ΠΑΝΕΠΙΣΤΗΜΙΟ ΔΥΤΙΚΗΣ ΑΤΤΙΚΗΣ ΣΧΟΛΗ ΜΗΧΑΝΙΚΩΝ
ΤΜΗΜΑ ΜΗΧΑΝΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ

Διπλωματική Εργασία

Ανάπτυξη και βελτιστοποίηση ενός συστήματος αδρανειακά σταθεροποιημένης πλατφόρμας (gimbal) για UAV: Μελέτη κίνησης και σύστημα μετάδοσης κίνησης

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Diploma Thesis

Development and optimization of an inertially stabilized platform (gimbal) system for UAVs: Motion study and drivetrain.

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«Είμαι συγγραφέας αυτής της πτυχιακής/διπλωματικής εργασίας και ότι κάθε βοήθεια την οποία είχα για την προετοιμασία της είναι πλήρως αναγνωρισμένη και αναφέρεται στην εργασία. Επίσης, οι όποιες πηγές από τις οποίες έκανα χρήση δεδομένων, ιδεών ή λέξεων, είτε ακριβώς είτε παραφρασμένες, αναφέρονται στο σύνολό τους, με πλήρη αναφορά στους συγγραφείς, τον εκδοτικό οίκο ή το περιοδικό, συμπεριλαμβανομένων και των πηγών που ενδεχομένως χρησιμοποιήθηκαν από το διαδίκτυο. Επίσης, βεβαιώνω ότι αυτή η εργασία έχει συγγραφεί από μένα αποκλειστικά και αποτελεί προϊόν πνευματικής ιδιοκτησίας τόσο δικής μου, όσο και του Ιδρύματος.

Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του πτυχίου μου».

**Επιθυμώ την απαγόρευση πρόσβασης στο πλήρες κείμενο της εργασίας μου μέχρι …………………… και έπειτα από αίτηση μου στη Βιβλιοθήκη και έγκριση του επιβλέποντα καθηγητή*

Ο/Η Δηλών/ούσα

*** Ονοματεπώνυμο /Ιδιότητα**
(Υπογραφή)

Ψηφιακή Υπογραφή Επιβλέποντα

**** Σε εξαιρετικές περιπτώσεις και μετά από αιτιολόγηση και έγκριση του επιβλέποντα, προβλέπεται χρονικός περιορισμός πρόσβασης (embargo) 6-12 μήνες. Στην περίπτωση αυτή θα πρέπει να υπογράψει ψηφιακά ο/η επιβλέπων/ουσα καθηγητής/τρια, για να γνωστοποιεί ότι είναι ενημερωμένος/η και συναινεί. Οι λόγοι χρονικού αποκλεισμού πρόσβασης περιγράφονται αναλυτικά στις πολιτικές του Ι.Α. (σελ. 6):***

https://www.uniwa.gr/wp-content/uploads/2021/01/%CE%A0%CE%BF%CE%BB%CE%B9%CF%84%CE%B9%CE%BA%CE%B5%CC%81%CF%82_%CE%99%CE%B4%CF%81%CF%85%CE%BC%CE%B1%CF%84%CE%B9%CE%BA%CE%BF%CF%85%CC%81_%CE%91%CF%80%CE%BF%CE%B8%CE%B5%CF%84%CE%B7%CF%81%CE%B9%CC%81%CE%BF%CF%85_final.pdf).

