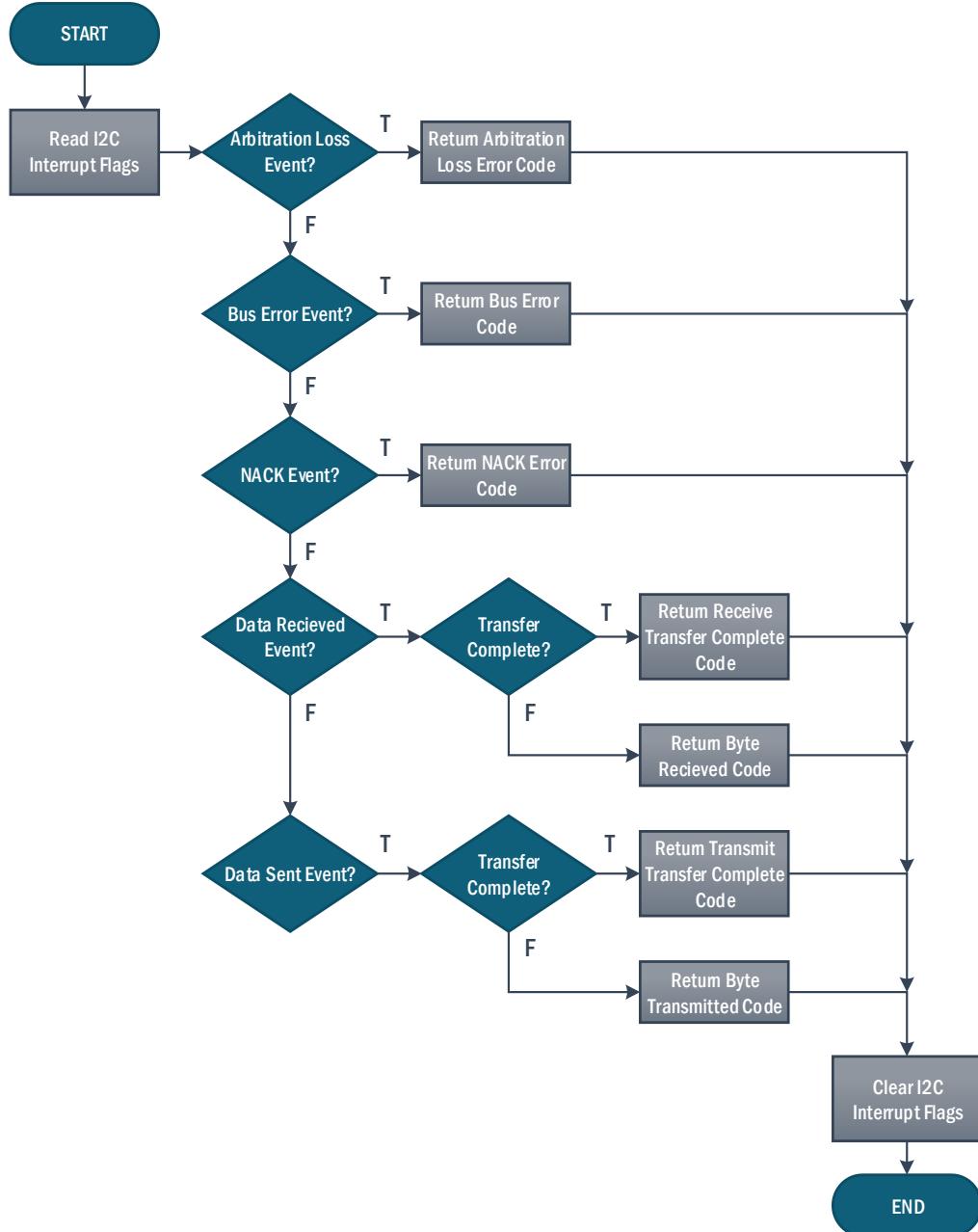


Figure 7-5: I²C interrupt cause determination function

The function above reads the status of the various interrupt flags enabled on the peripheral and returns an indication of which event caused the interrupt so that the I²C interrupt handler can take the appropriate action to complete the comms with the IMU.

7.2.7 SUBPROCESS 7: TRACKING AND STABILISATION CONTROL

In the Automatic state, after the IMU data has been read and the offsets have been subtracted, the program calls the Controller function from within the I²C interrupt handler. This function is tasked with running the tracking and stabilisation control loops designed in Sections 6.3 and 6.4 of the previous chapter and runs at a frequency of 500 Hz. As before,

with the implementation of the manual position controllers, the controller and compensator transfer functions were converted from z-plane representations to difference equations for use on the STM32.

The pitch tracking lag compensator between points 4 and 5 of Figure 6-40 became:

$$V_5 = \frac{MV_4 + NV_{4p} - PV_{5p}}{O}$$

where V_4 and V_5 represent the inputs and output of the transfer function respectively. Accordingly, the PI controller of the pitch stabilisation loop between points 7 and 8 became:

$$V_8 = \frac{AV_7 + BV_{7p} + 2V_{8p}}{2}$$

and the pitch stabilisation lag compensator between points 9 and 10 became:

$$V_{10} = \frac{CV_9 + DV_{9p} - FV_{10p}}{E}$$

In the same way, the tracking lag compensator, stabilisation loop PI controller and stabilisation lag compensator of the yaw channel became, respectively:

$$\begin{aligned} V_{35} &= \frac{MV_{34} + NV_{34p} - PV_{35p}}{O} \\ V_{38} &= \frac{GV_{37} + HV_{37p} + 2V_{38p}}{2} \\ V_{40} &= \frac{IV_{39} + JV_{39p} - LV_{40p}}{K} \end{aligned}$$

In addition to these difference equations, the gain term of the tracking controllers required scaling when implemented on the STM32. Target position data was sent to the STM32 as a pixel position rather than as an error angle from the LOS in radians in order to simplify the comms between the RPi running the image processing software and STM32 (see “Interaction with the STM32” in Section 7.3.2). Therefore, it was also decided to use an error signal in terms of pixels rather than radians to reduce the number of computations required to be done on the STM32. This meant scaling of the tracking controller gains was required to account for this change. The horizontal angle of view of the RPi Cam was 0.326 rad and the resolution of the camera set to be 640x480 (HxV) pixels, therefore, using a linear approximation, each pixel represented an angle of $0.326/640 = 0.51$ mrad. This meant a feedback sensor gain of $1/0.00051 = 1963.19$ was introduced to the tracking loops. To account for this and ensure no change in open loop from the modelled system, the tracking controller gains were reduced by a factor of 1963.19.

The angular rate feedback for the stabilisation loops was converted to a rad/s value on the STM32 before being subtracted from the rate command and, therefore, controller gain and integrator windup limit scaling was not required for the stabilisation loops. However, the terms of the controllers were again multiplied out beforehand to reduce the computational load on the CPU. Table 7-4 details the control parameters used on the MCU to implement the tracking and stabilisation loops.

Table 7-4: Implemented tracking and stabilisation loop parameters

Parameter	Value	Channel
K_{pt}	0.0031	Pitch
M	0.002	
N	0.002	
O	0.0338	Both
P	-0.0298	
A	0.1081	
B	-0.1041	
Integrator Windup Limit	± 0.02	
Stabilisation Gain	178200	Pitch
C	0.002	
D	0.002	
E	0.0041	
F	-0.0001	
K_{yt}	0.003	
G	0.1081	
H	-0.1041	
Integrator Windup Limit	± 0.0142	
Stabilisation Gain	252450	Yaw
I	0.002	
J	0.002	
K	0.0041	
L	-0.0001	

Figure 7-6 below shows the flowchart describing the operation of the tracking and stabilisation loop controllers for each channel. The first operation of done by Controller function is to reassign the data from the gyro axes to match the definitions of Figure 2-21 and ensure that data from the correct axes is used for the relevant feedback signals. The IMU is mounted on the telescope modeller such that x_{imu} axis is aligned with the $-z_p$ axis, the y_{imu} axis is aligned with the y_p axis, and the z_{imu} is aligned with the x_p axis. Consequently, ω_{xp} is set to the value of the data from the z_{imu} axis, ω_{yp} is set to the value of the data from the y_{imu} axis, and ω_{zp} is set to the value of the x_{imu} axis. After this data reassignment, ω_{zg} is calculated for use in the tracking and stabilisation controller function and the remainder of the function's operations are performed.

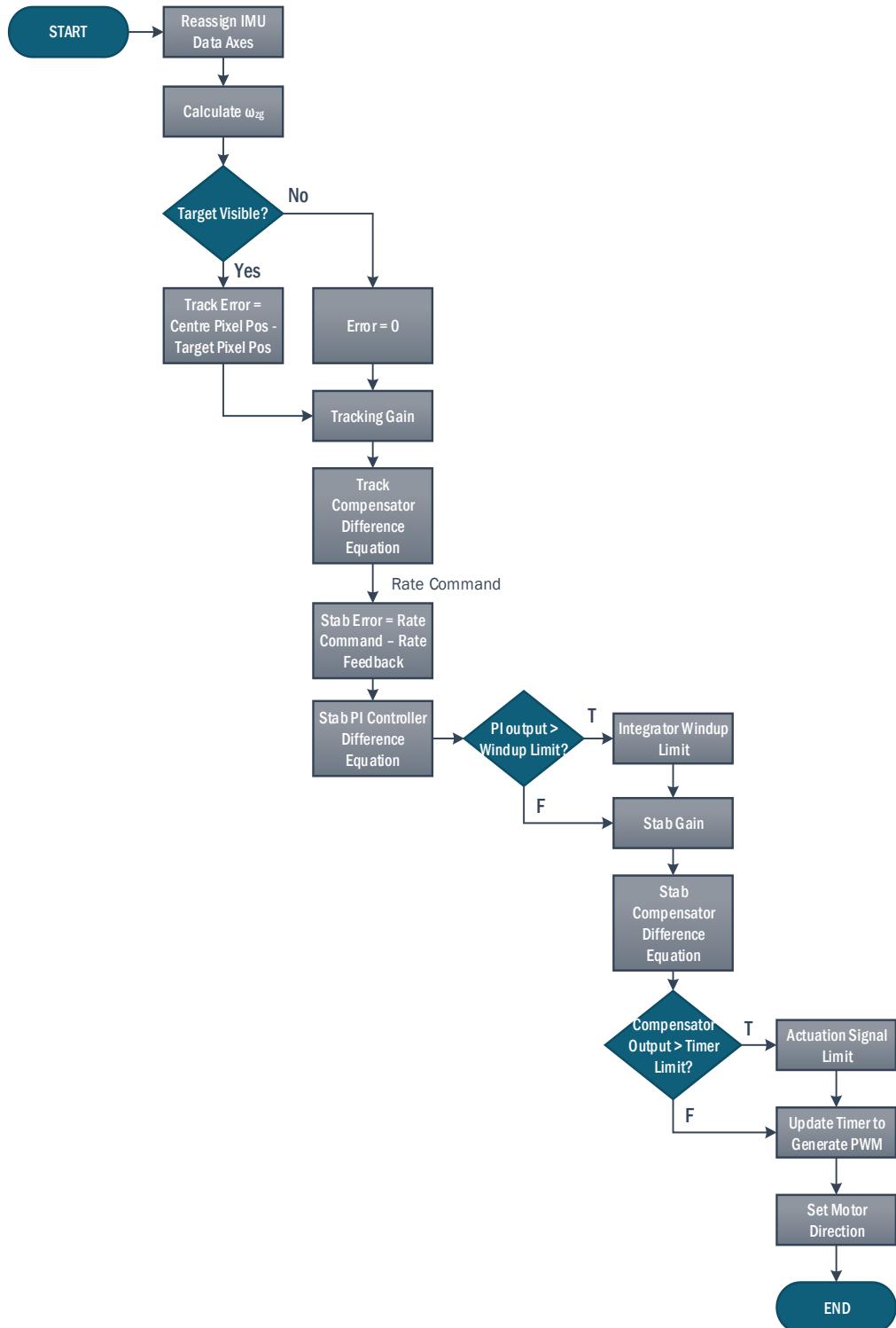


Figure 7-6: Implementation of the Controller function which runs the tracking and stabilisation control loops

7.2.8 FIRMWARE TIMING ON THE STM32

The firmware described above facilitated real-time sensor comms and control tasks for the stabilised platform developed. In the Automatic state, the various operations and subprocesses functioned in the sequence indicated at the end of Section 7.2.1 and were repeated every 2 ms until the system was stopped or the Automatic state exited. Figure 7-7 below shows the timing of these various tasks on the STM32.

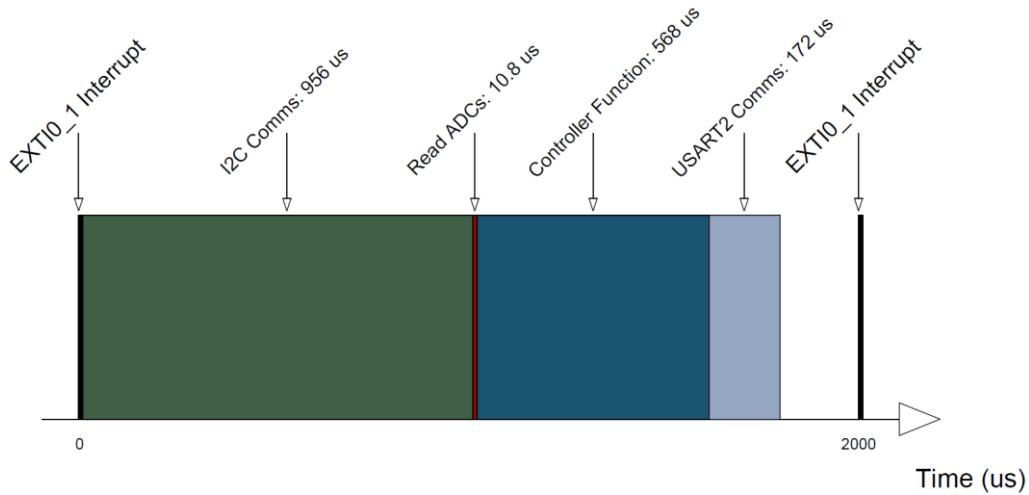


Figure 7-7: Automatic state firmware timing

Steps 1-5 of the general functional sequence take a combined total of 1706.8 μ s to perform. The final action of the general sequence is to initiate a transfer of system data to UI. This is done by setting the Data Ready flag after the controller function has exited. These comms take 2.20 ms to complete and, therefore, are not able to be completed within the 2 ms period available between new IMU data acquisitions. Hence, the transfer of data is performed in the main while loop when the Data Ready flag is set and if the CPU is not handling any of the other critical interrupt driven functions. Data transfer to the UI for data logging is the lowest priority function of the STM32 firmware and so takes place as and when the CPU is free to initiate the action.

7.3 TARGET TRACKER DEVELOPMENT (13.2)

As stated previously, the primary functions of the target tracker are to locate the target in the FOV of the camera sensor and determine its angular position in terms of the LOS of the camera. It was decided that the RPi Model 3 B would facilitate the image processing tasks required to achieve this and that the imaging sensor used would be the RPi Cam v1.3 with a modified CS Mount lens mounted on the sensor. This was intended to help facilitate the accomplishment of specification 8 of the system specifications which defined a requirement for the target tracker to be able to detect a rotation of 0.25 mrad of the LOS between the target and the camera. At a functional level, it was desired that the target tracker also be able to display the image and location of the target within the FOV to facilitate user interaction and observation.

7.3.1 TARGET TRACKER OPERATIONAL METHODOLOGY

In keeping with the overarching philosophy of this project as a low-cost approximation of an eventual high-performance system, it was decided to simplify the target tracking requirements as far as was possible. Accordingly, it was decided that the object to be tracked would be the Moon; being the largest and brightest object in the night sky made it conceptually the easiest object to acquire in the camera frame and to track with the ISP. The target tracker developed was a feature tracking algorithm in which the time-invariant point of interest to be tracked was chosen to be a defined colour range. The moon in the night sky shows as a predominantly white, bright object set against a black background, therefore an algorithm which isolates a particular colour range in an image, in this case, white, or colours close to white, and treats the largest area of such a colour range in the image as the target object would be sufficient to recognise and track the moon. Additionally, if this colour range was configurable on each run of the software allowing other colour ranges to be tracked, system testing could be accomplished outside of the night, or dark, conditions required to create the bright object on the dark background of the moon in the night sky.

The image processing software was written in the Python 2.7 programming language and made use of the OpenCV (v3.0.0) libraries to implement the image processing algorithm. OpenCV is a computer vision library designed for real-time applications and is free for academic and commercial use. Their large support base and online tutorials made the use of this library attractive and basic image processing easily accessible. Much of the algorithm developed here is based on their published tutorials [106]–[109]. The remainder of the subsections in Section 7.3.1 describe various factors which influenced the development of the image processing software described in Section 7.3.2.

COLOUR SPACES

As with most digital images the RPi Cam generates image frames in the RGB colour space. Each pixel is represented by a three-term vector containing a Red, Green, and Blue value. This model is based on the theory that all colours may be represented by the addition of various proportions of the three primary colours, red, green, and blue. However, the colour model is less suited to distinguishing a specific colour from an image than the HSV model which represents all colours as a measure of their hue (a representation of the typical meaning of the word “colour”), saturation (a measure of how much white is in the colour), and value (how dark the colour is). Figure 7-8 below compares the two models of the RGB and the HSV colour spaces.

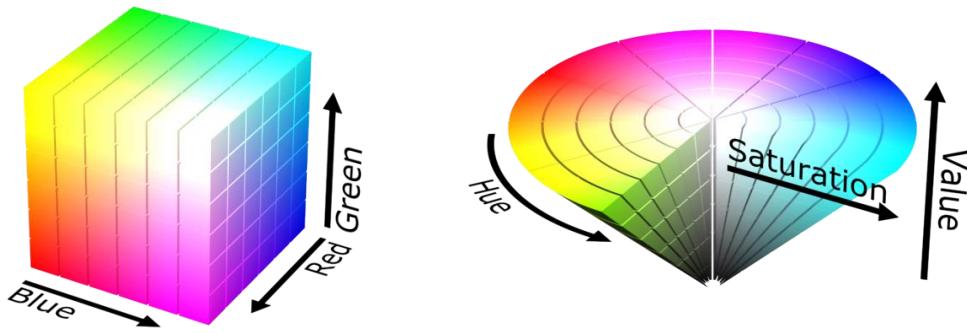


Figure 7-8: RGB and HSV colour models [110], [111]

It can be seen that in the HSV model, where Hue defines the colour, isolating a colour is a simpler task than in the RGB model where a combination of RGB values must be evaluated to determine colour. Additionally, the HSV space is well suited to the task of recognising the bright moon against a dark background; the bright object may be identified independently of Hue as long as the Value term is great enough and the Saturation term is low enough, whilst to identify a bright object in the RGB space requires an evaluation of all three terms. Due to these advantages, it was decided that the first step of the object recognition algorithm would be to convert the image from the RGB to the HSV colour space. The OpenCV function cv2.cvtColor() allows the colour model used by an image to be converted from its current colour space to another defined by the arguments passed to the function.