Περίληψη

Η διατριβή επιχειρεί μια διεξοδική εξέταση των συστημάτων σταθεροποίησης σε μη επανδρωμένα εναέρια οχήματα (UAV) και μικροαεροσκάφη (MAV), με ιδιαίτερη έμφαση στις αδρανειακά σταθεροποιημένες πλατφόρμες (ISP) για ωφέλιμα φορτία κάμερας. Η έρευνα αυτή έχει ιδιαίτερη σημασία για τον αμυντικό και τον εμπορικό τομέα, όπου η χρήση UAV και MAV αυξάνεται .Τα βασικά στοιχεία των συστημάτων σταθεροποίησης, όπως τα έδρανα, οι ενεργοποιητές και οι μονάδες αδρανειακής μέτρησης (IMU), αναλύονται αυστηρά. Παρουσιάζονται κατευθυντήριες γραμμές για την επιλογή αυτών των στοιχείων, δίνοντας έμφαση στην ικανότητά τους να διαχειρίζονται τόσο στατικές όσο και δυναμικές επιχειρησιακές δυνάμεις. Μεταξύ διαφόρων μεθόδων αντιστάθμισης σταθεροποίησης, ο αναλογικός ελεγκτής (P) προσδιορίζεται ως αποτελεσματική επιλογή. Η μελέτη χρησιμοποιεί εξειδικευμένα εργαλεία λογισμικού για την αξιολόγηση και τη βελτιστοποίηση των σχεδίων συστημάτων σταθεροποίησης. Οι προσπάθειες βελτιστοποίησης κατευθύνονται ιδιαίτερα στις παραμέτρους βάρους, ενισχύοντας έτσι την αποδοτικότητα του συστήματος και την επιχειρησιακή απόδοση. Αναγνωρίζονται οι ηγέτες της βιομηχανίας στις τεχνολογίες σταθεροποίησης, προσθέτοντας μια πρακτική διάσταση στην ακαδημαϊκή έρευνα. Η διατριβή ολοκληρώνεται με την οριοθέτηση της συμβολής της τόσο στην ακαδημαϊκή έρευνα όσο και σε πιθανές βιομηχανικές εφαρμογές και προτείνει περαιτέρω έρευνα στη συγκριτική ανάλυση τεχνικών σταθεροποίησης υπό διαφορετικές συνθήκες λειτουργίας. Η έρευνα χρησιμεύει ως μια κρίσιμη πηγή για την κατανόηση της πολυπλοκότητας που εμπλέκεται στο σχεδιασμό και τη λειτουργία των συστημάτων σταθεροποίησης σε UAV και MAV, συμβάλλοντας έτσι σημαντικά στην υπάρχουσα βιβλιογραφία στον τομέα της τεχνολογίας εναέριας επιτήρησης.

Summary

In this scholarly work, an in-depth analysis is conducted on stabilization systems utilized in Unmanned Aerial Vehicles (UAVs) and Micro Aerial Vehicles (MAVs). The primary focus is on Inertially Stabilized Platforms (ISPs) tailored for camera payloads. The importance of this project is very high in both the defense and aerospace sectors. Key elements of stabilization systems, such as bearings, actuators, and Inertial Measurement Units (IMUs), are rigorously analyzed. Guidelines for the selection of these components are presented, emphasizing their capacity to manage both static and dynamic operational forces. The study employs specialized software tools for the evaluation and optimization of stabilization system designs. Optimization efforts are particularly directed at weight parameters, thereby enhancing system efficiency and operational performance. Acknowledgment is given to industry leaders in stabilization technologies, adding a practical dimension to the academic research. The dissertation concludes by delineating its contributions to both academic research and potential industrial applications, and suggests further research in the comparative analysis of stabilization techniques under varying operational conditions. The research serves as a critical resource for comprehending the complexities involved in the design and operation of stabilization systems in UAVs and MAVs, thereby contributing significantly to the existing literature in aerial surveillance technology.

GLOSSARY

AC	Alternating Current
ACBB	Angle Contact Ball Bearing
BLDC	Brushless Direct Current (Motor)
CNC	Computer Numerical Control
DC	Direct Current
FEM	Finite Element Method
ISP	Inertially Stabilized Platform
LRF	Laser Range Finder
PSU	Power Supply Unit
UAV	Unmanned Aerial Vehicle

Contents

1. Introduction

The aerial surveillance technology has been fueled by unmanned aerial vehicles (UAVs) and micro aerial vehicles (MAVs). This is because such technologies yield quality data from above, these technologies have become extremely important in number of industries: defence and commercial uses.
The camera payloads are an integral part to these UAVs. Their major role entails the taking of stable and crisp imagery. However, attaining this stability relies on strong stabilisation systems especially when dealing with rugged flight environments. In here comes the gimbal system which is a mechanism to prevent accidental movements; hence ensuring that the camera remains steady while in flight.

One of the most important parts of the gimbal system is the drivetrain. It consists of many parts that have to effectively work together. An optimal drivetrain should be optimized to ensure the overall effectiveness of the gimbal system. This process of optimization has one having a choice of appropriate components and ensuring that they work together harmoniously.

This chapter discusses why UAV camera payload stabilization is important, what the drivetrain does in this process, and introduces some prelude for the more detailed exploration which follows in subsequent chapters.

1.1. Background of UAV Camera Payload Stabilization

Unmanned aerial vehicles (UAVs) and their smaller counterparts, Micro Aerial Vehicles (MAVs), have become vital instruments in various industries. Their impact is especially pronounced in the defence and surveillance sectors, where they've revolutionized task execution and information collection. The camera payloads on these aerial platforms are largely responsible for their success in obtaining high-quality visual data. It is crucial to make sure that these payloads are stable, especially while in flight. A gimbal system, which prevents any unwanted movements and guarantees the camera remains steady, is used to accomplish this stability.

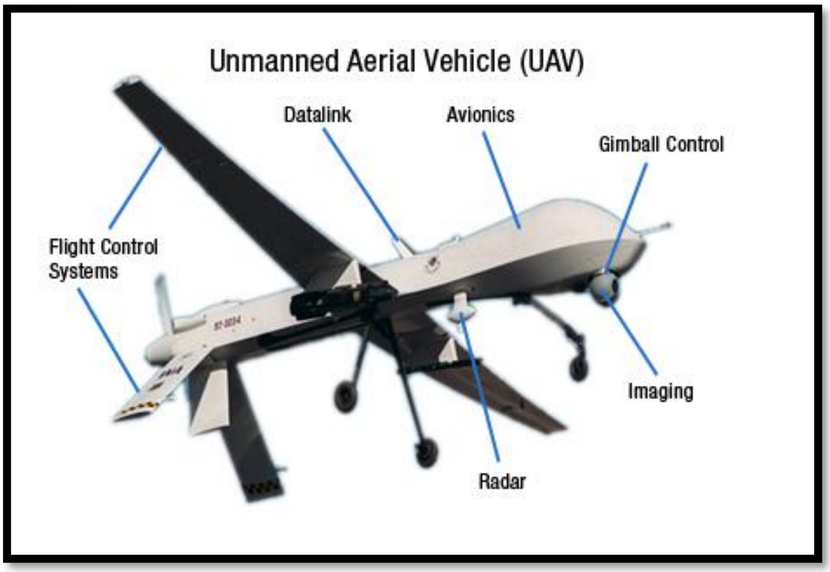

Figure 1 UAV

For many instances of contemporary electrical and optical devices to operate at their best, inertial stabilization is necessary. By attenuating rotational disturbances that may be linked from the host to the sensor and lower the sensor's performance, ISPs are systems that can isolate a sensor from its host. The performance of devices like missile seeker heads, communications systems, inertial navigation systems, surveillance systems, astronomical telescopes, and portable cameras, for instance, may be enhanced by using an ISP. (Hilkert, 2008)

Gimbal use in UAVs has a long history that dates back to the first days of aerial surveillance, especially for defence applications. Stable and crisp pictures became crucial as UAVs started to play a bigger part in defence operations. As a result, gimbals were created and integrated into UAV systems.

UAVs were mostly employed for reconnaissance in the beginning. The movement of the UAV frequently impacted the imagery that was taken, resulting in photographs that were hazy or blurry. Defence organisations and researchers were aware of this constraint and started looking into stabilisation techniques. The multi-axis rotation of the gimbal, which can counteract the motions of an unmanned aerial vehicle and keep the camera stable, proved to be a workable option. (1)

Figure 2 A UAV carrying a Gimbal

One of the earliest documented uses of gimbals in defence UAVs was during the Vietnam War. The U.S. military employed UAVs equipped with camera systems that utilized rudimentary gimbal mechanisms to capture aerial imagery of enemy positions.

1.2. Inertially Stabilized Platforms (ISPs)

To effectively capture and track targets with optical imaging sensors, the use of inertially stabilized platforms is essential. These platforms are key to obtaining sharp and accurate images, especially when there's movement between the target and the optical sensor. (Masten, 2008)

Figure 3 Various ISPs

The design of a dual-axis Inertially Stabilized Platform (ISP) for defence UAVs is a multi-faceted engineering task. The mechanical structure aims for lightness and strength, validated through Finite Element Analysis (FEA). Motor selection focuses on a balance between torque and energy efficiency, guided by optimization algorithms. Bearings and encoders are integrated for smooth operation and real-time angular feedback, essential for precise control. The electrical subsystem, managed by a dedicated microcontroller, handles power distribution and employs advanced control strategies for stability. Environmental protection measures are also incorporated to meet IP67 standards. The design undergoes post-creation optimization and a series of tests for validation.

Electromechanical Assemblies

Within the domain of ISPs, electromechanical assemblies are predominant. These assemblies often feature complex gimbals that allow rotation of either the whole sensor or certain optical elements within it. Broadly speaking, there are two main approaches adopted in this context.