THRESHOLD

Once the image is represented by an appropriate model, the concept of pixel value thresholding was important to the isolation of a defined colour range. Thresholding allows the value of a pixel to be changed to a defined value if its original value meets certain criteria. This can be used to isolate a colour range by evaluating the pixels' conformity to that range, assigning them a new value if they conform to the desired range of values, and another if they do not.

The cv2.inRange() function was used in this was to assign the pixels a white colour if their HSV representation fell within a defined range of HSV values, and a black colour if they did not, consequently a binary image was created. Figure 7-9 below shows the effect of thresholding an image using the cv2.inRange() function where the blue colour of the circle in the image on the left is in the desired range of HSV values, whilst everything else is not.



Figure 7-9: Effect of the `inRange()` function on an image

It can clearly be seen how a colour may be identified using only two OpenCV functions. If the target is of a uniquely identifiable colour it is conceivable that objection recognition by colour may be achieved with only these two steps. However, this is not likely in practice and more robustness from the algorithm was required. In the laboratory development environment, of the left-hand image, this was certainly a necessity as there were various objects of colour in the room which might interfere with the tracking of a given colour, but even in the intended environment, bright stars may interfere with the tracking of the moon.

EROSION AND DILATION

One method employed for increasing the robustness of the algorithm to an environment which might have multiple objects which satisfy the colour criteria of the threshold was the method of eroding the image followed by dilating the image. Erosion and dilation processes use a kernel (or structuring element) to modify the value of pixels in an image. The kernel is normally a small 2D array of values such as the 3×3 matrix, B, below.

$$B = \begin{array}{|c|c|c|} \hline 1 & 1 & 1 \\ \hline 1 & 1 & 1 \\ \hline 1 & 1 & 1 \\ \hline \end{array}$$

Figure 7-10: Image processing kernel

And the image to which it is applied is normally a binary image such as, A, below.

A =	0 1 1 0 1 1 0 1 1 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0
-----	---

Figure 7-11: Binary image before erosion or dilation

The anchor point of the kernel is defined to be the central element of the kernel. If this kernel was used as an eroding element on the binary image, A, the anchor point would be superimposed sequentially on each pixel. If each pixel value of the part image below the kernel matches the corresponding element of the kernel, the pixel beneath the kernel anchor retains its value, otherwise, it is set to zero. The output image would be given by C, below.

C =	0 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0
-----	--

Figure 7-12: Binary image after an erosion process

The white area in the upper left of image A has now been removed completely by the erosion process whilst the white area in the lower right of the image is retained although is contracted. If the smaller white area in A had been a false target, such as a star in the FOV of the camera and the Moon had been the large white area, this process would have removed the false target and increased the robustness of the algorithm. Dilation is simply the opposite of an erosion process; if any pixel under the kernel is the value of the corresponding kernel element, the pixel under the anchor is set to the value of the anchor. Whilst erosion has the effect of reducing a size of a feature in an image, dilation has the effect of increasing its size.

This is useful in cases where the target is small and increasing its size is beneficial to further processing operations that follow. The output image of dilating image C with the same kernel is given by D, below.

Figure 7-13: Binary image after a dilation process

If an erosion is followed by a dilation, as has proceeded here, a small false target may be removed without a loss in size or shape of the larger body if the same kernel is used for both processes. The implemented algorithm makes use of a 3×3 kernel for erosion and dilation.

CONTOURS AND MOMENTS

The OpenCV cv2.findContours() function detects the curve which joins the boundary of all points in an image which are of the same colour. This function was used to determine the boundaries of each white area in the image after the erosion and dilation process. The largest contour in the image was then treated as the target in this project.

The `cv2.moments()` function returns the moments of the image; a series of weighted averages of pixel intensities against various parameters. Together, the two functions were used to determine the centroid of the target according to the following method [109]:

The x and y positions of the centroid, C, are given by:

$$C_x = \frac{M_x}{M}$$

$$C_y = \frac{M_y}{M}$$

Where M is the overall intensity, M_x is the x moment, and M_y is the y moment of the contour selected.

MULTITHREADING

The final technique used to improve the performance of the image processing algorithm on the RPi was to implement the software in a multi-threaded manner. Acquiring the image

on the RPi is an I/O heavy application and can cause a bottleneck in the processing algorithm as it waits for a new image to be acquired before processing can continue. To offset this, the image frame acquisition was moved to an independent processing thread which continually polls the camera for new frames. The main processing algorithm then ran on a second thread which simply used the most recent frame available from the acquisition thread. Using this technique, it was possible to increase the number of frames processed per second (FPS) from approximately 7 FPS to approximately 11 FPS. The imutils library written by Adrian Rosebrock and method described by him were used as a base for the implementation of this behaviour [112]–[114].

7.3.2 FUNCTIONAL DESCRIPTION OF IMAGE PROCESSING ALGORITHM

The previous subsections described the main processes that were involved with the implementation of the image processing algorithm used to identify the Moon or simulated target colour in the camera FOV. This subsection describes the software written from a functional perspective using a flowchart and how the target position data is transferred to the STM₃₂.

INTERACTION WITH THE STM₃₂

Figure 6-53 of Section 6.5 previously, defines the target tracker to be a system which takes the target position, host vehicle rates, and the gimbals' orientation as inputs to the system and returns the yaw and pitch tracking errors as outputs. The image processing algorithm introduced to this point has only indicated how the pixel positions of the centroid of the target might be determined in the image frame. Knowing the angle covered by the FOV of the sensor, it is possible for the yaw and pitch tracking errors in radians from the LOS to have been determined on the RPi. However, to simplify the comms between the RPi and the STM₃₂ which requires these error signals to run the tracking controllers, it was decided to send the pixel positions of the centroid to the STM₃₂ rather than the error values. The tracking errors would almost certainly be non-integer values which are more complex to send over the USART comms link between the two devices than the integer pixel positions. Consequently, the STM₃₂ performs part of the target tracker's function and is tasked with converting these pixel positions to tracking errors on which to perform the tracking control operations.

In order manage the timing of comms transfers between the devices, several pins on the STM and RPi were allocated to act as flags whose values indicate various states of operation. On the RPi, these pins are Pins 31, 33, 35, and 37 which are connected to the STM₃₂ at PA4, PBo, PB1, and PB2 respectively. The procedure by which the comms sequence is completed is detailed below.

- I. When PBo on the STM₃₂ is raised HIGH from its default LOW state, the image processing script knows that the STM₃₂ has moved into the Automatic state due to the HIGH value being read on P33. In this state, P31 is then raised by the RPi when

- a new frame has been processed and target position data is ready to be sent to the STM32. This causes an EXTI interrupt on PA4 of the STM32.
2. The EXTI interrupt handler for PA4 then acknowledges that new target data is ready to be sent by lowering PB2 on the STM32 which is connected to P37 on the RPi. It also disables the new IMU data interrupt until the comms sequence has completed. Until the RPi sees P37 lowered, the program waits and does not initiate the comms transfer.
 3. Once P37 is lowered, the RPi sends four bytes of data to the STM32 via a USART connection. On receipt of four bytes, the STM32 re-enables the new IMU data interrupt and raises PB2 (P37).
 4. The RPi then sets P31 (PA4) low to complete the comms sequence.

If the STM32 raises PB1 at some point during the image processing algorithm or comms cycle, a system stop condition is met and the image processing script is stopped.

FUNCTIONAL FLOWCHART DESCRIBING THE IMAGE PROCESSING SCRIPT

The flowchart shown in Figure 7-14 below describes the image processing script used in this project whilst the Python code itself may be found in Appendix C.

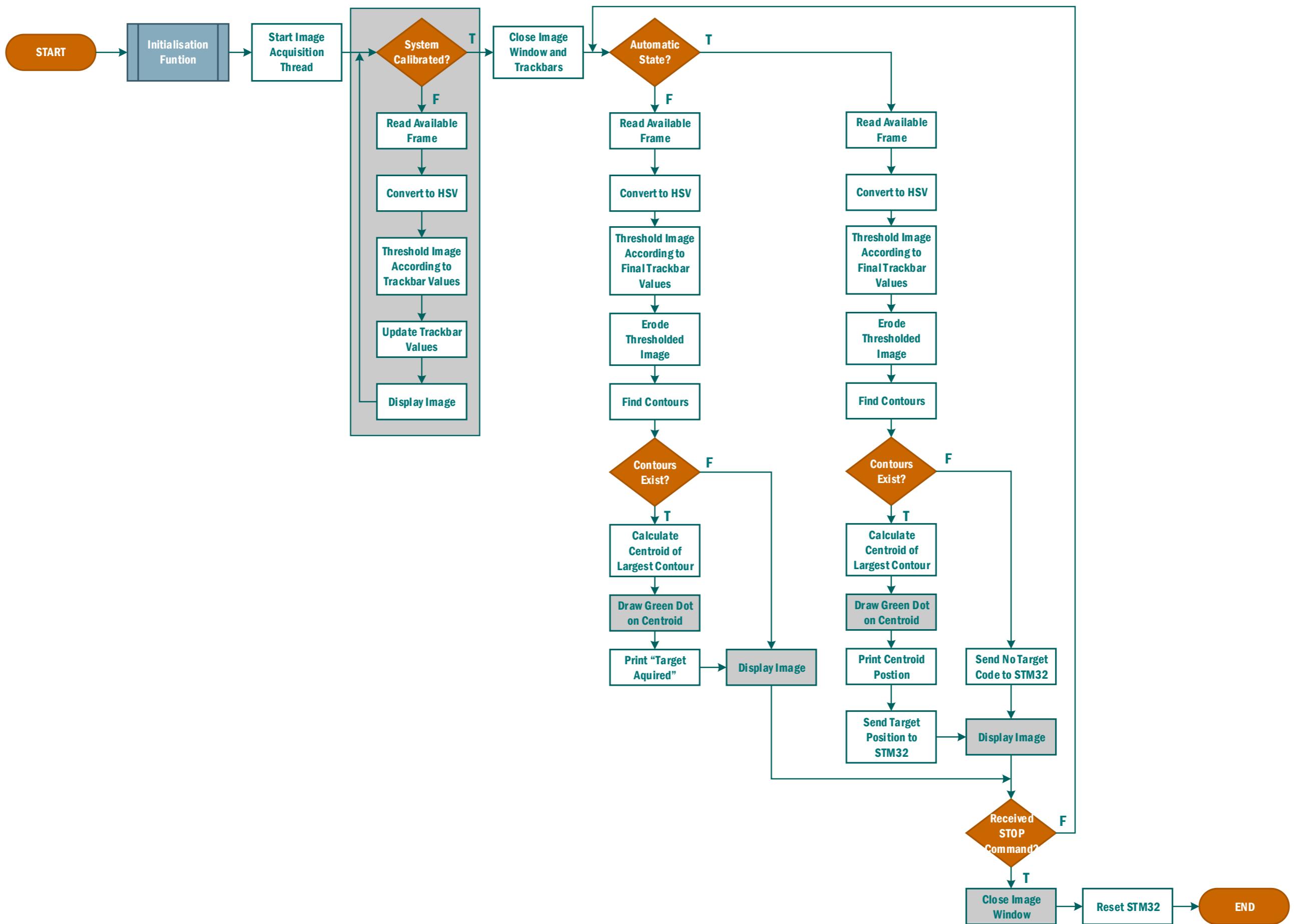


Figure 7-14: Image processing functional flowchart

In the flowchart above, the Initialisation Function subprocess performs the tasks of including the libraries used by the script, initialising the global variables used, configuring the GPIOs of the RPi, configuring the serial port used to communicate with the STM32, and creating the trackbars used in the first part of the software where the threshold function limits are calibrated. Serial comms on the RPi with the STM32 use a baud rate of 230400 bps with even parity and one stop bit and use pin P8 as the TX pin. RX is not used by this script. The calibration part of the software displays a thresholded image along with the trackbars can be used to adjust the threshold on the display of the RPi. This is shown in Figure 7-15 below.

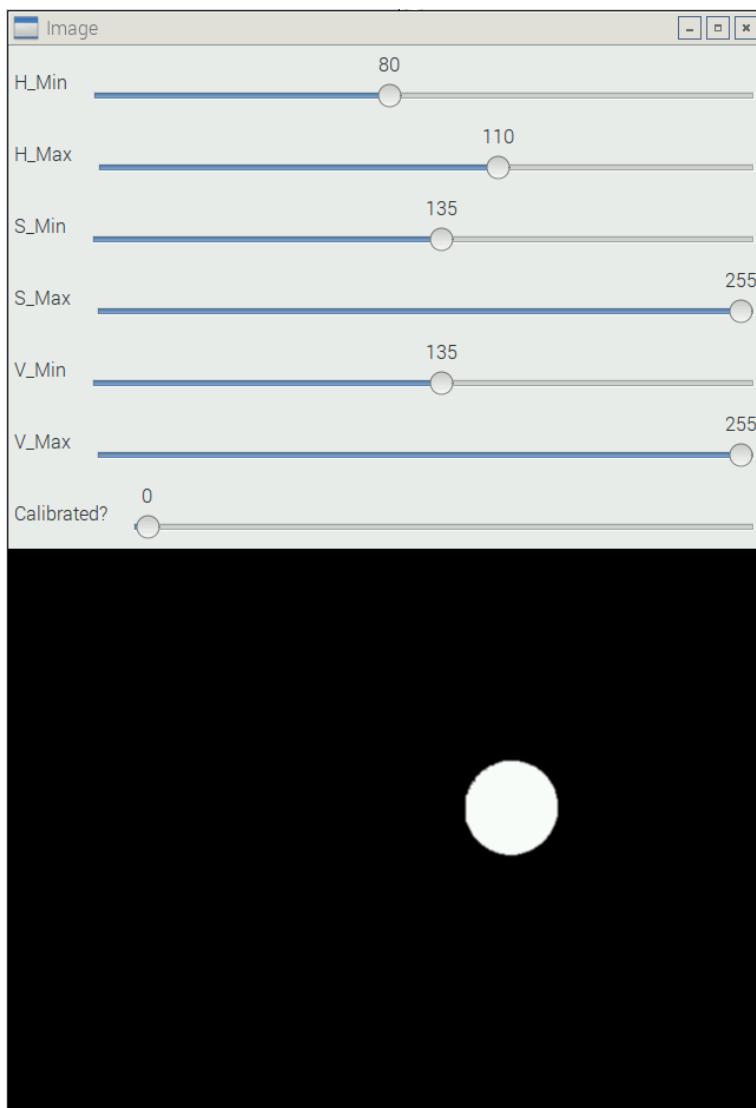


Figure 7-15: Calibration mode of the image processing script

The thresholded image above applies the `cv2.inRange()` function to an image similar to that of the left image of Figure 7-9 with limits defined by the upper and lower values for the H, S, and V trackbars. Once the appropriate range has been determined, moving the “Calibrated?” slider to the right closes this window and saves these limits for use over the remainder of the program runtime. At this point, if the system is in the Manual state, the

processed image is displayed and “Target Acquired” is printed on the terminal if a target is visible, as shown in Figure 7-16 below.

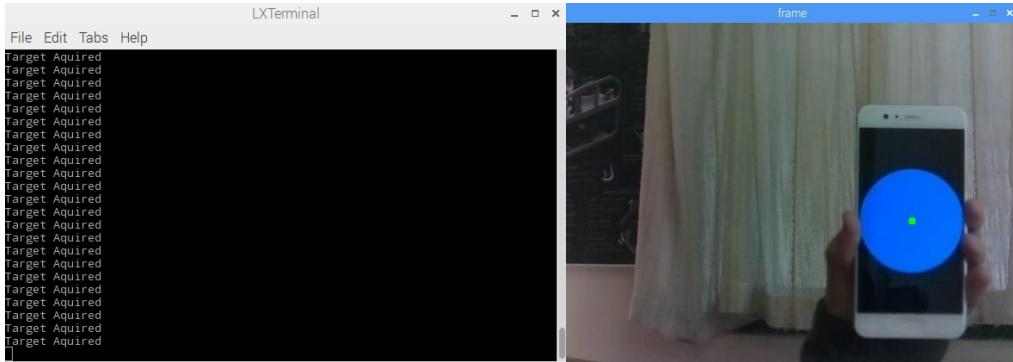


Figure 7-16: Image processing display in the Manual state

Conversely, if the system is in the Automatic state, the processed image is displayed and the centroid position data is printed on the terminal if a target is visible, as shown in Figure 7-17 below. If no target is visible, then “Target Lost” is printed on the terminal.

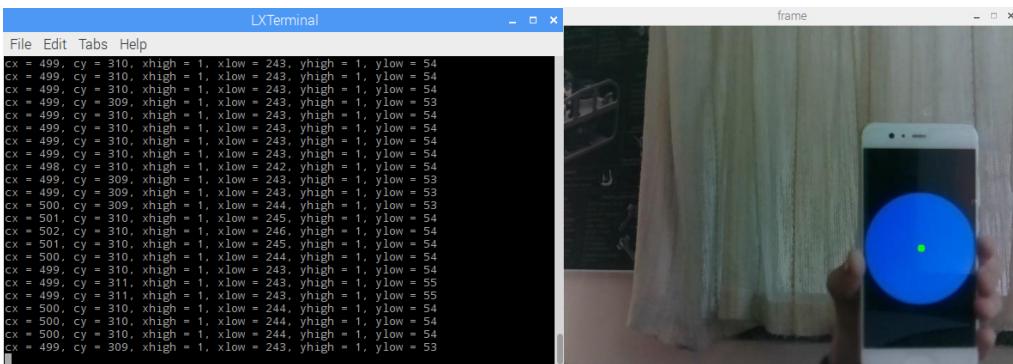


Figure 7-17: Image processing display in the Automatic state

7.3.3 PERFORMANCE OF THE IMAGE PROCESSING PROGRAM

Overall, the image processing script achieved a minimum processing rate of 10.5 FPS whilst operating in the manner defined by Figure 7-14. However, in order to achieve this the resolution of the camera was required to be reduced to 640x480 pixels as previously indicated. This rendered the effective angle covered per pixel of the FOV to be only 0.51 mrad and, therefore, specification S8, which defined the required detectable angular resolution to be 0.25 mrad, was not met. Consequently, specification S5, which defined the maximum tracking error for the system to be 0.25 mrad was also not met as the camera sensor was not capable of detecting a rotation of the target to this resolution. Higher resolution images proved too computationally intensive for the RPi to process at a rate which would have been suitable for providing target position data to be used in the tracking loops of the control system. Using an image resolution of 1296x972 pixels, which meant specifications S5 and S8 were just met, in conjunction with a gate to process only a specified region of the image (see Figure 2-14 and description) was trialled with some success. However, system performance

was smoother using the lower resolution image frame and the image itself could be displayed with a smoother video stream, resulting in a better user experience of the system and so it was decided to use the lower resolution in the final version of the image processing script.

In addition to the laboratory tests, the final system was tested tracking the Moon over a period of four hours. The results from this test, a sample of which are shown in Figure 7-18 below, indicated good tracking capabilities over extended periods of time. In conjunction with the tracking loops which were running during the test, a maximum pixel error of 1-pixel deviation from the centre (320×240) pixel on either axis was observed over the entire test once the target had been located and gimbals moved to centre the camera on the target.

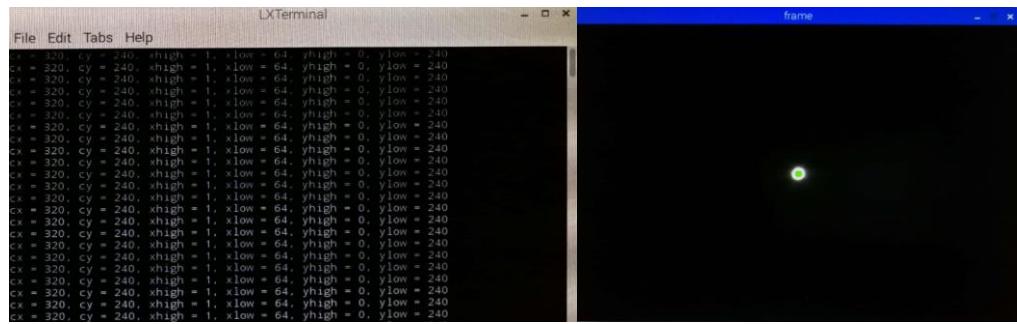


Figure 7-18: Moon tracking test samples

In addition to the script described by Figure 7-14, a second image processing script was written for applications where the user did not require a display of the image seen by the camera. This script could be run automatically on start-up of the RPi and could be monitored by the user via the terminal if a display was connected. If no display was connected the script still ran successfully and provided target position data to the STM32 if the target could be seen. This script was fundamentally the same as that previously described, however, the blocks shaded grey in Figure 7-14 were not included in this program and a pre-defined threshold region was used instead of allowing the operator to configure the range on initiation. The benefit of using this script consisted in having fewer peripherals connected to the stabilised platform and the fact that as the operating system of the RPi was not required to run the Raspbian GUI, higher image processing rates of up to 17 FPS were observed as more resources could not be allocated to the script.

7.4 USER INTERFACE (I_{3.1})

The final piece of software developed in this project was the User Interface, prime item I_{3.1}. Whilst its development was not strictly necessary for the successful implementation of the ISP system, as target tracking was performed by the RPi and all control tasks and sensor comms were managed by the STM32, system specification S₁₃ specified that a method of computer control of the system was desired to facilitate ease of use of the ISP. It provides a safe, user-friendly way of controlling the operation of the ISP as well as provides a means for the data logging of system runtime data otherwise not recordable on the STM32.

The primary goals for the UI can be summarised as follows:

1. Provide a means to initialise and stop target tracking and stabilisation.
2. Provide a means to control the gimbals' orientation whilst in the manual mode of operation.
3. Provide a real-time visualisation of the ISP assembly.
4. Indicate the target position in the camera FOV.
5. Indicate current inertial rates of the telescope.
6. Provide a means of data logging of the system runtime data.

7.4.1 DESCRIPTION OF THE COMPONENTS OF THE UI

As previously indicated in Section 5.2.6, the UI was written in the LabVIEW environment due to its ease of use for developing supervisory control programs. Figure 7-19 below shows the GUI of the final UI.

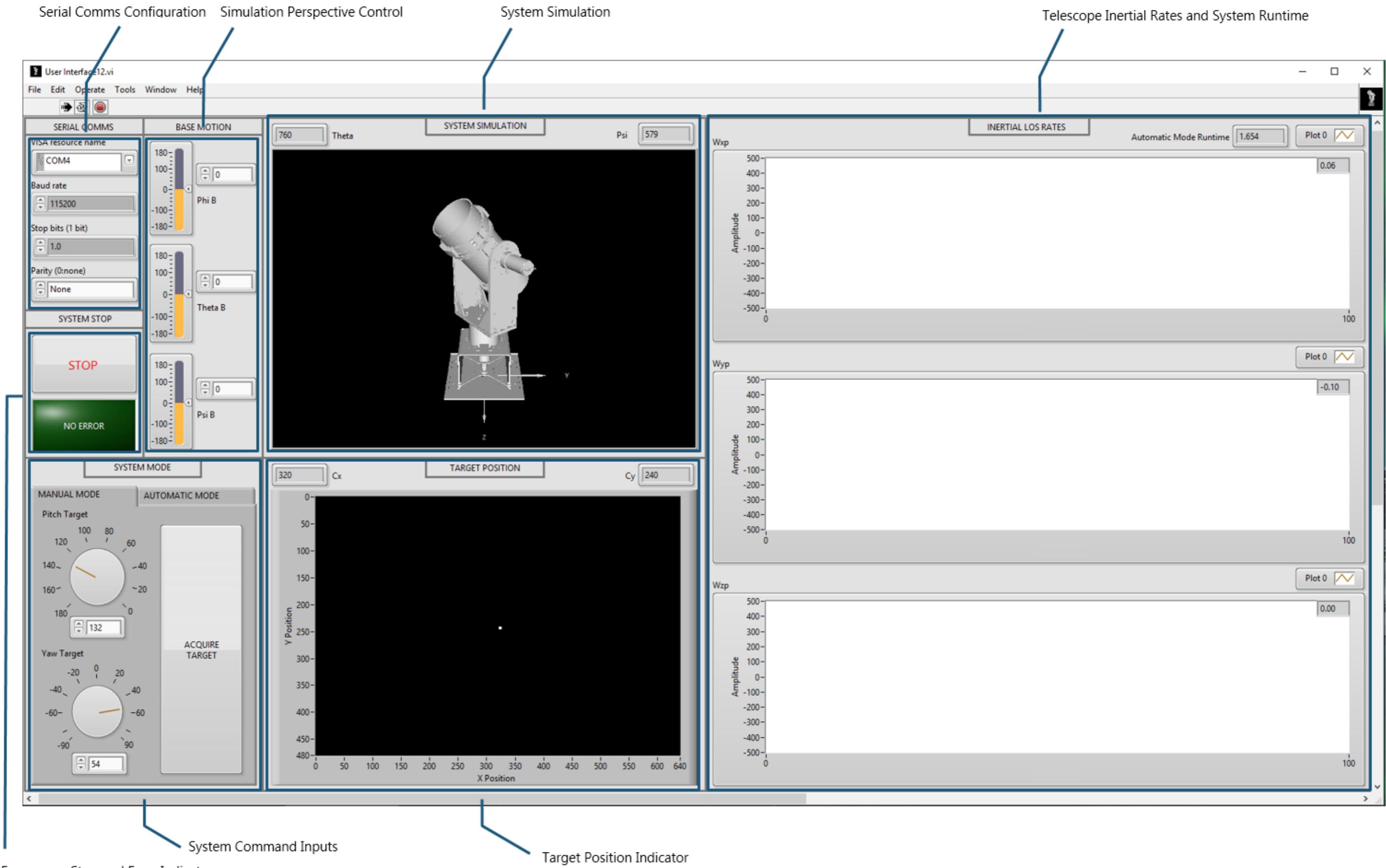


Figure 7-19: Final User Interface developed in LabVIEW

The UI above contains various controls and displays, these are summarised below working from the top-left of the GUI.

SERIAL COMMS CONFIGURATION

This tool allows the parameters of the serial comms of the UI to be configured each time the program is run so as to allow for possible changes in configuration of the target STM32 with which the UI interacts. The settings required for use are those that match those of the USART1 peripheral on the STM32, namely, a baud rate of 115200 bps, 1 stop bit, and even parity.

SIMULATION PERSPECTIVE CONTROL

These sliders allow for the observer perspective of the graphical simulation to be changed according to the operator's preference. They may also be controlled by typing the desired angles in degrees into the indicator boxes.

SYSTEM SIMULATION

This graphical simulation of the ISP platform allows the operator to visualise the orientation of the ISP. In the Manual mode, the pitch and yaw angles of the simulation model are controlled by the position of the radial dials shown in the System Command Inputs region of the UI. In the Automatic mode these angles are controlled by the relative angle position data signal acquired by the UI whilst the system is running. This allows for a real-time indication of the gimbal angles to be displayed during the system runtime.

TELESCOPE INERTIAL RATES AND SYSTEM RUNTIME

This region of the UI shows a real-time indication of the platform inertial rates in °/s. The x-axis is a measure of the number of data packets received. System time is shown in the top-right corner of this region. Figure 7-20 below shows an example an axis of this section from a system runtime sample.



Figure 7-20: Inertial rate, ω_{yb} , during system operation

TARGET POSITION INDICATOR

This region of the UI plots the pixel position of the target whilst it is visible and the system is in the Automatic mode. Due to there being no direct comms link between the RPi and the UI, it was not possible to transfer image data efficiently between the devices. Therefore, it was decided to simply transfer the position data of the target and visualise it appropriately in the UI.

SYSTEM COMMANDS INPUT

This section of the UI facilitates user command of the STM32 MCU behaviour and program state. The tab control allows either the Manual mode operations or Automatic mode selection to be made. The Manual Mode tab contains two radial dials which are used to select angle commands for the yaw and pitch manual position controllers. These are sent to the STM32 on the click of the “Acquire Target” button. In the Automatic mode a simple “RUN/PAUSE” button is found, as shown in Figure 7-21 below which shows the appearance of the button in its default state, after one click, and after a second click.

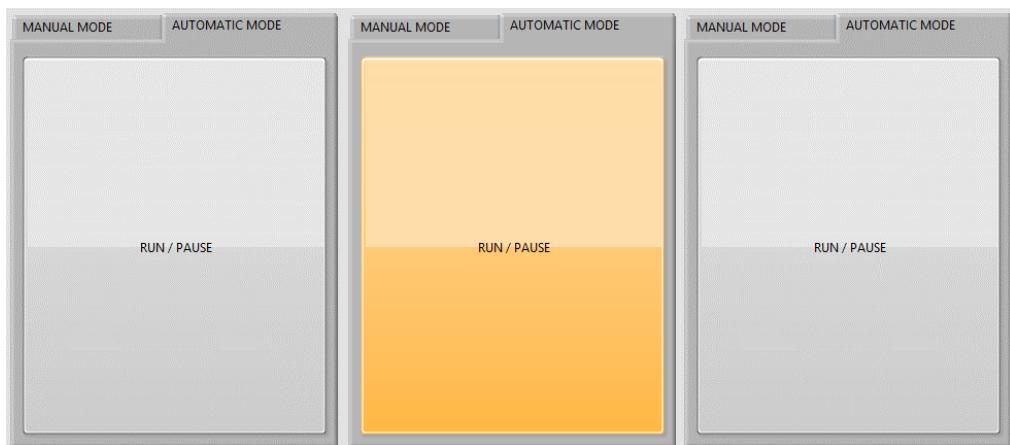


Figure 7-21: Automatic mode system command input – Unclicked, Clicked, Second Click

On click of this button, the UI sends the relevant command to the STM32 to trigger the Automatic state. After this, the system waits until the start of data packet identifier byte is received on the serial port. It then reads the 17 bytes of the data packet send by the STM32 and updates the GUI displays accordingly and stores this data set as a new row of an array containing the system runtime data. It then returns to wait for another data packet before repeating the same process. On second click of the button the UI sends the command for the STM32 to return to the Manual state to await new target data. Subsequent clicks of the button will repeatedly toggle the state of the STM32 program between the Automatic and Manual states whilst the UI performs the appropriate supervisory function depending on the MCU state.

EMERGENCY STOP AND ERROR INDICATOR

The final region of the GUI contains the system stop button and an error indicator. On press of the stop button the UI sends the STOP command to the STM₃₂, which in turn sends the shutdown signal to the RPi. It then writes the data logs to a spreadsheet file and displays a dialog box to the operator indicating that the stop button was pressed and that the data logs have been saved. If a limit error is detected the same stop process is followed, but the dialog box indicates that a limit error stopped the system, and the green indicator is lit red.

7.4.2 FUNCTIONAL DESCRIPTION OF THE USER INTERFACE

The flowchart shown in Figure 7-22 below describes the User Interface software developed for this project. The LabVIEW project containing the main VI and sub-VIs used by the software may be found in Appendix C.

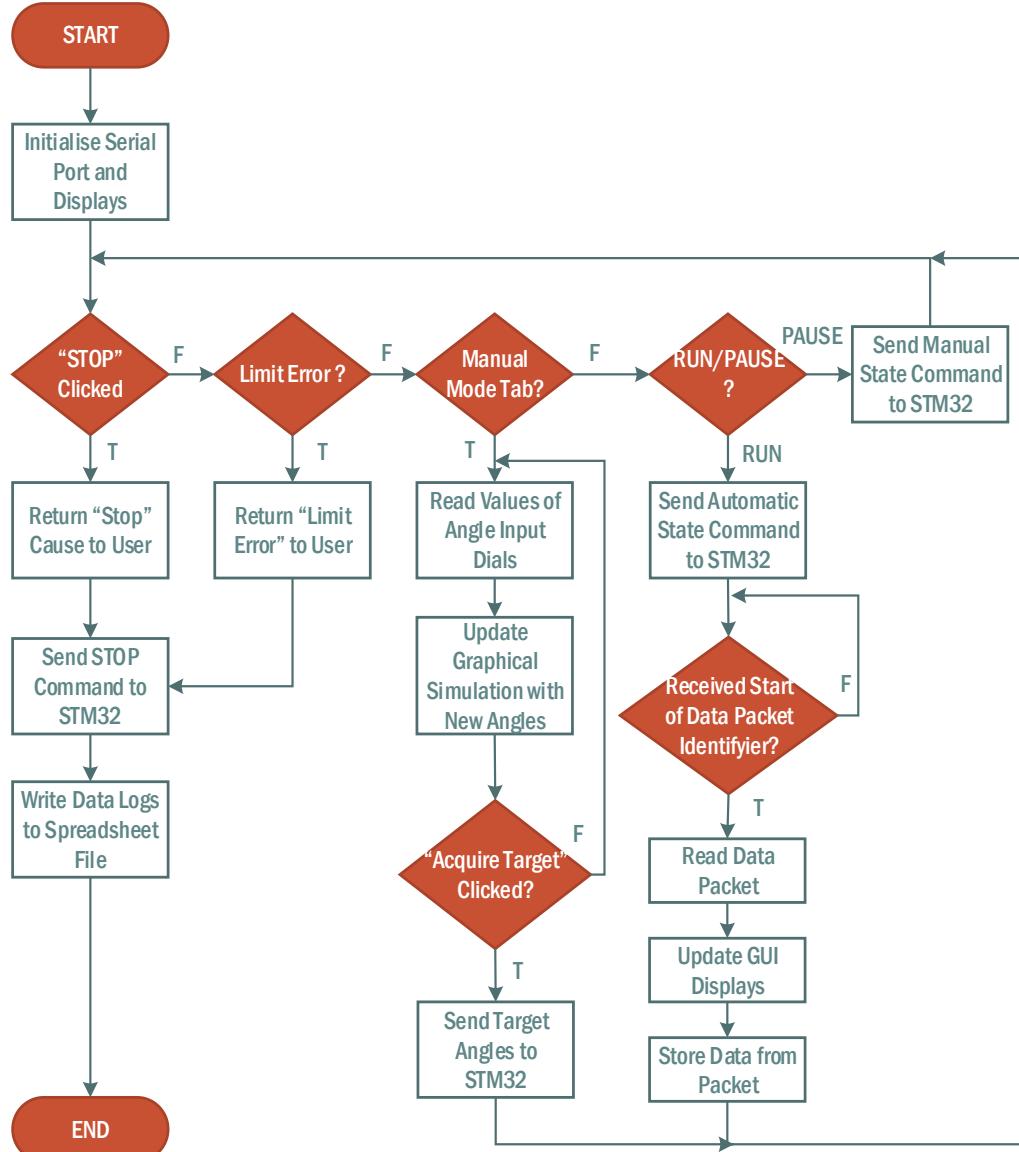


Figure 7-22: Functional flowchart of the User Interface software operation

7.5 CHAPTER CONCLUSION

This chapter began by describing the firmware written for the STM₃₂F0 microcontroller. This firmware was written in C and performed all sensor communications, controller algorithm functions and system limit protection tasks. It also managed the timing of comms transfers contain target position data from the RPi. Finally, the firmware performed the task of sending runtime data from each run of the controller algorithm to the LabVIEW UI.

After the description of the STM₃₂ firmware, the multi-threaded image processing software which performed most of the target tracker tasks was detailed. This software was

written in Python 2.7 and implemented on the RPi computer to process the image acquired by the RPi Cam such that a target could be identified and located in the FOV of the camera.

Finally, the chapter concluded with a description of the User Interface software written in LabVIEW. This software facilitated user control of the ISP system in a safe, user friendly manner, and performed data logging operations on the system runtime data sent by the STM₃₂ to the host computer.

The next chapter describes various system tests that were run to characterise the performance of the implemented ISP and to determine the correlation between the hardware and simulation results.

8

ISP PERFORMANCE AND MODEL VERIFICATION

8.1 INTRODUCTION

The previous four chapters described the development of the various components of the ISP developed in this project. This chapter describes the results of testing the overall ISP system and compares these results to those of the simulation. First, the step tracking responses of the ISP are evaluated, before an evaluation of the maximum tracking rates is given. Following these tests, base motion isolation is evaluated and compared to the simulation and the jitter of the telescope modeller in response to various base motions is evaluated.

8.2 STEP TRACKING RESPONSES OF THE ISP

The step response of the gimbals was evaluated by setting up the system such that the target tracker could see a fixed target at the limit of the FOV of the camera. From this position, the system was then set to the Automatic mode and allowed to actuate the gimbals such that the target was placed onto the LOS of the camera. The pixel positions of the target centroid were recorded during this test using the LabVIEW data logging VI originally used to test the Allan Variance of the IMU in Section 5.2.2. These pixel positions were then converted to angle measurements from the LOS of the sensor to the target using the linear approximation described in Section 7.2.7 where it was shown that 1 pixel represented 0.51 mrad of the camera's FOV. Five tests were performed for each axis and the average results are shown in Figure 8-1 for the pitch channel and Figure 8-2 for the yaw channel.