1. Platform Stabilization: In this technique, the whole payload is rotated within a gimbal setup, which modifies the sensor's Line of Sight (LOS) in relation to the host vehicle. (Masten, 2008)

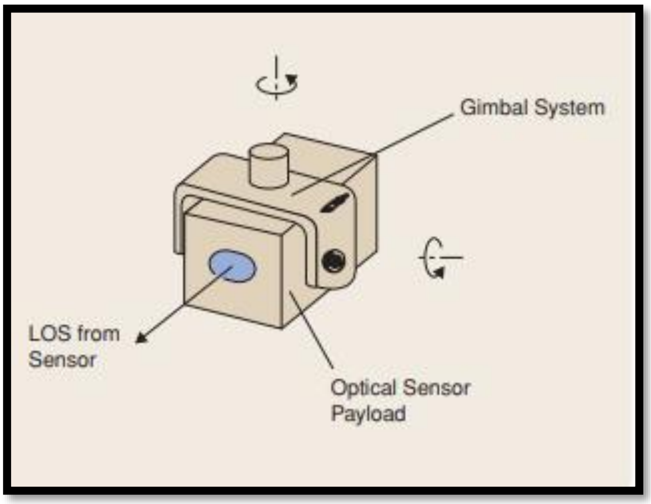

Figure 4 Platform Stabilization

2. Steering Stabilization: While not elaborated in the given excerpt, this method generally involves turning specific parts, like mirrors, to adjust the LOS without shifting the entire sensor.

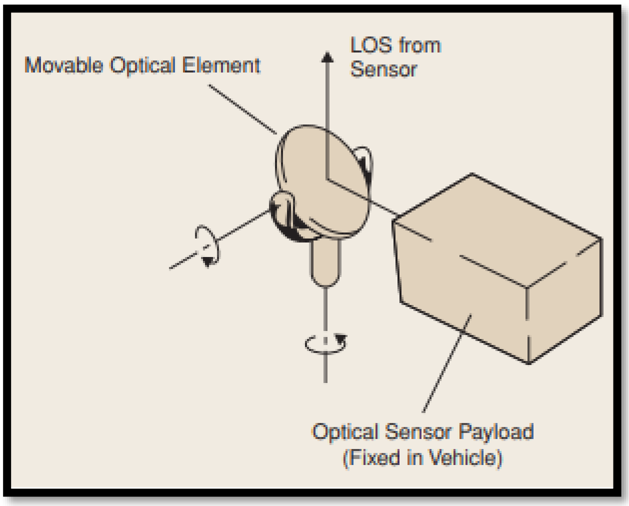

Figure 5 Steering Stabilization

Stabilization Challenges: The main hurdle for ISPs is ensuring stabilization despite various external influences. These encompass the vehicle's translation and rotation, environmental conditions, and the target's own movement1.

Compensation Techniques for Stabilization:

There are diverse compensation strategies used in the stabilization loop to attain the desired outcome. Traditional options include:

- **Proportional (P) Controller**: This design is straightforward and provides satisfactory command response. Yet, its capability to reject low-frequency disturbances isn't as effective as other models. (Masten, 2008)

- **Proportional-Integral (PI) Controller**: A bit more intricate, this design offers good responsiveness. Its ability to reject low-frequency disturbances is moderate compared to other models. (Masten, 2008)
- **Proportional-Integral-Derivative (PID) Controller:** Being the most complex, it can be unstable in terms of command response. However, it excels in rejecting low-frequency disturbances. (Masten, 2008)

To sum up, ISPs are vital for optical imaging setups, ensuring the capture of clear images even under tough scenarios. Both their structural design and the selection of compensation methods significantly influence their efficiency.

1.3. Problem identification

When a camera or sensor is mounted on a moving or especially an airborne platform as a UAV, precise multi-axis rotational control is essential to track targets or areas of interest as they move or change position. Given the UAV's dynamic flight environment, disturbances can cause undesired rotations across all three axes of inertial space. As such, a gimbal system, where inertial rotation across multiple axes is managed, becomes crucial to stabilize and shield the camera from these rotational disturbances. Without an integrated target tracking system, a minimum of three axes of control is necessary to ensure the camera's stability.

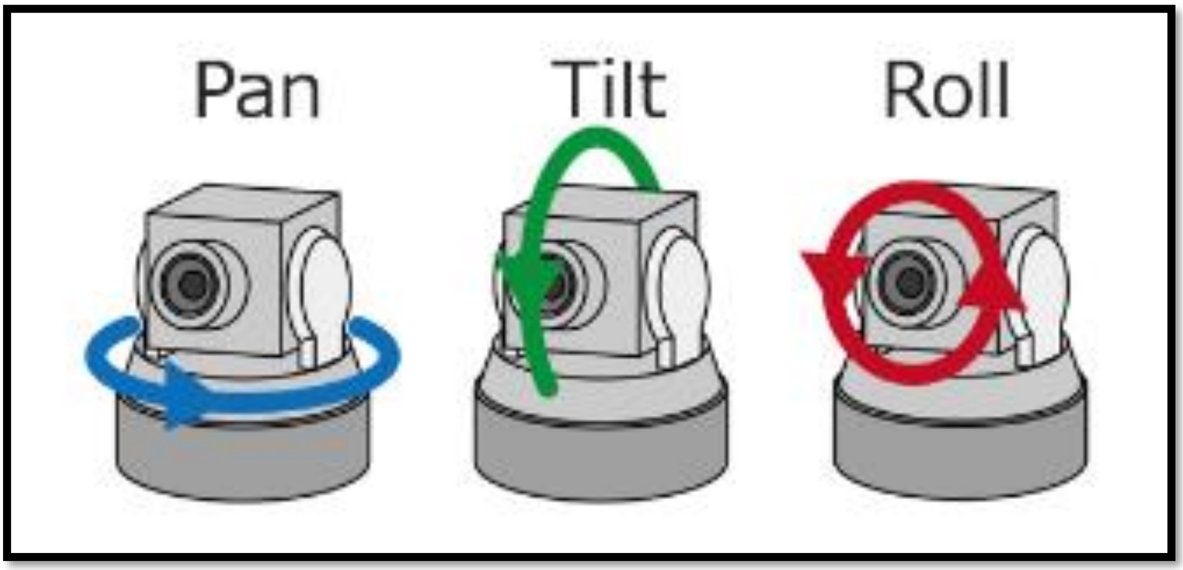

Figure 6 3 axes of rotation on gimbal

However, this can be reduced to two axes if image rotation along the UAV's Line of Sight (LOS) is electronically stabilized given that the payload enables us to do so. The core proposition of this project is that a multi-axis closed-loop stabilization controller, when paired with an automatic target tracker, can be effectively utilized to keep a UAV's camera or sensor consistently aimed at a target or region of interest. This is achievable in both stationary and dynamic UAV flight conditions by leveraging advanced image processing and control system design techniques, especially vital for defence applications where precision, real-time tracking, and stability are paramount.

1.4. Payload Review

The payload consists of a thermal camera, a day camera and a laser range finder, or LRF.

The thermal camera is the [redacted] with a motorized zoom manufactured by Ophir. The [redacted] is a lightweight, compact, thermal imaging lens optimized for smaller size 10 µm pitch 640x512 FPA detectors. It features a unique folded optics design that significantly reduces the length of the lens and, therefore, the overall size and weight of the optical system in which it is incorporated. The lens is 65% smaller than existing MWIR 10 µm 640x512 lenses. It is suitable for the purposes of building a very lightweight ISP.

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Figure 7 Thermal camera on the payload

To accompany the thermal camera a laser range finder or LRF will also be used. Model is [redacted]

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Figure 8 Laser range finder

To finalize the payload a day camera will also be used. [redacted].

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Figure 9 The day camera

1.5. Objectives of the Study

The object of the whole project and as a result the object of the dissertation therefore is as following:

To develop a state-of-the-art Inertially stabilized platform the objectives that should be met are:

- To pinpoint the requirements that a competitive ISP would need
- To search for the suitable components to accompany the payload
- To design a prototype using CAD
- To validate and evaluate the designs using FEM and other software
- To optimize the design parameters in order to reach the requirements

2. Literature review

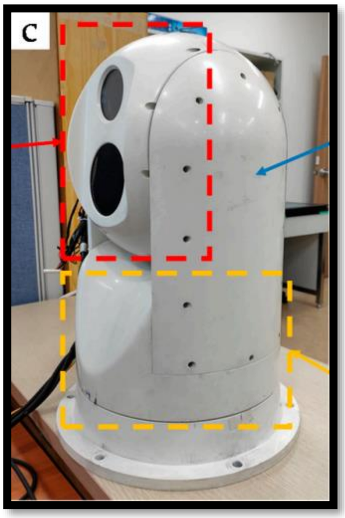
This section analyses essential factors for achieving the objectives in Chapter 1. It begins with an exploration of gimbals' fundamental systems and technologies, focusing on UAVs for defence purposes. An overview of the domain is provided, followed by a detailed investigation of the key sub-components of gimbals. The text then transitions to an examination of the primary challenges and performance limitations inherent in stabilization systems. This is followed by an analytical review of gyroscopic sensors, essential for the proper functioning of a gimbal system. A concise summary of target tracking methodologies and existing camera technologies is also included. The section concludes with a complex description of the dynamic model of a standard two-axis gimbal system utilized in UAVs.