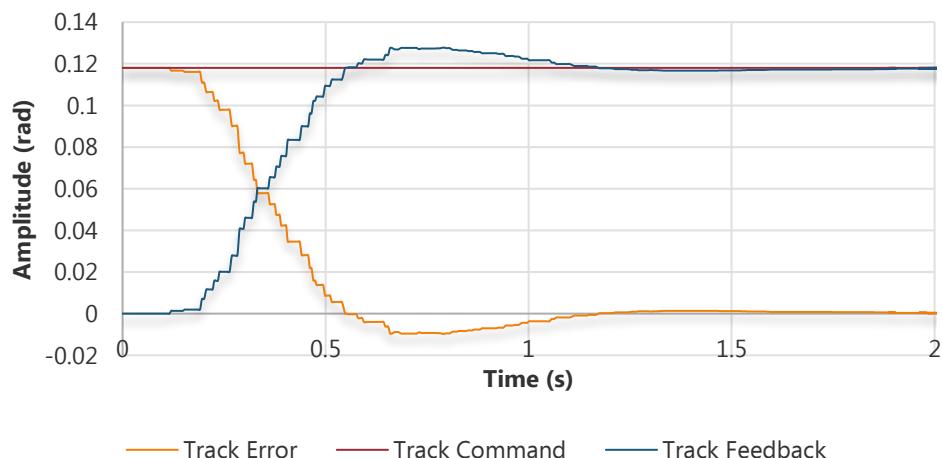


Figure 8-1: Step Tracking response of the yaw channel

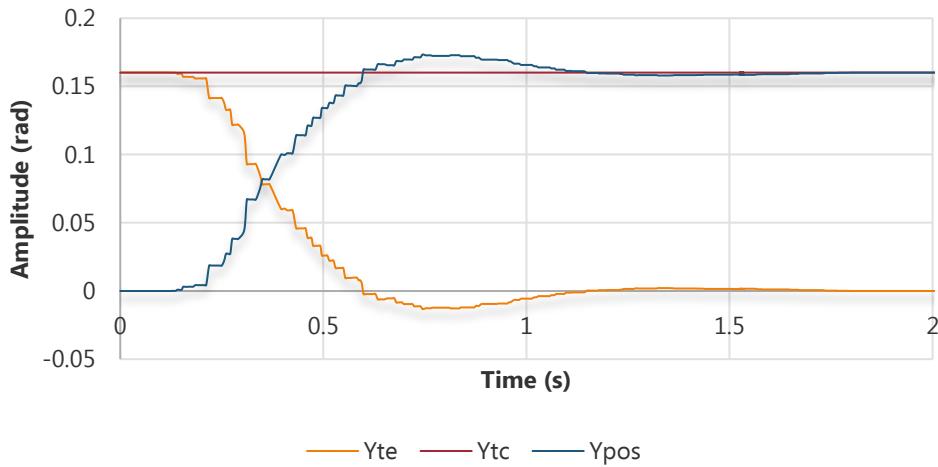


Figure 8-2: Step tracking response of the pitch channel

The quantisation effects of the low target tracker frame rate are very noticeable in the results above, but do not affect the performance of the controllers much. Both controllers overshoot the step command by $\sim 8\%$ before settling to the desired state within 2 s of the command. This overshoot for the pitch channel in response to the largest possible track command signal is ~ 11.6 mrad and for the yaw channel is ~ 12.3 mrad. Both show a time constant of approximately 0.4 s. These responses show similar shapes to that of the simulation which was run with the same step commands as in the tests above, but are slower to respond by a factor of two. The simulation result showing the tracking error signals is shown in Figure 8-3 below.

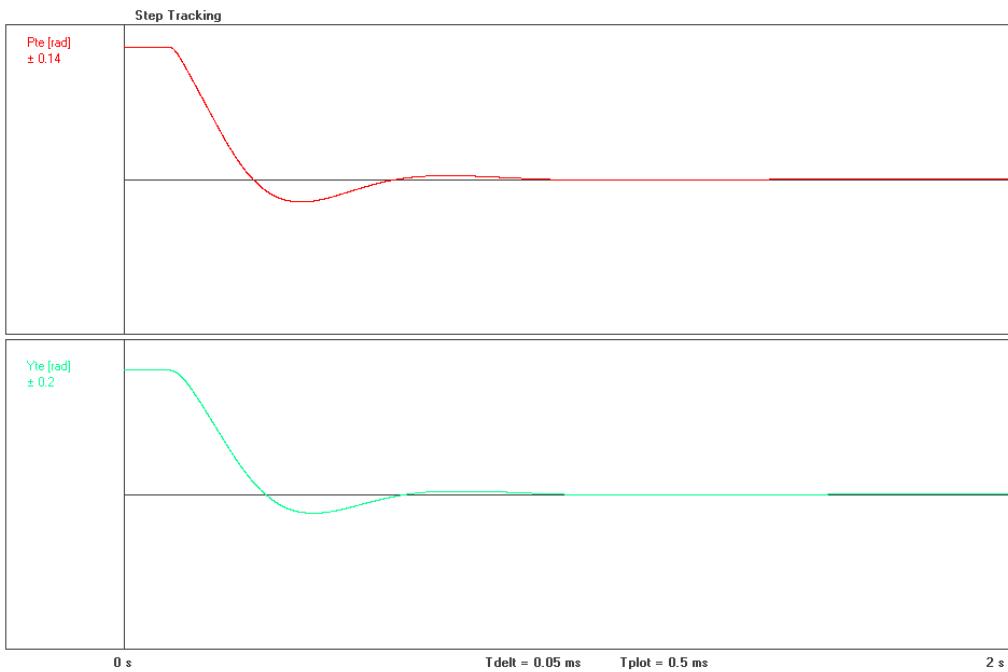


Figure 8-3: Simulated step tracking with the test command signals

Due to the shape of the responses being similar between the simulation and the tests, it is theorised that the difference in response times was due to a current limit being applied to the power supply used during system testing which limited the total current in the system to 2 A. This was done to prevent the motors from drawing more current than their 2.3 A_(continuous) rating for extended periods during the testing process. This was validated by running the simulation with a current limit of ± 2 A applied to each model in the model which slowed the response as shown in Figure 8-4 below.

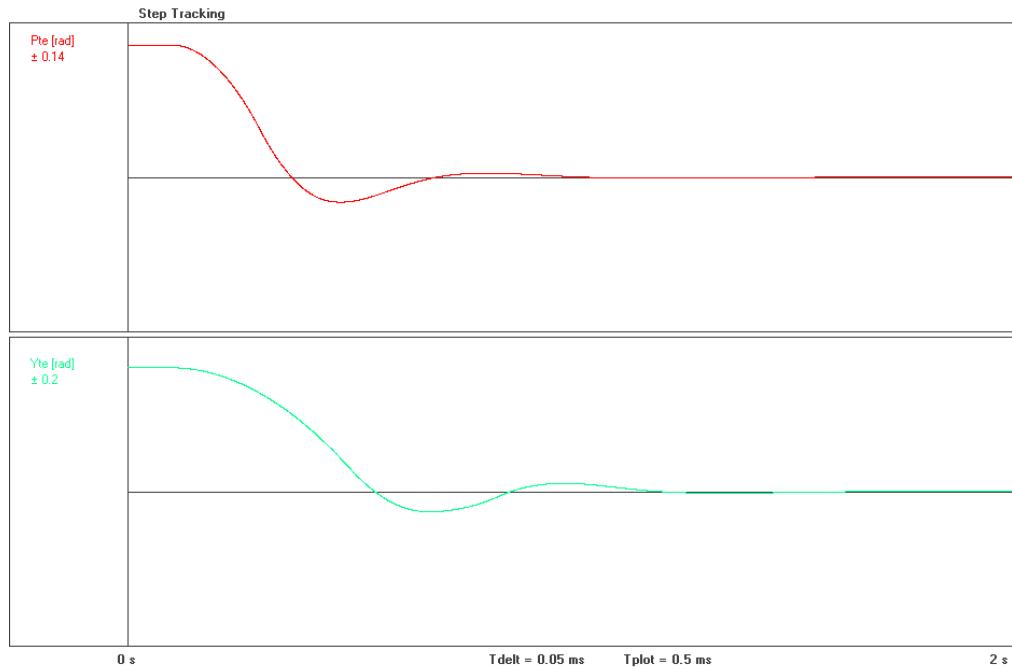


Figure 8-4: Step tracking with current limited motors

The effects of the current limit are more noticeable on the yaw channel in the simulation than the pitch channel. However, it was concluded that overall, that the step response of the simulation matched the hardware response well.

8.3 EVALUATION OF MAXIMUM TRACKING RATES

The maximum tracking rate of each gimbal axis defines the maximum angular rate at which tracking of a moving target might be maintained by the ISP. This maximum rate is, therefore, the maximum rate at which each gimbal can rotate, in response to a tracking loop command.

To evaluate this, the control firmware on the STM32 was modified to feed the tracking loop with a fixed pixel position of the target at the limit of the FOV of the camera. This allowed the maximum tracking error signal to continually feed the control loop and caused the actuator to move the gimbals at their highest tracking rate. For the yaw tracking loop, the target was modelled at pixel position 640 to create an error of 320 pixels or 0.163 rad, whilst the pitch tracking loop received a target position of 480 pixels to create a constant error of 0.122 rad. Measurements of the gimbal rates were taken by the feedback gyro as the gimbal

accelerated and reached its maximum angular rate. The loops were tested independently of each other such that motion from one gimbal did not affect motion in the other. For the yaw gimbal test, the pitch platform was fixed in position with $\theta = 0^\circ$ so that the maximum possible inertia was seen by the yaw motor and the test results would represent the worst-case tracking rate for the yaw tracking loop. A series of five tests were run for each channel according to the method described above. The results from these tests were then averaged and used to plot the graph shown in Figure 8-5.

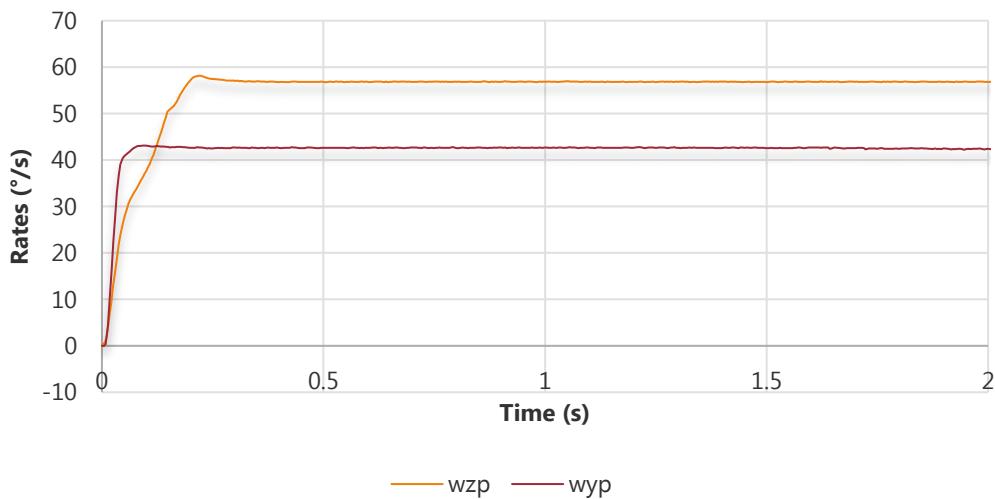
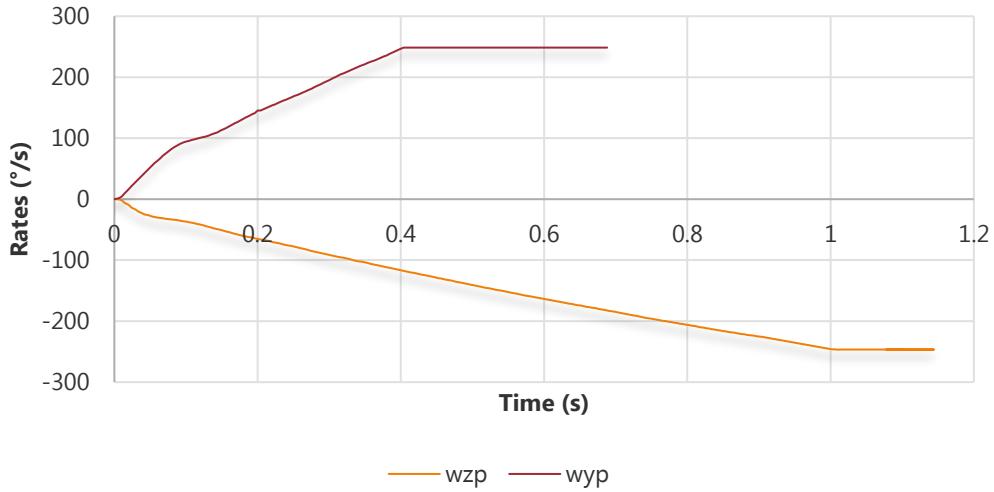


Figure 8-5: Yaw tracking rate test results

The figure above shows the average profile of ω_{yp} signal showing the pitch rate, and the ω_{zp} signal which was equal to the yaw gimbal rate for the yaw channel tests. These tests showed a maximum tracking rate for the yaw channel of $56.9\text{ }^\circ/\text{s}$ or 0.99 rad/s , and $42.7\text{ }^\circ/\text{s}$ or 0.75 rad/s for the pitch channel. The pitch channel accelerates faster than the yaw channel due to the lower inertia seen by its motor, however, the maximum tracking error on the pitch channel is smaller than the yaw channel due to the smaller angular range of the camera FOV in this direction. As P controllers were used for the tracking loops, in response to this smaller error signal, the maximum rate of the channel is limited to a lower value than for the yaw channel.

These tracking rates should not be confused with the maximum possible controlled angular rates of the ISP which occur when the motors saturate due to a maximum error present on the stabilisation controllers. These rates were tested by programming a constant maximum stabilisation error onto the STM32 and monitoring the telescope modeller rates accordingly. These results are shown in Figure 8-6 below. Again, the pitch platform was set to $\theta = 0^\circ$ when testing the yaw performance.

**Figure 8-6: Maximum rates of the gimbals**

Here it can be seen that with a sustained maximum stabilisation error, both the yaw and pitch motors accelerate to 250 °/s, after which their rates were no longer detectable by the feedback gyro. They continue at that rate until stopped by the position limit detection system on the STM32. Therefore, the theoretical maximum controlled LOS rate of the telescope modeller is 250 °/s for both control axes.

8.4 BASE MOTION ISOLATION AND JITTER PERFORMANCE

Base motion isolation and jitter performance were tested for various configurations of ISP orientation and disturbance motion. All tests were performed following the methodology below.

1. A second MPU-9150 was affixed to the base of the ISP system mounting stand. This was read by a second STM32Fo MCU running firmware that setup this gyro to precisely the same settings as the main feedback gyro used on the ISP. This STM32 was also setup to be electronically triggered by the main control STM32 when readings were required to begin. This was done to ensure that measurements were taken in phase with each other from both the base gyro and the ISP gyro. This second STM32 was connected to a laptop running the data logging VI used previously. The main control STM32 also communicated with another instance of the data logging VI running on the laptop.
2. After the initialisation of both MCUs and gyros, the main control MCU was set to the Automatic state. At this point, the second STM32 was triggered and gyro readings began simultaneously. The main control STM32 ran the tracking and stabilisation controllers and provided measurements of the inertial rates of the telescope modeller whilst the second STM32 and gyro measured the motion of the base. Both sets of rate data were then sent to the LabVIEW data logging VIs.
3. Base motions were then applied by hand to relevant base axes whilst the ISP attenuated these motions.

4. The data loggers were then stopped and rate data saved in spreadsheet files.
5. By comparing the peak amplitudes of the corresponding disturbance and telescope modeller rate signals contained in these files, BMI could be evaluated.
6. Another VI written to perform an integration of the rate data signals was then used to provide a measure of the angular displacement of the axis in response to its inertial rate. This was used to approximate jitter on the telescope modeller.

8.4.1 PITCH BASE MOTION ISOLATION IN THE HOME POSITION

The first test performed was that of providing a base motion about the y_b axis and measuring its attenuation about the y_p axis whilst the ISP was oriented in its home position. This test provided a measure of the performance of the pitch stabilisation loop in its worst case: when $\psi = 0^\circ$, the maximum proportion of ω_{yb} is coupled to the y_p axis and the disturbance on the pitch motor is greatest. The performance of the pitch channel when $\psi = 0^\circ$ is independent of θ . Figure 8-7 below shows the base motion input ω_{yb} over a period of the test between 5 – 15 s.

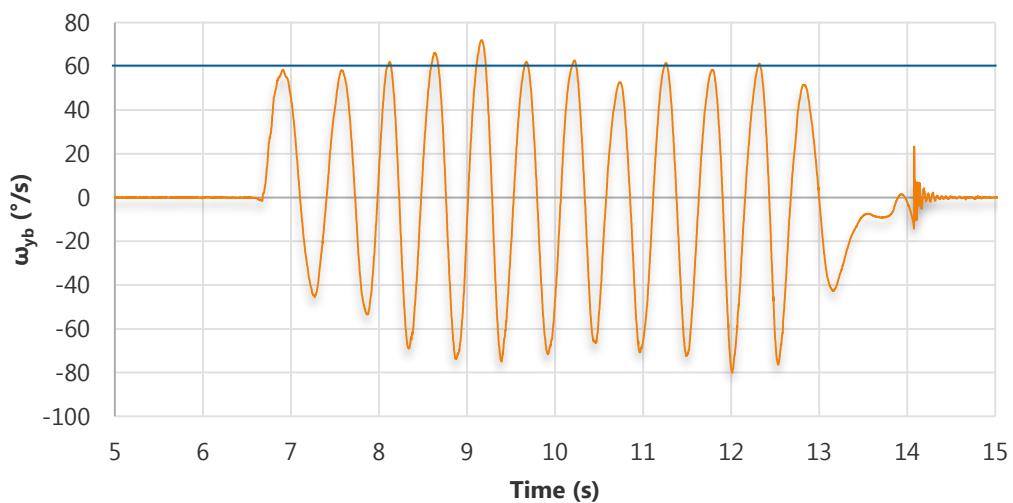


Figure 8-7: Base motion, ω_{yb} , for the pitch channel BMI test in the home position

For the period between 8 – 13 s, this base motion signal has a median value of $60.89\text{ }^\circ/\text{s}$ for positive disturbances at a dominant frequency of approximately 1.8 Hz. These are shown as the blue line on the figure above. The corresponding inertial rate of the telescope modeller, ω_{yp} , is shown in Figure 8-8 below.