2.1 Introduction

2.2 Overview of Gimbals

Gimbals or ISP’s have become an integral part of Unmanned Aerial Vehicles (UAVs) gimbals provide the necessary stabilization for onboard cameras and sensors, ensuring accurate data collection and real-time monitoring. An analysis was conducted that showed the impact of gimbals on the exterior orientation parameters of UAV-acquired images. Their study revealed that the use of a gimbal significantly improves the geometry and spatial bundles of rays in UAV photogrammetric surveying. The results showed that the discrepancies between data were four times smaller when a gimbal was used (Jurjevic, 2017), highlighting its potential for application in real conditions. UAVs are frequently employed for tasks such as reconnaissance, surveillance, and identifying targets. The research underscores the role of gimbals in enhancing the stability and security of UAV systems. They not only elevate the calibre of data collection but also augment the reliability and efficiency of UAV operations.

Figure 10 Octopus E180



ISPs on ground vehicles, ships, aircraft, and spacecraft routinely stabilize and direct visible and infrared cameras. These systems serve various missions, including the scrutiny of military targets, detailed mapping, and the generation of high-resolution imagery for environmental surveys. Additionally, specialized ISPs are mounted on vehicles to stabilize and aim communication antennas as well as pencil-beam laser communication devices.

The diversity of SP electromechanical configurations matches the variety of applications they are intended for. ISPs generally include an assembly made up of structural components and mechanical elements such as bearings and motors, which together they consist a gimbal. A gyroscope, or multiple gyroscopes, is mounted to this gimbal. In some configurations, the sensor or payload needing stabilization is directly mounted on the gimbal assembly. In other setups, mirrors or additional optical elements are affixed to the gimbal, while the sensor is securely attached to the vehicle.

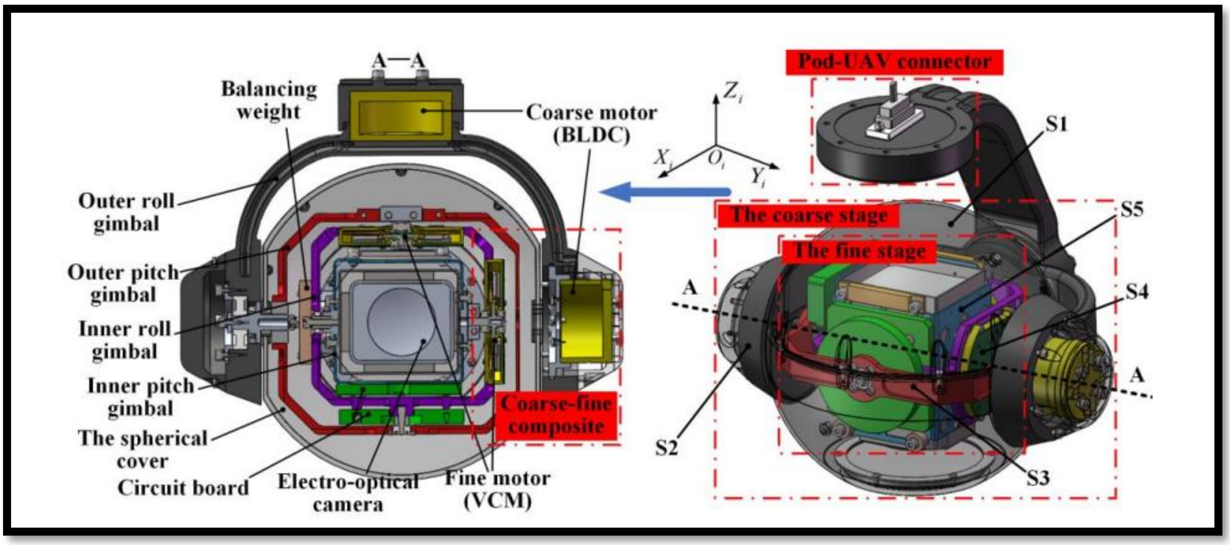


Figure 11 4-axis Electro-optical ISP designed with two stage isolation

Numerous firms are actively involved in the manufacturing of inertially stabilized platforms, dedicating their efforts to the development of this advanced technology. Among the leaders of the industry are world renowned companies such as DJI, Octopus, Flir and WESCAM