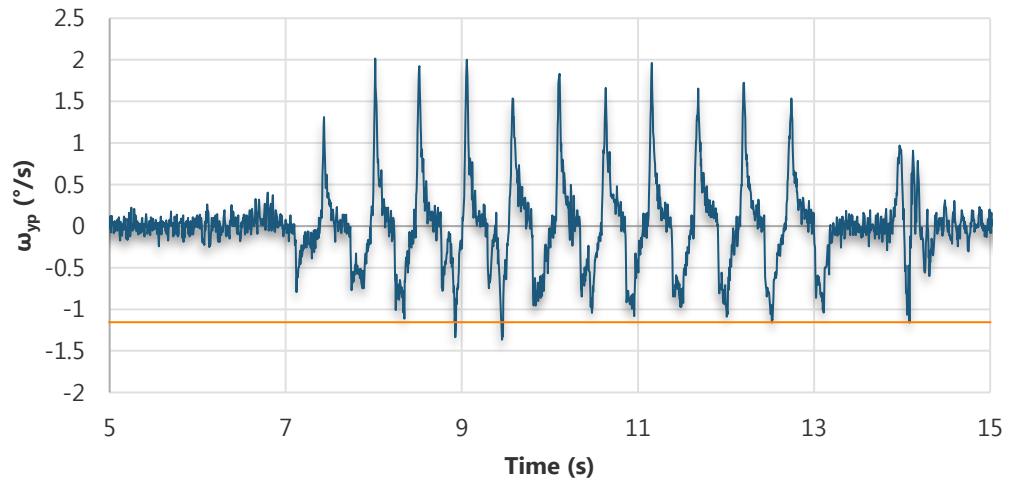


Figure 8-8: Inertial rate, ω_{yp} , for the pitch channel BMI test

For the same period, the inertial rate, ω_{yp} , has a median value of $-1.16 \text{ } ^\circ/\text{s}$ for negative disturbances in response to the positive rates of the base motion. Using the definition of BMI previously given in Section 6.3.3, a BMI of $b = -34.4 \text{ dB}$ was estimated on the pitch channel in the home position. The system simulation was then run with a sinusoidal disturbance with amplitude $60.89 \text{ } ^\circ/\text{s}$ and frequency 1.8 Hz about the y_b axis to determine the correlation between the simulation and the hardware. This result is shown in Figure 8-9 below.

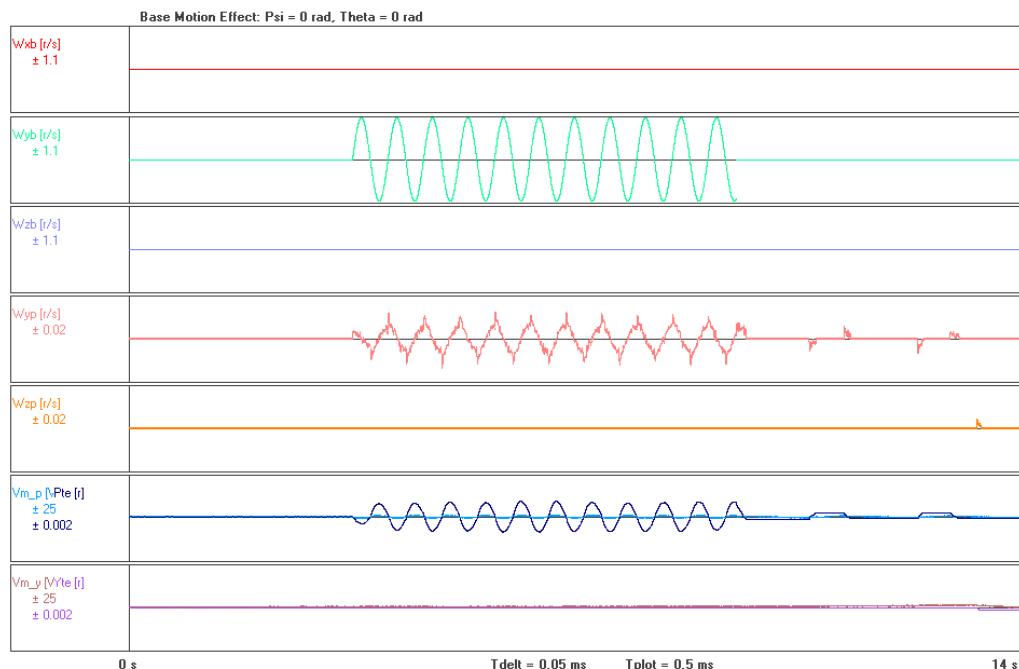


Figure 8-9: Simulation response to a 1.8 Hz, $60.89 \text{ } ^\circ/\text{s}$ ω_{yb} signal

Simulation responses above are shown in rad/s rather than °/s, however, the simulated performance is better than that of the hardware with an expected peak ω_{yp} of 0.011 rad/s rather than the 1.16 °/s = 0.0202 rad/s evident in the test results. However, as stated in Section 6.2.1, the $Fric_x$ and Kfr_x of the friction model used in the simulation for both gimbals were purely estimate values, whilst the $Stic_x$ values had been experimentally determined. Therefore, by varying the value of these estimated parameters it was possible to bring the pitch channel of the simulation into alignment with the hardware performance. Table 8-1 below shows the changes made to these parameters.

Table 8-1: Friction parameters of the Pitch Channel

Parameter	Initial Estimate	Adjusted Value
$Stic_p$	18.0 mNm	18.0 mNm
$Fric_p$	5.4 mNm	12.6 mNm
Kfr_p	6.13 mNm/(rad/s)	1.31 mNm/(rad/s)

Using these friction parameters, the simulation matched the test results, as shown in Figure 8-10 below.

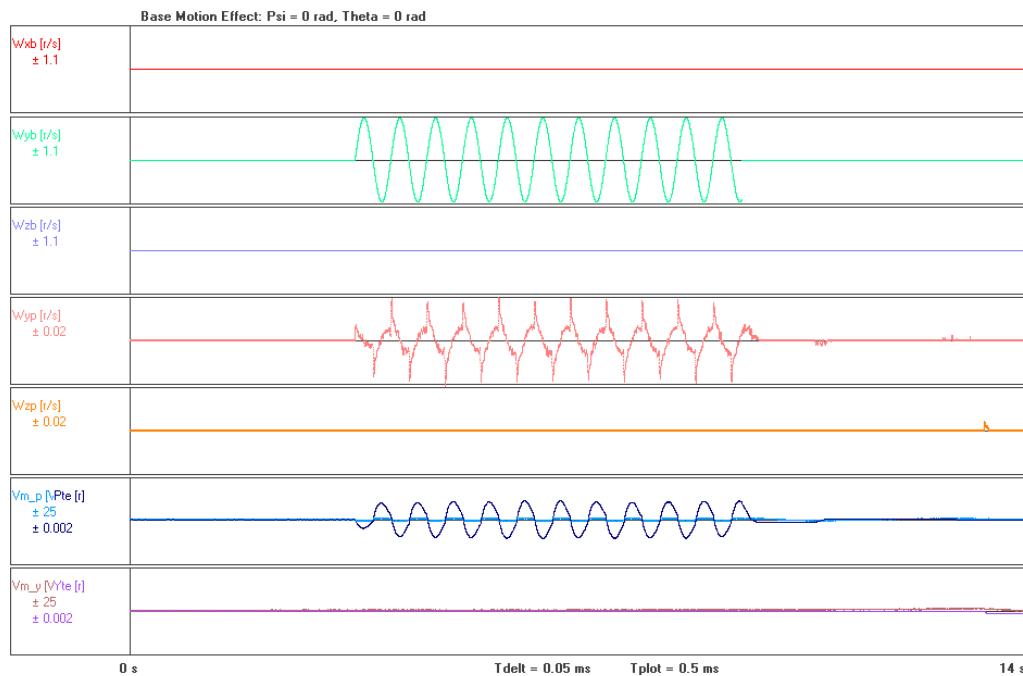
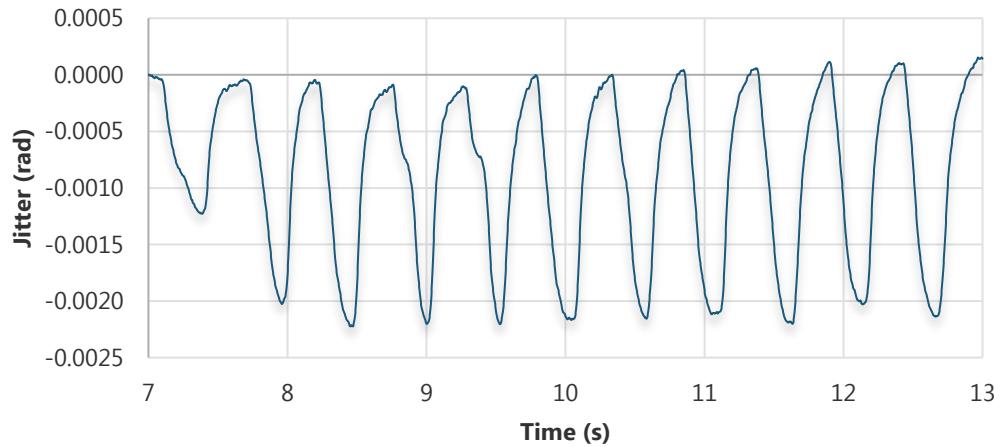


Figure 8-10: Pitch channel base motion isolation with corrected friction model

Here, the peak of ω_{yp} is 0.02 rad/s = 1.15 °/s and matches the hardware result very closely. An approximation of jitter about the y_p axis, as shown in Figure 8-11, was estimated by the integral of the ω_{yp} data.

**Figure 8-11: Pitch channel jitter estimation**

It can be seen from the figure above, that jitter between 7 - 13 s peaks at 2.22 mrad and therefore remains approximately within the specification set by S6 of 2 mrad. Jitter was also concurrently evaluated during this test using the analogue method below.

1. A laser pointer was mounted on the telescope modeller such that it was aligned with the camera LOS.
2. A piece of graphing paper was placed on a wall a known distance, x_p , from the origin of the pitch platform frame.
3. A fixed target recognisable to the target tracker was mounted on the graph paper to keep the camera LOS on a fixed origin point on the graph paper.
4. On application of the base motion input the deflection, z_p , of the laser pointer dot on the graph paper in the vertical plane was recorded.
5. Measuring the deflection from the fixed point then allowed the maximum jitter angle to be calculated according to:

$$\text{Jitter Angle} = \tan^{-1} \left(\frac{z_p}{x_p} \right)$$

This method of jitter approximation yielded the following results.

Table 8-2: Analogue pitch jitter estimation

Measurement	Reading
x_p	2010 mm
z_p	5 mm
Jitter angle	2.49 mrad

This jitter estimation matches that of the estimation by rate data integration within 11 % and confirms the jitter performance of the pitch channel in the home position to be approximately 2.35 mrad in response to ω_{yb} signals of the order of 1 rad/s amplitudes at 2 Hz.

8.4.2 YAW BASE MOTION ISOLATION IN THE HOME POSITION

Using the same method as above, with the ISP in the home position, the second test evaluated the yaw stabilisation loop in the home position. This test represented the worst-case conditions for the yaw channel where the maximum possible inertia was seen by the yaw motor. A base motion was applied to the z_b axis and the output inertial rate about the z_p axis was measured. The base motion signal, ω_{zb} , is shown in Figure 8-12 below.

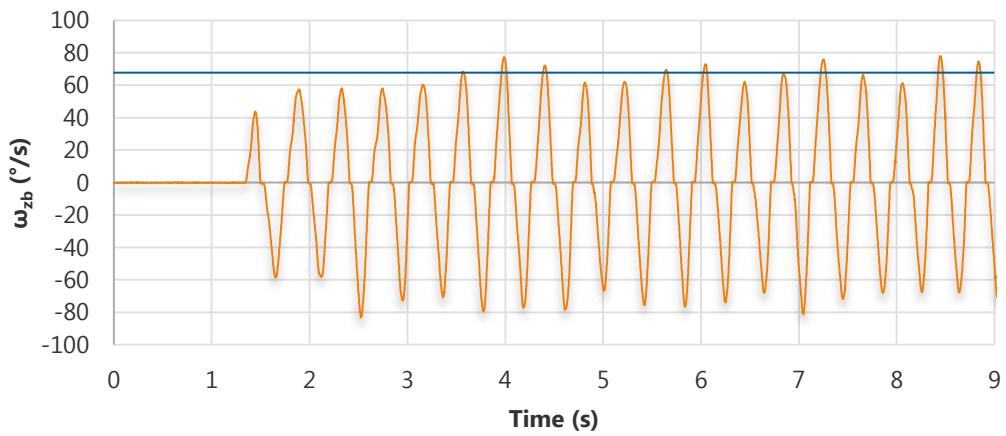


Figure 8-12: Base motion, ω_{zb} , for the yaw channel BMI test in the home position

For the period between 2 – 9 s, ω_{zb} has a median value of 66.50 °/s for positive disturbances at a dominant frequency of approximately 2.5 Hz. The corresponding inertial rate of the telescope modeller, ω_{zp} , is shown in Figure 8-13 below.

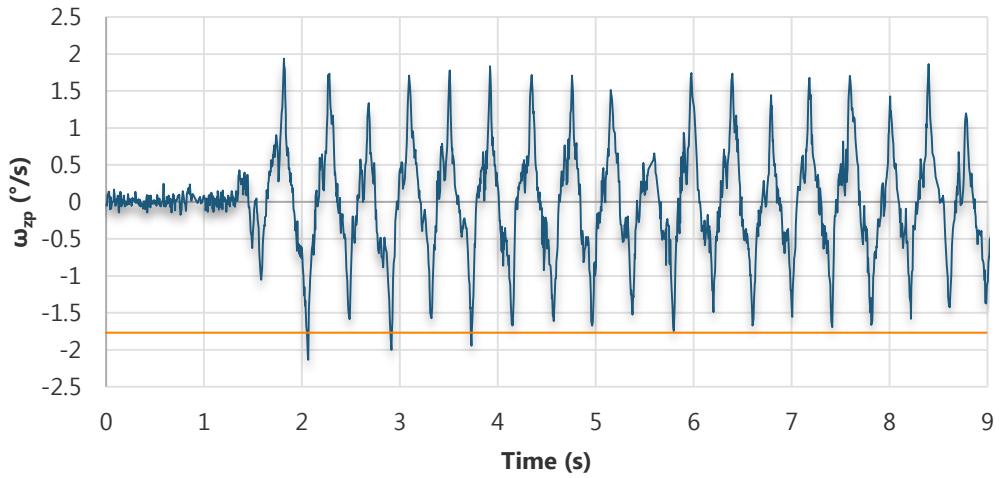


Figure 8-13: Inertial rate, ω_{zp} , for the yaw channel BMI test

For the same period, the inertial rate, ω_{zp} , has a median value of -1.76 °/s for negative disturbances in response to positive rates of the base motion. BMI for the yaw channel is, therefore, estimated at -31.5 dB in the home position at 2.5 Hz. The system simulation was then run with a sinusoidal 66.50 °/s amplitude at 2.5 Hz disturbance about the z_b axis to

determine the correlation between the simulation and the hardware. This result is shown in Figure 8-14 below.

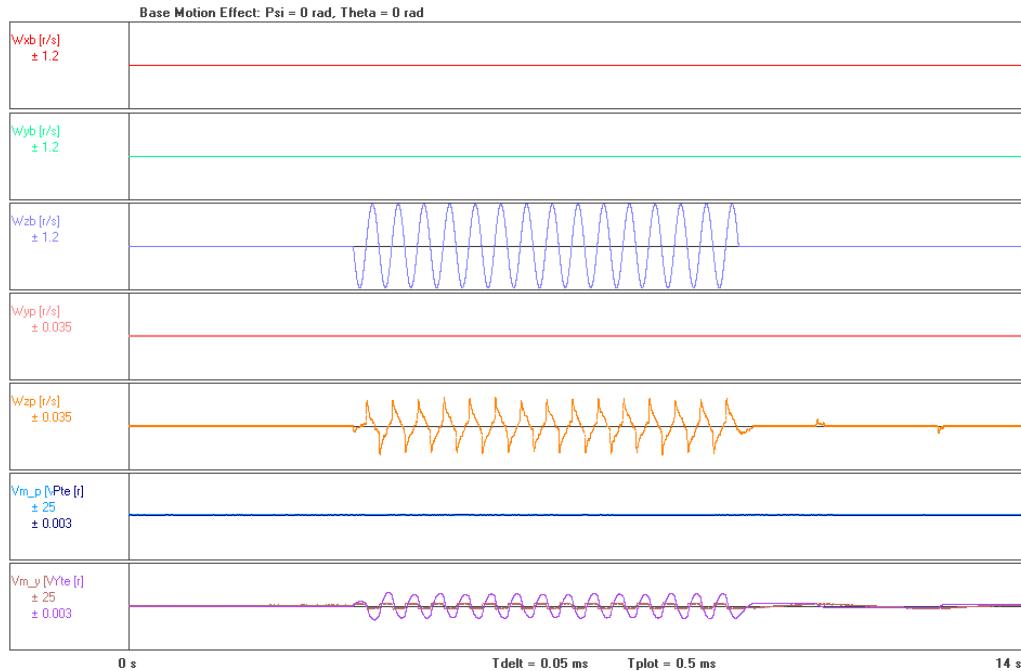


Figure 8-14: Simulation response to a 2.5 Hz, 66.50 °/s ω_{zb} signal

In the figure above, the peak of ω_{zp} reaches 0.0236 rad/s or 1.35 °/s which is slightly less than the experimental data of Figure 8-13. To adjust for this, $Fric_y$ was modified in the model to bring its performance into accordance with the hardware.

Table 8-3: Friction parameters of the Pitch Channel

Parameter	Initial Estimate	Adjusted Value
$Stic_y$	41.0 mNm	41.0 mNm
$Fric_y$	24.6 mNm	28.7 mNm
Kfr_y	1.75 mNm/(rad/s)	1.75 mNm/(rad/s)

These adjustments resulted in a simulation result as shown in Figure 8-15 below.