ISPs find utility in optical imaging systems to enhance the system's performance. The evolution of optical imaging capabilities has necessitated stabilization techniques to fully exploit the available imaging technology. Known as digital image stabilization and optical image stabilization, both digital manipulation and physical sensor stabilization approaches have been employed to elevate imaging performance. In these systems, the Line of Sight (LOS) originates from the center of the Field of View (FOV) of the camera or sensor, aiming at the target object. Often, the sensor's target is dynamic, requiring tracking while preserving image clarity and sharpness. In high-performance imaging systems, it is reasonable to expect jitter reduction to less than 10 µrad, even in highly dynamic conditions. (2)

When working together with a target tracker, an ISP can effectively meet the challenge at hand. The term "target tracker" is a broad one, covering any hardware or software capable of both detecting and positioning a target within the sensor's field of view. ISP's have two purposes regarding optical imaging. Firstly, to capture high-quality images of the selected target, and secondly to accurately determine the target's location relative to absolute coordinates set by the user. The operating environment, host vehicle motion, and target motion are three main categories of characteristics that may have an impact on the image's quality.

In its simplest form, an Inertially Stabilized Platform (ISP) aims just to keep the stabilized object from rotating in inertial space, without necessarily maintaining a fixed Line of Sight (LOS) to a moving target or object. However, outside of a few specialized applications in navigation or science, the key motion that needs to be managed is usually the relative movement between two objects. Using Figure 5 as an example, the components of motion and apparent motion of the LOS between two moving objects can described by Equation 1 and Figure 4.

$$\omega_{\frac{target}{FOV}} = \left(\frac{V_{T\perp}}{R} - \frac{V_{i\perp}}{R}\right) + \omega_M - \omega_i \qquad (1)$$

Equation 1

- $\omega_{\frac{target}{FOV}}$ Being the rotational speed or the motion of the target inside the FOV of the payload
- $\left(\frac{V_{T\perp}}{R} - \frac{V_{i\perp}}{R}\right)$ Being the motion caused by the target and sensor moving at right angles to the Line of Sight (LOS), referred to as parallactic motion.
- ω_M Apparent motion caused by optical distortion of LOS. The distortion is caused by the media in which the light travels through to reach the sensor.
- ω_i The rotational velocity of the sensor.

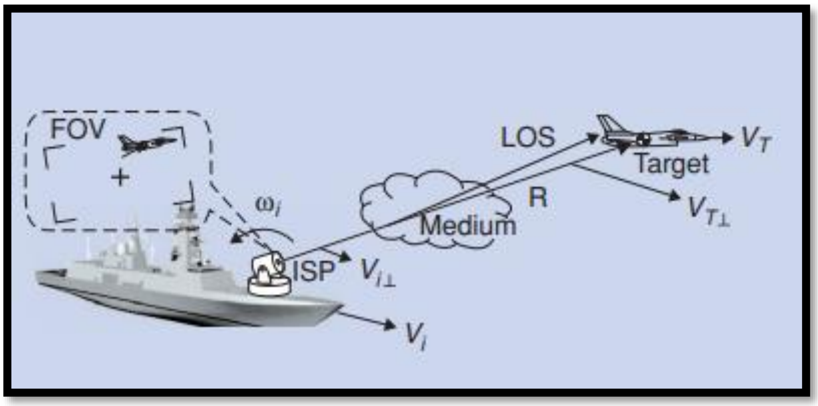


Figure 12 An inertially stabilized platform or gimbal, mounted on a sea vessel targeting an airborne vehicle. The LOS is focusing on the moving jet airplane and stabilized in two orthogonal axes.

Whenever the target or sensor has a velocity component that's perpendicular to the Line of Sight (LOS), it results in parallactic motion of either the aim point or the image within the Field of View (FOV). To manage this, a pointing or tracking system is typically used in tandem with the Inertially Stabilized Platform (ISP). If the target's motion is unpredictable or not well-defined, automated radar or imaging trackers are essential. On the other hand, when the target is at a known, fixed location, some pointing systems utilize navigation sensors to negate the parallactic motion effectively.

An erratically moving target could easily exit the Field of View (FOV), and the host vehicle's own motion could contribute to tracking loss. Additionally, environmental variables like atmospheric conditions can pose challenges to the ISP's operating environment and target tracking capabilities. Therefore, an ISP must be designed to work seamlessly with its target tracker, ensuring that these variables don't compromise the system's performance beyond its defined operational limits.

2.3 Gimbal components

Gimbals are generally divided into 3 sub-assemblies each tasked with their own function. The first and most important sub-assembly is the payload of the gimbal which consists of the sensors or the tools that need to be stabilized in order to be functional. The second sub-assembly consists of the elements that contribute to the motion of the LOS of the gimbal, such as motors and bearings. The final sub-assembly consists of the control elements of the gimbal which actuate the motors to constrain or rotate the gimbal to the desired position, which includes feedback elements such as encoders, gyros and the electronic drivers of the motors.