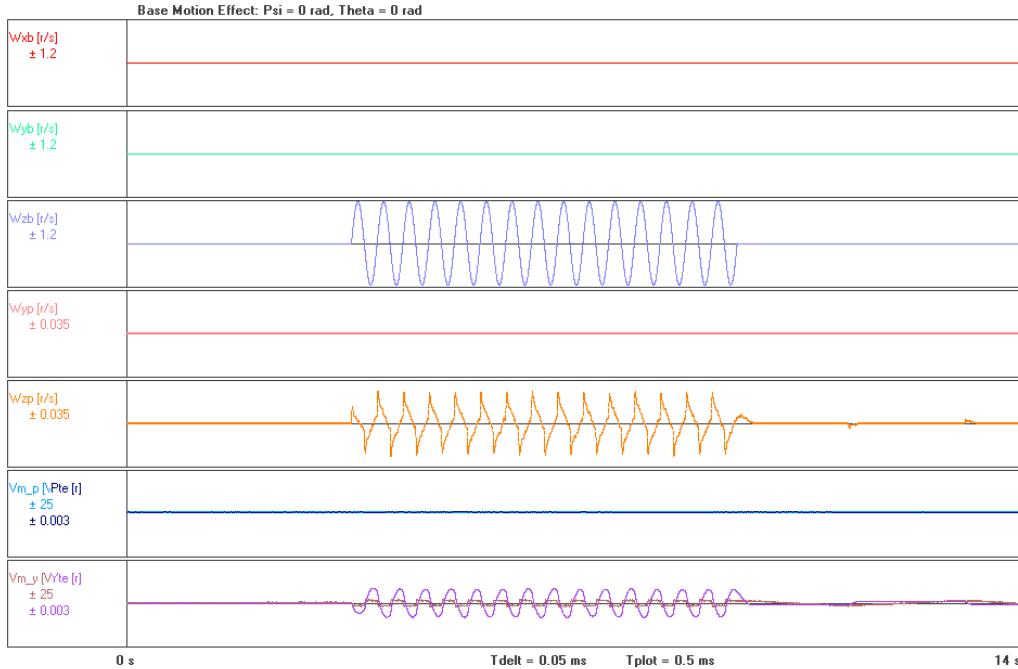


Figure 8-15: Yaw channel base motion isolation with corrected friction model

Here, the peak of ω_{zp} is now 0.0236 rad/s or 1.50 °/s, matching the experimental data reasonably well. Jitter for the yaw channel was estimated according to Figure 8-16 below which shows the result of integrating the ω_{zp} signal.

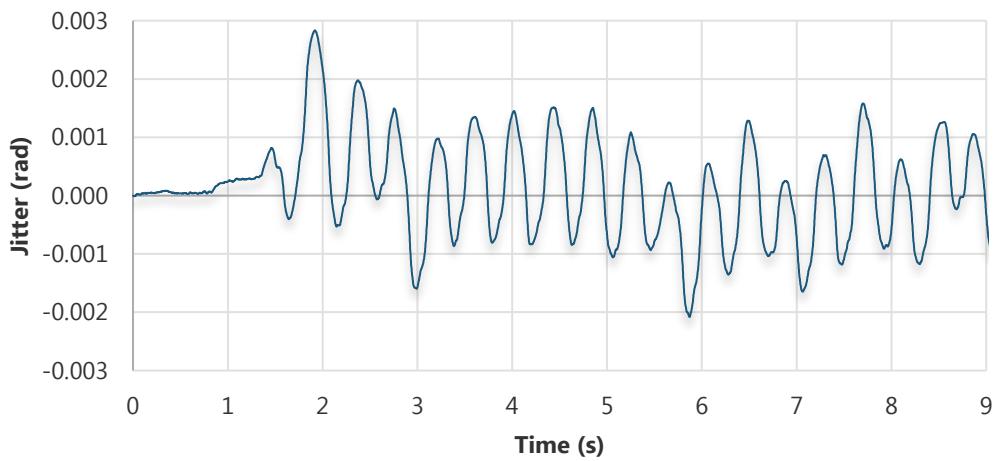


Figure 8-16: Yaw channel jitter estimation

In the figure, yaw jitter can be seen to peak at 2.80 mrad, however, for most of the test it remains within the 2 mrad specification of S6a. Using the same method as before, an analogue approximation of the yaw channel jitter was performed during this test which yielded the following results.

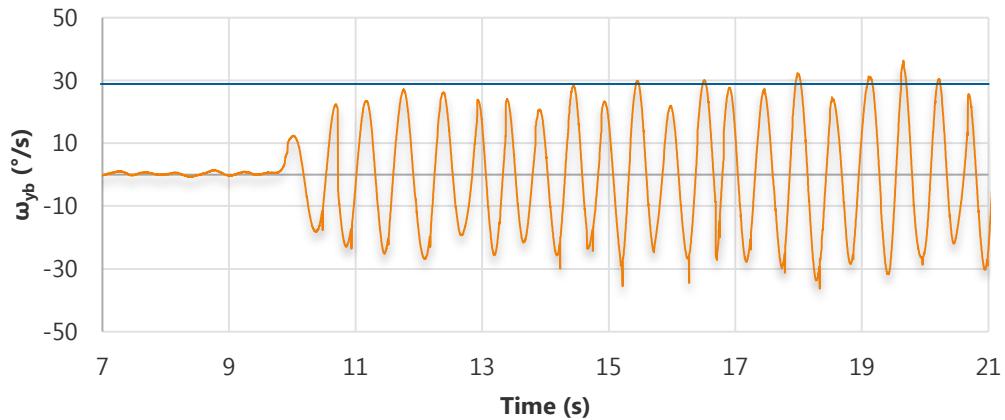
Table 8-4: Analogue pitch jitter estimation

Measurement	Reading
x_p	2010 mm
Horizontal Deflection, y_p	4.5 mm
Jitter angle	2.24 mrad

This jitter estimation matches that of the estimation by rate data integration within 20 % and confirms the jitter performance of the pitch channel in the home position to be approximately 2.52 mrad in response to a 1.2 rad/s ω_{yb} input signal at 2.5 Hz.

8.4.3 PERFORMANCE OF THE ISP IN THE WORST-CASE POSITION

The third test performed tested the performance of the system whilst in the worst-case position of $\psi = -45^\circ$, $\theta = 45^\circ$. The ISP was oriented in this configuration and a base motion about the y_b axis was applied. Due to the ψ being between 0° and 90° , this base motion coupled into the x_p and z_p axes and caused disturbances about those axes as well as about the y_p axis. The ω_{yb} signal applied to the base is shown in Figure 8-17 below.

**Figure 8-17: Base motion, ω_{yb} , for the worst-case orientation BMI test**

This disturbance had a median amplitude of approximately $28.93^\circ/\text{s}$ at 1.5 Hz for positive disturbances about the y_b axis between 11 - 21 s of the test, and caused a disturbance of the telescope inertial rates as shown in Figure 8-18 below.

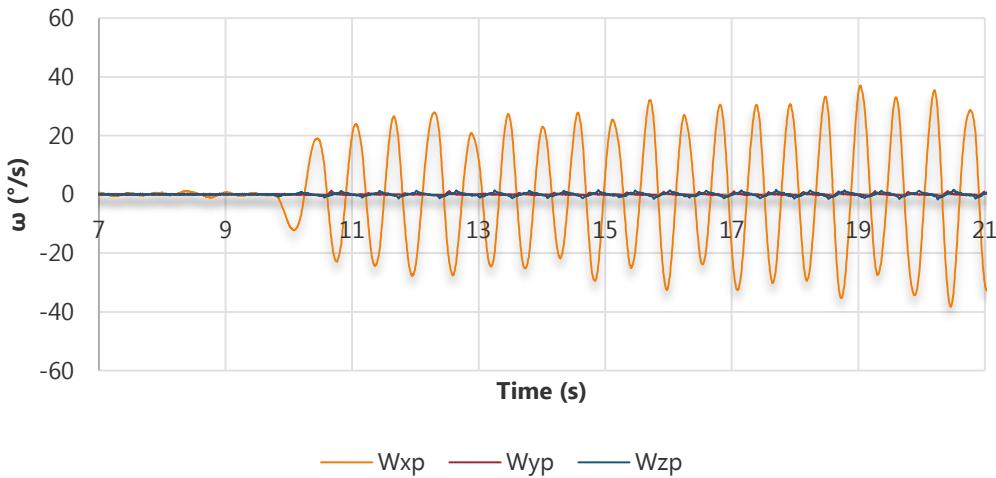


Figure 8-18: Inertial rates of the telescope modeler during the worst-case orientation BMI test

It can be seen here, how the ISP is able to attenuate disturbances coupled into the y_p and z_p axes but is completely unable to attenuate disturbances about the x_p axis, with ω_{xp} being approximately equal but opposite to the ω_{yp} disturbance. Figure 8-19 below shows the inertial rates ω_{yp} .

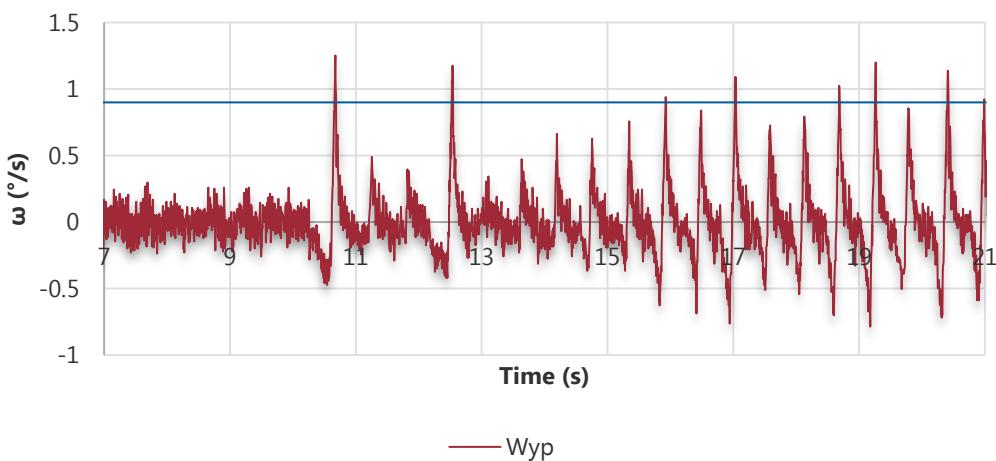


Figure 8-19: Inertial rate, ω_{yp} , during the worst-case orientation BMI test

The median peak value of ω_{yp} over 11 - 21 s is 0.91 °/s. This represents a BMI from ω_{yb} to ω_{yp} of -30.0 dB. Figure 8-20 below shows the cross coupled rate, ω_{zp} , as induced by ω_{yb} .

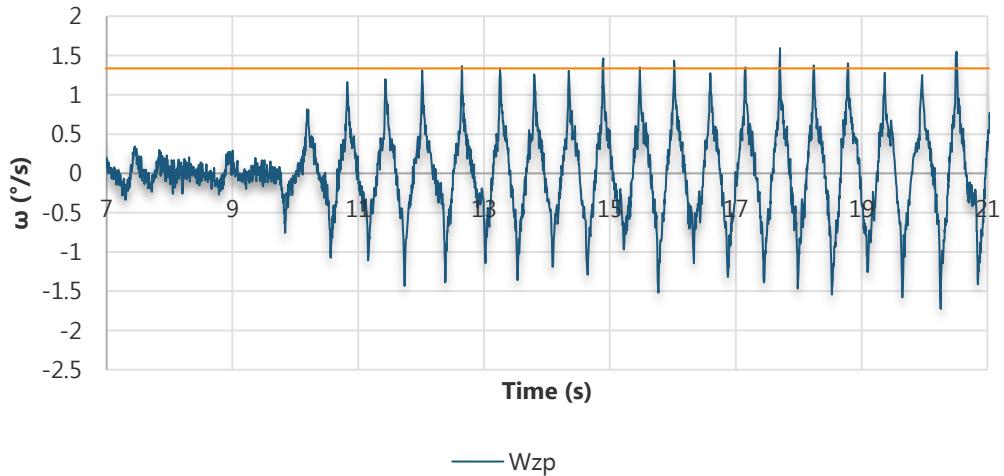


Figure 8-20: Inertial rate, ω_{zp} , during the worst-case orientation BMI test

This signal had a median peak value of approximately $1.39 \text{ } ^\circ/\text{s}$ resulting in a cross-axis BMI from ω_{yb} to ω_{zp} of approximately -26.3 dB . After this test, with the friction models now corrected, the simulation was run using a sine wave base motion of amplitude $28.93 \text{ } ^\circ/\text{s}$ at 1.5 Hz about y_b . The result of this test is shown in Figure 8-21 below.

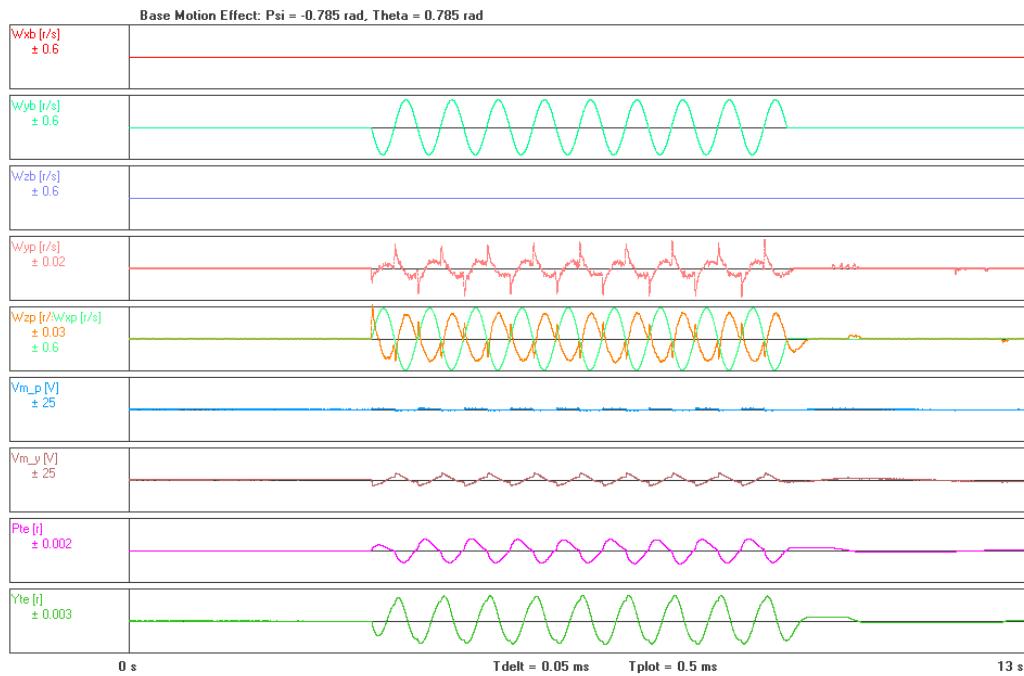


Figure 8-21: Base motion effects about the y_b axis in the worst-case orientation

The simulation shows a similar response to the hardware results above with ω_{yb} being coupled directly into ω_{xp} . Inertial rate, ω_{yp} , peaks at 0.017 rad/s or $0.97 \text{ } ^\circ/\text{s}$ which matches the test data within 8 %, whilst ω_{zp} , has a peak value (disregarding the initial peak) of 0.025 rad/s or $1.43 \text{ } ^\circ/\text{s}$ which matches the test results within 3 %. This test was also an equivalent test of the system response to a disturbance about the x_p axis. This can be seen by Figure 8-22

below which shows the results of the simulation when the disturbance is changed from ω_{yb} to ω_{xb} .

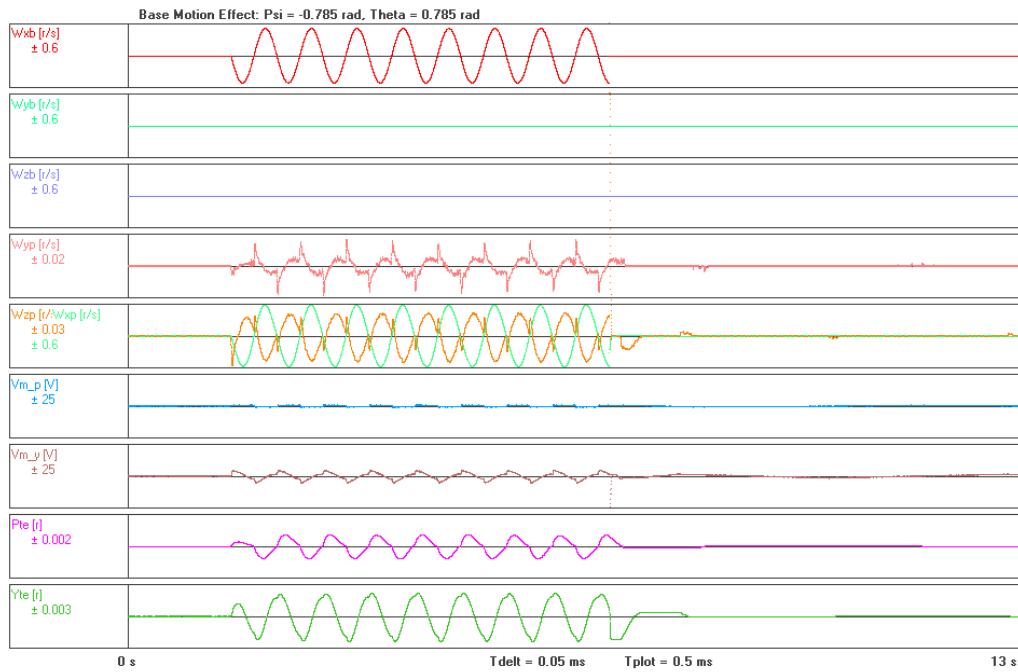


Figure 8-22: Base motion effects about the x_b axis in the worst-case orientation

If the base motion had been applied purely to the z_b axis, performance would be expected to be similar in form but better in response than Figure 8-15.

Jitter about the y_p and z_p axes was estimated by the integral of ω_{yp} and ω_{zp} respectively. These are shown in Figure 8-23 and Figure 8-24 below.

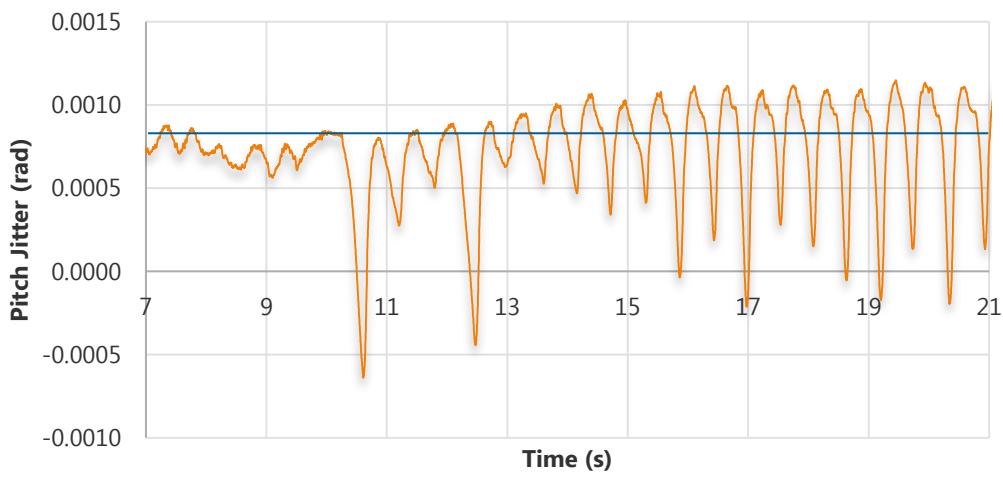
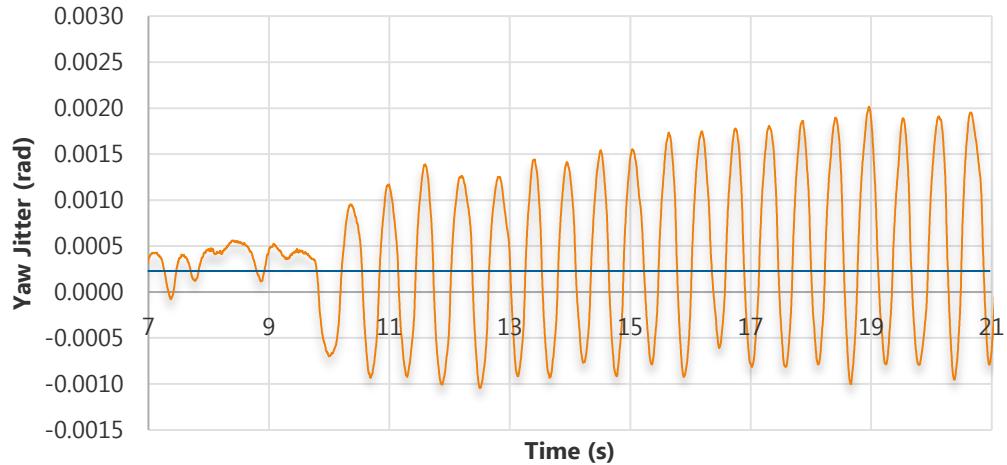


Figure 8-23: Pitch jitter estimate from the worst-case test

**Figure 8-24: Yaw jitter from the worst-case test**

Here, pitch jitter was approximately 1.25 mrad, whilst yaw jitter was approximately 1.70 mrad from the mean positions shown by the blue lines in the figures above. Both axes therefore perform with the bounds of the specification S6a when the ISP is in its worst-case position with a base disturbance, ω_{yb} , peaking at 0.51 rad/s at a frequency of 1.5 Hz.

8.4.4 STATIONARY SYSTEM JITTER

The final system test completed was that of determining the jitter of the LOS whilst under stationary base motion conditions. Jitter here was caused by the drift of the gyro axes working against the tracking loop trying to maintain the target on the camera LOS. This was evaluated for the yaw and pitch channels by the analogue method described previously. The results of this test are summarised in Table 8-5 below.

Table 8-5: Approximation of system jitter under stationary base conditions

Measurement	Reading
Distance to Target, x_p	2010 mm
Veridical Deflection, z_p	2 mm
Horizontal Deflection, y_p	1 mm
Pitch Jitter Angle	1.0 mrad
Yaw Jitter Angle	0.5 mrad

Here, the yaw channel meets the specification S6b, of 0.5 mrad jitter under stationary conditions, whilst the pitch channel does not. The pitch channel performance does, however, meet the marginal value for the jitter specification of 1.0 mrad in Table 3-1 which defined ideal and marginal values for the system metrics.

8.5 CHAPTER CONCLUSION

This chapter described the various tests performed on the ISP hardware, and evaluated the system performance against that of the simulation developed in Chapter 6. Certain discrepancies were identified between the hardware and the simulation that were caused by an inaccurate friction model in the simulation. By modifying the relevant parameters in that model, the simulation was then shown to model the hardware performance well. Overall, it may be concluded that the simulation is accurate enough to be used to test future hardware developments with confidence that the results output by the model will reasonably match the performance of new hardware, software, or control implementations if they are correctly modelled.

To conclude the review of the performance of the ISP, the following performance parameters, summarised in Table 8-6 below, can be verified from the tests described here. It may also be assumed that the results closely represent the performance of the simulation under the same conditions, as has been shown by the tests described here.

Table 8-6: Summary of ISP tested performance parameters

Metric	Pitch Channel	Yaw Channel
BMI with disturbance axis aligned with attenuation axis	-34.4 dB (1.1 rad/s at ~2 Hz disturbance)	-31.5 dB (1.2 rad/s at ~2.5 Hz disturbance)
BMI with disturbance axis cross-coupled with attenuation axis	-30.0 dB (0.5 rad/s at ~1.5 Hz disturbance)	-26.3 dB (0.5 rad/s at ~1.5 Hz disturbance)
Maximum tracking rate	0.75 rad/s	0.99 rad/s
Maximum track overshoot	11.6 mrad	12.3 mrad
Maximum track step settling time	1.5 s	1.5 s
Maximum dynamic jitter	2.35 mrad	2.52 mrad
Maximum stationary jitter	1.0 mrad	0.5 mrad

9

CONCLUSION AND RECOMMENDATIONS

9.1 INTRODUCTION

This project aimed to develop a two-axis stabilised platform with an automatic target tracker capable of controlling the orientation of a telescope such that automatic tracking of a celestial object might be accomplished from a moving host. Initially the project had aimed to develop and test such a system using an actual telescope, however, due to budget constraints it became necessary to develop an approximated system which modelled the intended outcomes and provided a means for the system to be ultimately expanded to achieve the initial aim.

The previous chapters described the development and performance of the various systems that comprised the ISP that was implemented. This chapter, therefore, aims to comment on those systems and make recommendations as to improvements that can be made in future tasks. It was stated in Section 2.3 the ISPs typically consist of three main subsystems; a sensor payload, an electromechanical assembly, and a control system. Comments made in this section are, therefore, broken down by those categories.

9.2 SENSOR PAYLOAD

The primary sensor intended for this, and future projects on this system, whose motion was to be controlled by the ISP, was the Meade ETX90 telescope. Being of small overall size it was suitable for use in this project due to its portability, yet its 3.5" diameter compound design meant that high quality observations could still be made. Inertial angular rate feedback of the motion of the mounting platform designed for this telescope and its mechanical modeller was provided using an InvenSense MPU-9150 IMU. The final sensor which formed part of this payload was the RPi Camera v1.3 which facilitated the acquisition of the image seen through the lens mounted on the telescope modeller and ultimately will provide the same function for the telescope image.

9.2.1 SPECIFICATIONS OF THE SENSOR PAYLOAD

The specifications listed in Appendix A which are associated with the sensor payload and the performance of the implemented systems in relation to these specifications are detailed in Table 9-1 below.

Table 9-1: Performance of the sensor payload against its specifications

Specification	Metric	Value	Achieved Performance	Comment
S1 – Telescope size	Diameter (inches)	3.5	3.5	Met
S5 – Tracking error	Tracking error _(peak) (mrad)	0.75 (marginal); 0.25 (ideal)	0.5 mrad	Marginal value met
S8 – Image sensor angular resolution	Angle (mrad)	0.25 (marginal); 0.125 (ideal)	0.51 mrad	Not met
S10 – Gyro minimum rate sensing limit	Angular rate (°/s)	100	250	Met
S11 – Gyro Bandwidth	Frequency (Hz)	120	188	Met

From the table above, it can be seen that most of the system specifications for the sensor payload developed at the start of the project were achieved. The two specifications not met were associated with the target tracking system. As detailed in Section 7.3.3, this was due to the RPi computer not being able to process images of a high enough resolution to meet the specifications at a rate suitable for the tracking loops of the ISP control system.

9.2.2 IMAGE PROCESSING

In future development, the image processing tasks should be moved to higher performing hardware capable of processing the high-resolution images needed to meet the specifications, at frame rates at least equivalent to the 10.5 FPS currently achieved. This would also suit the needs of progressing the image processing system to be able to recognise and track more complex targets than the Moon which would require additional computational resources. Alternatively, if development must proceed with the RPi research much be performed into methods of improving the efficiency of the current algorithm.

9.3 ELECTRO-MECHANICAL ASSEMBLY

The electro-mechanical assembly designed and built for this project included all systems required to mount and constrain the motion of the ETX90 and its mechanical modeller. Namely, these were, the telescope modeller itself, the yaw gimbal, the mounting stand, motors, relative angle sensors, and the associated electrical interfaces.

9.3.1 SPECIFICATIONS OF THE ELECTRO-MECHANICAL ASSEMBLY

The specifications listed for the overall system which are associated with the electro-mechanical assembly, and the performance of the final system against these specifications are listed in Table 9-2 below.

Table 9-2: Performance of the electro-mechanical assembly against its specifications

Specification	Metric	Value	Achieved Performance	Comment
S2 – Number of control axes	-	2	2	Met
S3 – Overall dimensions	Size (mm)	350x350x350	485x360x320	Not met
S4 – Total mass	Mass (kg)	9	6.7	Met
S9 – Gimbal relative angle measurement resolution	Angle (mrad)	0.25	6.1 mrad	Not met
S12 – Battery runtime	Time (hrs)	2	4	Met

Of the specifications listed above, the system failed to meet the intended size of the initial system and the intended resolution of the relative angle sensors. Both specifications had low priority and their failure to meet the specifications did not impact the overall performance of the ISP. In addition to these specifications, metric 12 of Table 3-1 in Chapter 3 defined an ideal structural resonance bandwidth of the system to be greater than 300 Hz. An evaluation of this metric was ultimately deemed to be beyond the scope of this work, and therefore it is unknown whether the structure designed achieves this metric.

9.3.2 MECHANICAL DESIGN

The mechanical assembly designed performed the task of mounting the telescope modeller well, however several issues presented a challenge to the assembly and configuration of the system. For parts that were required to be bolted or screwed together, inadequate consideration was given to the challenge of aligning these parts correctly on assembly. For instance, the horizontal base and vertical arms of the yaw gimbal contained no alignment grooves or other tools to ensure their correct alignment. This meant that the distance between the arms at their tops was slightly smaller than at their bases. As these parts performed the function of mounting the pitch platform along its y_p axis, axial misalignments along this axis were evident. These misalignments were compounded by the fact that misalignments also existed between parts of the telescope modeller that were supposed to be colinear with the y_p axis. These misalignments created frictional problems where friction was dependent on the pitch angle and was not constant in both directions of rotation. This required much time to be spent in calibration and adjustments to the alignment of parts to

overcome, and any disassembly of the structure will once again cause this issue to present itself on reassembly. Whilst some of these issues were caused by inaccurate manufacturing, the effects of these issues could have been reduced had greater care been taken in the design phase to consider how to align the parts. It is recommended that future projects replace axis creating parts with redesigned versions which have been designed to facilitate correct alignment.

Should additional funding become available for this project, it is also recommended that the yaw gimbal be replaced with a new design that has been manufactured from a single piece via a CNC process. This should ensure better parts alignment and reduce frictional disturbances on the ISP which were seen to have a substantial impact on performance. In addition, a finite element analysis of the overall structure is recommended to be performed in future work to determine the structural resonance properties of the assembly. Knowledge of these will improve the accuracy of the simulation model and may result in improved controller performance being possible.

9.3.3 YAW MOTOR

It was seen in Section 6.4.2 that for large base motion disturbances about multiple axes, the yaw motor channel saturates and control command tracking is lost. Whilst suitable for the operating conditions of this project, the yaw motor used will not be suitable for applications under harsher conditions. It is therefore recommended that the yaw motor either be changed for one capable of providing more torque than the Faulhaber 3257024CrR used here, or that a gearbox be used to help increase the torque delivered to the yaw gimbal.

9.3.4 ELECTRICAL INTERFACES

As can be seen in Figure 4-23, the electrical systems of the project consist of various development board type systems, or discrete function PCBs. Designing a PCB which can host an equivalent motor controller and the STM32Fo on one board would reduce the form factor of the electronics and improve the quality of the system developed. Additionally, a better cable management system should be investigated in future projects. Whilst the current system is functional, a system making use of slip rings, for example, would allow for continuous rotation of the yaw gimbal and telescope platform and so increase the mechanical robustness of the ISP and prevent system damage due to cables catching on protrusions on the assembly.

Finally, a thermal protection system should be implemented on the motors to prevent them drawing too much current and overheating whilst under prolonged dynamic disturbances. This would eliminate the need for a limiting of the total current delivered to the system under operation and help improve certain system performance parameters such as target tracking step response.

9.4 CONTROL SYSTEMS

The control system is here termed to broadly define all the hardware and software systems through which the controller algorithms of Chapter 6 are implemented. They are used to drive the electro-mechanical assembly in the manner required to appropriately control the orientation and inertial rate of the sensor payload.

9.4.1 SPECIFICATIONS OF THE CONTROL SYSTEM

The system specifications which are associated to the broad control systems tasks, and have not already been evaluated, are listed and compared to the final performance of the ISP in Table 9-3 below.

Table 9-3: Performance of the control system against its specifications

Specification	Metric	Value	Achieved Performance	Comment
S6a – LOS Jitter – Dynamic Host	Angle (mrad)	4.0 (Marginal); 2.0 (Ideal)	2.35 (Pitch); 2.52 (Yaw)	Marginal value met
S6b – LOS Jitter – Stationary Host	Angle (mrad)	1.0 (Marginal); 0.5 (Ideal)	1.0 (Pitch); 0.5 (Yaw)	Met for yaw, marginal met for pitch
S7 – Able to point to celestial coordinates	Yes/No	-	No	Not met
S13 – Computer controlled	Yes/No	-	Yes	Met
S4 – Total mass	Mass (kg)	9	6.7	Met

Of the specifications listed above, the only one that was not met was the desired ability to point to given celestial coordinates. This specification had no bearing on the system performance and was decided to be unnecessary considering that the ISP can be oriented manually by the UI as required. The jitter specifications were met according to their marginal values for the large amplitude, single axis disturbances that were tested in Section 8.4. The system simulation developed as part of this control system category did however predict that the jitter specifications would be met under the expected operating conditions of a moving vehicle.

Apart from these specifications, minimum bandwidths for the tracking and stabilisation control loops were set at 5 Hz and 60 Hz respectively in Table 3-1 of Chapter 3. Neither of these specifications were met with the linear bandwidths of the tracking and stabilisation loops being constrained to minima of approximately 1Hz and 38 Hz respectively. However, due to the low frequency nature of the expected disturbances in the designated operating environment and the almost steady state tracking requirements for celestial objects, these were deemed to be acceptable for this project.

9.4.2 CONTROL HARDWARE, SOFTWARE AND FIRMWARE

The STM32F051C6 microcontroller used in this project was a suitable choice and was able to run the main system firmware that was developed. However, the code size of the final version written using the STM SPL abstraction libraries was almost exactly the same size as the flash memory on the MCU meaning that no additional memory is available for firmware developments. It is, therefore, suggested that the MCU be upgraded to another in the STM32F051 series with 64 kB of flash, such as the STM32F051C8, which is fully compatible with the code developed in this project. If, however, increased computational performance is required, it is suggested that the MCU be upgraded to one from the STM32 F4 series which all have FPUs and higher clock frequencies than the STM32F0 range. This should ensure majority code portability whilst providing increased computational performance.

It is also recommended that if significant future firmware development is required, that the use of the SPL library on the MCU be discontinued. The library has now been deprecated by STMicroelectronics and the use of their Hardware Abstraction Layer (HAL) is now recommended by them for the development of new projects. In line with this, it is suggested that major developments now proceed using this library which has greater code portability between MCUs within the STM32 family, and has a larger support base to assist with firmware development.

For the LabVIEW User Interface, it is recommended that the software be re-written using a parallel loop architecture to improve the overall performance if increased data logging rates are required by future project tasks.

9.4.3 CURRENT MINOR LOOPS

To reduce the effects of inter-gimbal friction on the performance of the ISP it is suggested that high-gain, current minor loops be incorporated onto the system as shown by Figure 2-3. These loops have been noted by the literature surveyed to improve the effects of viscous damping of gimbal actuators. They might be incorporated using analogue electrical controllers and need not be implemented in firmware.

9.4.4 GYRO-DRIFT COMPENSATION

Drift of the gyro bias offsets were not compensated by the controllers developed in this project due to the fact that their effects are removed by the tracking control loops of the system. As the rate feedback drifts and causes an error signal on the stabilisation controllers the gimbals are actuated. The tracking loops see this as a tracking error and then actuate the gimbals to return the LOS to the target. These controllers working against each other cause tracking errors and jitter to be evident on the system. It is suggested that gyro-drift be evaluated and compensated at the sensor feedback level to improve system performance. Possible methods by which this might be done include Kalman or equivalent filtering of the IMU data, or by using the long-term average of the stabilisation controller actuator signals to

estimate offset drift. For a stabilised platform these outputs should be zero for an ideal system achieving perfect stabilisation and tracking of an inertially stationary target.

9.4.5 CONTROLLER IMPLEMENTATION

It is also recommended that if the base motion isolation performance of the ISP is required to be improved beyond approximately -35 dB, that an investigation be made into the use of a modern control method, or a feedforward scheme as the control method. As stated in Section 2.3.3, these have been shown to be able to provide better base motion rejection at the low frequencies evident in the operating environment of this project than the classical PI scheme used here.

9.5 SUMMARY

The final specification that influenced the ISP developed was cost. Initially limited to R20 000.00, but revised to approximately R5 000.00 early in the design process, this specification was the determining factor in many design decisions made over the course of the project. Ultimately the project ran over this budget and a total of approximately R6 700.00 was spent on the project.

Overall, as can be seen by the comparisons of system performance to the specifications above, a two-axis mass stabilised platform was successfully developed which was able to approximate the initial aim of the project well. Automatic target tracking was achieved, and an expansion friendly mechanical design was implemented which can facilitate the inclusion of the ETX90 telescope easily. Controllers were designed and tested using a telescope modeller which inertially and geometrically modelled this telescope, and therefore it is not expected that the control algorithms will require much adjustment to effectively stabilise the ETX90 once it has been included.

The thesis of this project was, therefore, confirmed. A multi-axis closed-loop stabilisation controller working in conjunction with an automatic target tracker may feasibly be implemented to keep an optical telescope sensor pointed at a celestial target in both static and dynamic host environments using image processing and control system design techniques. The overall performance of the system developed fell short of achieving success of all the specifications, but it may be concluded that with further development work and the implementation of some of the recommendations made in this chapter that these might be met and the initial project aim be achieved.

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APPENDIX A

SYSTEM SPECIFICATIONS

A.1 INTRODUCTION

This appendix details the process by which the systems specifications for the ISP and its associated systems were developed. The chapter first defines a set of qualitative desired performance requirements which were then analysed to determine a functional allocation of requirements to primary system items. The relations of these functions to each other are then shown in a high-level functional flow chart. Finally, a set of quantitative specifications for the system prime items, developed from the initial requirements and functional allocation is given and target specifications for specific components of the overall system are detailed.

A.2 PURPOSE OF THE ISP

The initial aims of this project were to design, simulate implement and test a robust multi-axis ISP to facilitate the high precision automatic tracking of celestial objects through an optical telescope mounted on a moving vehicle. The project entailed the development of all subsystems associated with the overall ISP including the electro-mechanical assembly of the ISP, the control system, and electronic interfaces.

The purpose of the system is, therefore, to achieve automatic tracking of a celestial body using an optical telescope, and to ensure that high-quality celestial observations can be made through the attenuation of disturbance torques incurred onto the imaging sensor by the host vehicle motion. The following sections, therefore, list the performance requirements needed to achieve this purpose.

A.3 PERFORMANCE REQUIREMENTS

Sections A.3.1 to A.3.6 detail the performance requirements developed for the different aspects of the overall ISP's operation.

A.3.1 FUNDAMENTAL PERFORMANCE

- R1. The system should stabilise a 3.5" telescope.
- R2. The target tracker should automatically detect and follow an astronomical object.
- R3. The ISP control system should maintain the stable tracking of the object when the assembly is moved or disturbed.

- R4. The system should enable clear sharp images to be acquired by the imaging sensor.
- R5. The system should be able to measure the LOS position.
- R6. The system should be able to point to specified celestial coordinates.

A.3.2 SYSTEM CONSTRAINTS

- R7. The system should be mechanically robust to allow for transport and multiple installations and removals.
- R8. The assembly should not be excessively large in size.
- R9. The system should be operable from dual power sources; mains AC or rechargeable batteries.
- R10. The system should be as self-contained as possible with the control system being housed within the assembly.

A.3.3 USAGE

- R11. The system should be safe to operate.
- R12. The system should be designed with ease of use being a high priority.
- R13. The assembly should be easily manoeuvrable and therefore should not be too heavy.

A.3.4 INTERFERENCE

- R14. The ISP controller and target tracker should be insensitive to electromagnetic interference from the motors and auxiliary components.

A.3.5 COMMUNICATIONS

- R15. The system should allow for communication (comms) with a PC.
 - R15.1. The system should include a means by which a live feed of the sensor image may be acquired.
 - R15.2. The system should provide feedback of relevant data such as LOS position and rates to be used for data acquisition and external system monitoring.

A.3.6 DESIGN REQUIREMENTS

- R16. The assembly should allow for future expansion of the ISP system. Specifically, the future implementation of a strap-down gyro or accelerometer is expected.

R17. The system should be implemented at a low cost constrained to a budget of R20000.00.

A.4 PRIMARY ITEMS

Figure A-1 below shows the primary items of the ISP assembly and highlights which of the primary items have an interface between them.

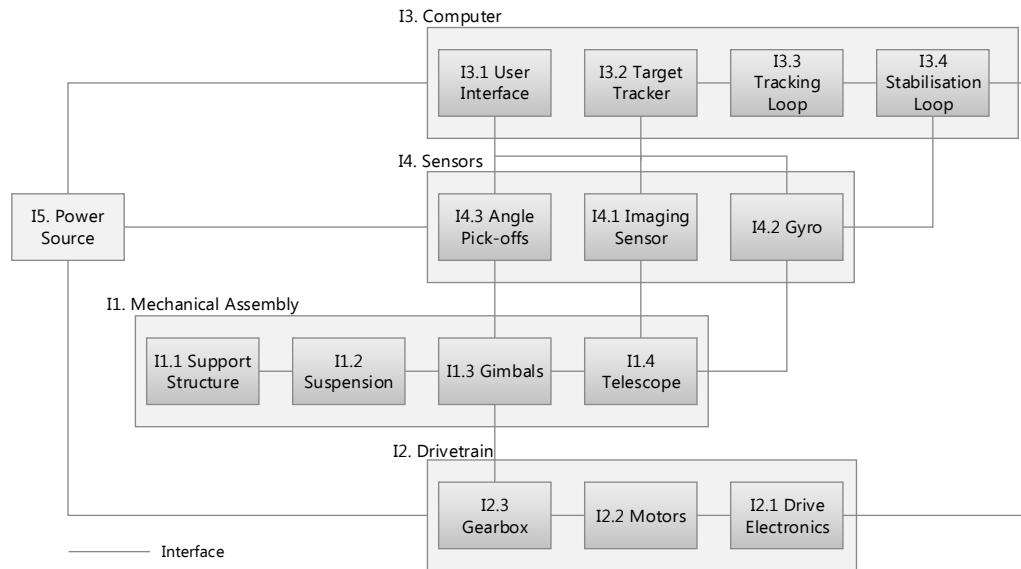


Figure A-1: Prime item diagram

A.5 FUNCTIONAL ALLOCATION AND FLOW CHART

By considering the system requirements developed in Section A.3 and the system primary items shown above, the functional allocation given in Figure A-3 below was developed.

	Primary Item				
Function	1. Mechanical Assembly	2. Drivetrain	3. Computers	4. Sensor Package	5. Power source
F1. Constrain payload motion	O	X			
F1.1 Mount assembly on host vehicle		X			
F1.2 Govern platform orientation		X			
F1.3 Facilitate inter-gimbal rotation		X			
F1.4 Mount the imaging sensor		X			
F1.5 Mount the feedback gyro		X			
F2. Control operation			O		
F2.1 Facilitate operator I/O			X		
F2.2 Track the target			X		
F2.3 Govern LOS position			X		
F2.4 Attenuate disturbances			X		
F2.5 Manage communications			O		
F3. Sense physical parameters				O	
F3.1 Measure LOS rate				X	
F3.2 Measure LOS position				X	
F3.3 Acquire images				X	
F4. Actuate gimbals	O	X			
F4.1 Amplify motor voltage commands		X			
F4.2 Move the gimbals		X			
F4.2 Increase motor torque		X			
F5. Provide power				O	

Figure A-2: Functional allocation

Figure A-3 below shows the high-level functional flowchart defining the intended operation of the system.

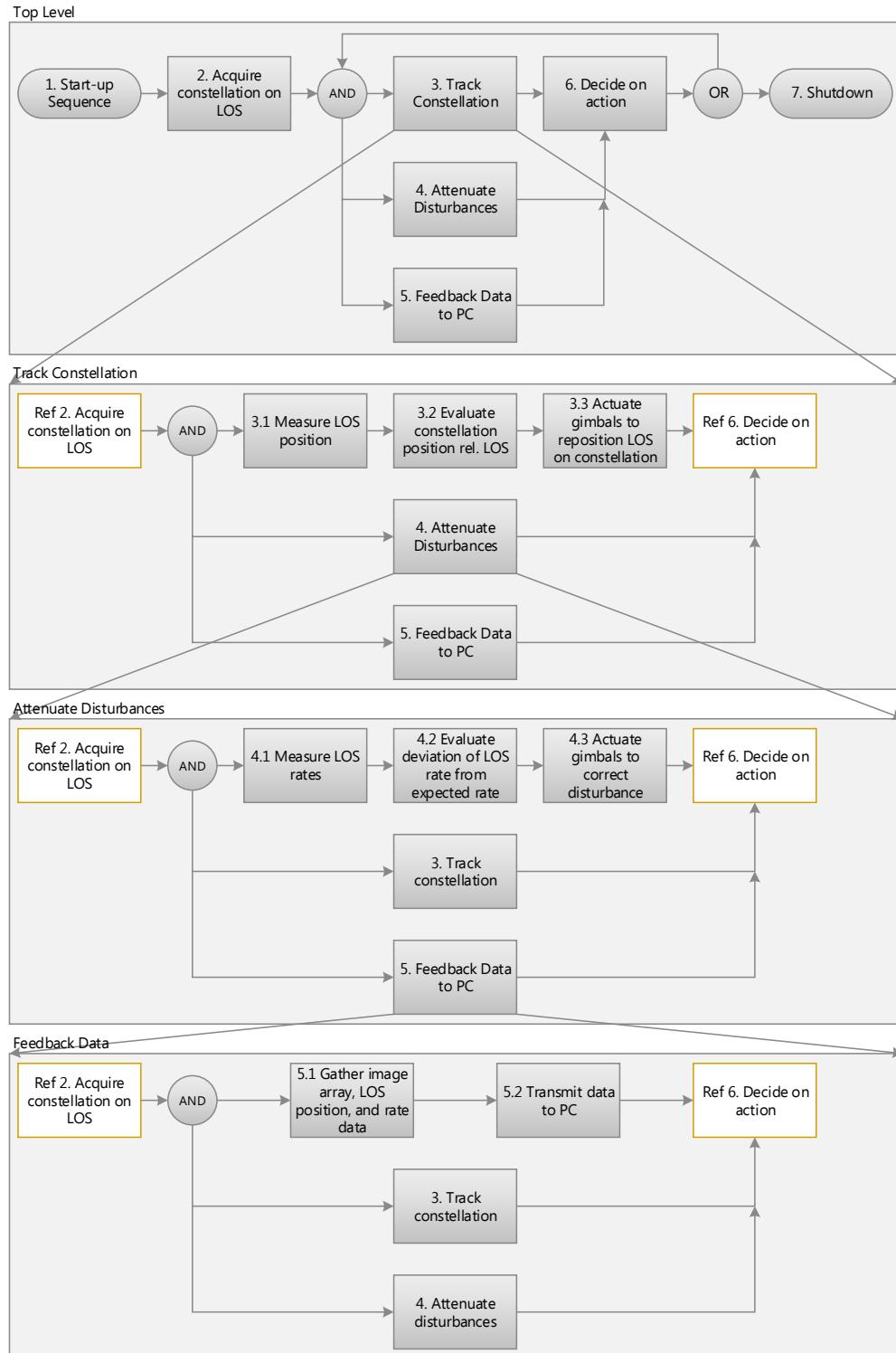


Figure A-3: High-level functional flow chart

A.6 SYSTEM SPECIFICATIONS

From the analysis of the performance requirements, functions, and primary items of the system, the following specifications have been drawn to govern the design and testing of the system.

Glossary

Trace:	Rx	-	Requirement number from the list of requirements.
	Fx	-	Function number from the Functional Allocation.
Priority:	H	-	High.
	M	-	Medium.
	L	-	Low.
MoC:			Means of Compliance.

A.6.1 MECHANICAL SPECIFICATIONS

- S1. The system shall facilitate inertial control of a 3.5" telescope.

Rationale: 3.5" telescopes are a common size for personal telescopes which offer good light gathering properties without being overly large.

Trace: R1

Priority: L

MoC: Choose telescope to satisfy the specification.

- S2. The mechanical assembly shall allow for motion control about a yaw and pitch axis.

Rationale: Yaw (azimuth) and pitch (elevation) are the two axes required to be controlled for a star to be tracked as it moves across the sky.

Trace: R3, F1.2

Priority: H

MoC: Design ISP such that yaw and pitch are controlled.

- S3. The overall dimensions of the system shall be less than 350x350x350 mm.

Rationale: The system should not be too large to compromise its portability.

Trace: R8, R10

Priority: L

MoC: Design for conformance and inspect once assembled.

- S4. The total mass of the system shall be less than 9 kg.

Rationale: The system should be manoeuvrable by a single female in the 5th percentile of anthropometric data. Using data from [115], it has been estimated that a male in the 5th percentile has an average arm strength of 65.7 N per arm. In the absence of available

data, it has been estimated that a 5th percentile female has an arm strength of 70% of a 5th percentile male, resulting in a double arm lift capacity of 9.4 kg with the arms alone.

Trace: R₁₃

Priority: M

MoC: Physical measurement

A.6.2 OPERATIONAL SPECIFICATIONS

- S5. The target tracker shall have a tracking error less than 0.25 mrad.
Rationale: For jitter to be reduced as far as possible, error in the target tracker must be kept to a minimum.
Trace: R₂, F_{2.2}, F_{2.3}
Priority: H
MoC: Testing of the target tracking software.
- S6. The ISP control system shall result in jitter of less than a) 2 mrad whilst the host vehicle is undergoing dynamic motion, and b) less than 0.5 mrad whilst the host is stationary.
Rationale: Astronomical observations require stabilisation to approximately 5 µrad. Therefore, as a proof of concept at least these parameters are required.
Trace: R₃, R₄, F_{2.2}, F_{2.4}
Priority: H
MoC: Simulations and physical testing.
- S7. The system shall be capable of pointing to specified celestial coordinates.
Rationale: In order to first acquire the target.
Trace: R₆, F_{2.3}
Priority: M
MoC: Testing of the system.
- S8. The imaging sensor and lens system shall be capable of detecting an angular rotation of the target relative to the camera of less than 0.25 mrad.
Rationale: To achieve tracking with an error of less than 0.25 mrad, the imaging system must be capable of detecting rotations less than this value.
Trace: R₄, F_{3.3}
Priority: H
MoC: Design and testing.
- S9. The angle pickoffs shall be capable of determining the position of the LOS to 0.25 mrad.
Rationale: To provide high-accuracy LOS position data and assist with testing S₅ and S₆.
Trace: R₅, F_{3.2}

Priority: L

MoC: Selection of components rated for the specified accuracies.

- S10. The feedback gyro shall be capable of measuring angular rates of up to 100 °/s.

Rationale: LOS rates for the ISP are not expected to exceed 100 °/s (Hilkert, 2008), especially given the application of star tracking.

Trace: R₃, F_{3.1}

Priority: H

MoC: Selection of components rated for the specified parameter.

- SII. The feedback gyro shall have a bandwidth of at least 120 Hz.

Rationale: To prevent the gyro from being the limiting factor in the overall system bandwidth.

Trace: R₃, F_{3.1}

Priority: H

MoC: Selection of components rated for the specified parameter.

- S12. The system shall be battery operable for at least 2 hours.

Rationale: With the future product in mind, the system may be used in an outdoor location without mains electricity.

Trace: R₉, F₅

Priority: L

MoC: Selection of components rated for the specified parameter.

- S13. A user interface computer program should facilitate operation of the ISP.

Rationale: A safe, user-friendly method of operation providing high-level control and data-logging is required.

Trace: R₁₁, R₁₂, R₁₅, F_{2.1}

Priority: H

MoC: Design to satisfy the specification.

A.6.3 CONSTRAINTS

- S14. The system shall be developed for total cost of less than R20000.00

Rationale: The budget for the project is limited to R20000.00

Trace: R₁₇

Priority: H

MoC: Keeping careful account of project expenses.

A.7 CHAPTER CONCLUSION

From the above specifications and requirements, the following target specification summary is presented in Table A-1 below. These target specifications served as design goals for the duration of the project.

Table A-1: Target specifications

Metric No.	Trace	Metric.	Imp.	Units	Marginal Value	Ideal Value
1	S5	Tracking error	H	mrad	0.75(_{PEAK})	0.40(_{PEAK})
2	S6	Jitter				
		Dynamic host	H	mrad	4.0(_{PEAK})	2.0(_{PEAK})
		Stationary host	H	mrad	1.0(_{PEAK})	0.5(_{PEAK})
3	S3	Gimbal assembly dimensions	L	mm	-	350x350x350
4	S4	Total mass	M	kg	<10	<8
5	S14	Development cost	H	R	20 000.00	10 000.00
6	S8	Min detectable rotation on image sensor	H	mrad	<0.25	<0.125
7	S1	Telescope size	L	"	3.5	3.5
8	S12	Battery run-time	L	hrs	2	3
9	S10	Maximum LOS rate	H	°/s	100	100
10	R2, R3	Tracking loop bandwidth	M	Hz	5	10
11	R3	Stabilisation loop bandwidth	M	Hz	60	80
12	R3	Minimum structural resonance bandwidth	M	Hz	>300	-
13	S11	Gyroscope bandwidth	H	Hz	>120	-
14	S8	Angle pickoff resolution	H	mrad	<0.25	-
16	R2, S2	Minimum axis rotation range				
		Yaw	H	°	250	270
		Pitch	H	°	180	250

APPENDIX B

MECHANICAL DESIGN

Due to the number of parts designed, and the excessive potential length of this appendix, it was decided to provide a link to a repository which contains the design files. This repository contains all the SOLIDWORKS parts, assembly and drawing files used to manufacture the ISP. The overall system assembly is entitled “System Assembly”. An additional folder within the repository also shows the technical drawing of these parts in PDF format. Additionally, the mechanical design calculations used to verify the implementation of specific parts and components are also shown in a folder here.

Repository: https://bitbucket.org/JamesHepworth_UCT/isp-solidworks-design/

APPENDIX C

SOFTWARE AND FIRMWARE SYSTEMS

This appendix provides access to the source code for the various software and firmware systems developed in the project. As code sizes are relatively large, this software has been made publicly accessible via the author's git repositories on Bitbucket to shorten the length of this document. Software in these repositories is detailed below.

STM32FO FIRMWARE

Repository: https://bitbucket.org/JamesHepworth_UCT/stm32fo-mcu-firmware/src

The main control firmware for the STM32 is entitled “ISP System Firmware”, whilst the firmware written to measure motion using an MPU9150 and a data logging VI is entitled “Motion Measurement”. The entire eclipse IDE projects have been included under these folders. To view the main program code of both pieces of firmware, navigate to the *src/main.c* file of the relevant program.

TARGET TRACKER IMAGE PROCESSING PROGRAM

Repository: https://bitbucket.org/JamesHepworth_UCT/target-tracker/src/

The main program is entitled “Target Tracker with Display.py”, whilst the script which initialises the image acquisition thread is entitled “webcamvideostream.py” and is a modified version of the corresponding file from the imutils [114] library which must be installed according to the method given in the reference link. The corresponding file must then be replaced with the version from this repository.

LABVIEW SOFTWARE

Repository: https://bitbucket.org/JamesHepworth_UCT/labview-software/src

This repository contains the main user interface, entitled “User interface”, the VI written to perform FFT functions on gyro rate data, entitled “Spectral Analysis”, and the data logging VIs which are contained in the folder entitled “Data Logging VIs”. All LabVIEW files were developed in LabVIEW 2015 and therefore are not backwards compatible with older versions of LabVIEW. The NI-VISA toolbox is also required for use with these VIs.

SYSTEM SIMULATION

Repository: https://bitbucket.org/JamesHepworth_UCT/simul_c_em-isp-system-simulation/src

This repository contains the system simulation written in Simul_C_EM. The main simulation is a C++ file entitled “Final_Simulation_Model.cpp”. If required, please contact the author or the project supervisor for details on how to run this simulation.

APPENDIX D**EBE Faculty: Assessment of Ethics in Research Projects**

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zakiya Chikte (Zakiya.chikte@uct.ac.za); New EBE Building, Ph 021 650 5739).

Please note – It is important to keep a signed copy of this form as students must include a copy of the completed form with the dissertation/thesis when it is submitted for examination.

Name of Principal Researcher/Student: James Hepworth **Department:** Mechanical Engineering
If a Student: **Degree:** MSc (Eng) **Supervisor:** A/Prof Henrie Mouton

If a Research Contract indicate source of funding/sponsorship: N/A

Research Project Title: Control and Dynamics of a Multi-Axis Stabilized Platform to Facilitate Astronomical Observations

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

Principal Researcher/Student:	Full name and signature	Date
	James Hepworth <i>[Signature]</i>	01/02/2015

This application is approved by:

Supervisor (if applicable):	HENDRIK DANIEL MOUTON <i>[Signature]</i>	1/2/2016
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.	R.D. KNUSTON <i>[Signature]</i>	02/02/2016
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.		