2.3.1 Gimbal payload

The sensor payload is the most important feature of an ISP system. It’s the most influential feature that pays a key role into what dimensions, what stabilizing assembly and what control elements will accompany it to create a gimbal. Any system whose performance is considerably improved by nullifying its vibrations and rotary disturbances may potentially be a candidate for developing a dedicated ISP. The payload of ISP’s primarily consists of camera sensors, but any system who operates on a LOS and needs to be stabilized is considered potential payload, such as vehicle mounted weapons. However big the difference in payload of each Inertially stabilized system may be, there are some components that are shared universally.

2.3.2 IMU (Inertial Measurement Unit)

An Inertial Measurement Unit (IMU) is a device that typically consists of gyroscopes to measure and report angular rate and accelerometers to measure and report specific force. (Vectornav, 2023)

An IMU typically consists of:

- Gyroscopes: providing a measure angular rate.
- Accelerometers: providing a measure specific force/acceleration.
- Magnetometers (optional): measurement of the magnetic field surrounding the system. Less common in UAV ISP’s

The stability of a system is measured by comparing its actual inertial rotational rate ωi to the desired rate, making these sensors indispensable in the development of an Inertially Stabilized Platform (ISP). Errors introduced by the gyro are intrinsically linked to the system's overall performance. In fact, these errors have been identified as the main limiting factors in the performance of smaller, stabilized platforms. Therefore, the selection of the proper IMU is critical to the correct function of a gimbal.

2.3.3 Bearings

Most inertially stabilized platforms operate on the bases that the disturbances acted upon it are rotational. An indispensable component of every rotating system is a machine element which enables it to rotate with low friction, high accuracy and no eccentricity, the bearing. The purpose of a bearing is to support a load while permitting relative motion between two elements of a machine. (Robert L. Mott, 2014). To achieve effective stabilization, the system must mitigate the undesirable disturbances introduced by friction. On the other hand, a system with insufficient stiffness could see a drop in performance due to multiple resonance effects. This creates a design dilemma in the construction of an ISP's rotating joints and mounts: while stiffer mechanisms generally add more friction, they also excel in terms of their structural resonance characteristics. (Hilkert, 2008) Angular contact ball bearings are commonly used in gimbals for their high load-carrying capacity relative to size and low friction. These bearings are often made from advanced materials like ceramic or specialized alloys to ensure durability and performance.

2.3.4 Motors

In an Inertially Stabilized Platform (ISP), gimbal actuators come in a variety of forms. DC electric motors are most commonly used, but hydraulic actuators are also an option, especially when high torque at low speeds is required. Beyond these, hydraulic and pneumatic drive systems are sometimes incorporated into ISP designs. As for how these actuators are coupled to the gimbals, there are two main approaches. They can either be directly mounted as direct torquers or connected via gear or belt drivetrains. It's crucial for these actuators to have quick response times to effectively counteract disturbances and meet the tracking specifications. Additionally, they should provide adequate torque without introducing issues like excessive hysteresis, cogging, or backlash.

Given that the maximum velocity required for an ISP is usually low, often not exceeding 100º/s, gearing can be an option to reduce the actuator's size and weight, especially when high torque is needed. For systems with low angular displacement needs, steel bands can be used to achieve a transmission ratio, thereby avoiding the backlash and indexing issues commonly associated with gear teeth. However, gearing in ISPs comes with its own set of drawbacks. Regardless of the mechanism used for the gear ratio, the reaction torques from a geared actuator introduce an equivalent torque disturbance that can negatively impact stabilization performance. Moreover, most gearing setups inevitably add extra friction and torsional resonances to the system. As a result, direct drive actuators are generally preferred, unless specific practical considerations dictate otherwise. (Hilkert, 2008)

Among the most commonly employed direct-drive actuators, permanent magnet DC torque motors stand out. These motors are designed with a high pole count to deliver substantial torque even at low speeds. Voice-coil motors, another category of limited-motion permanent magnet DC devices, are particularly well-suited for applications requiring limited rotation. These motors are not only easy to control but also exhibit minimal cogging and boast rapid response times, often less than a millisecond.

2.3.5 Encoders (Relative motion transducers)

Alongside inertial sensors, ISPs commonly incorporate relative-motion transducers, also known as encoders. These sensors measure the displacement between the axes as well as between the gimbal and its base. These measurements are essential for two main reasons:

first, they enable accurate alignment of the gimbal relative to its base; second, they help pinpoint the Line of Sight (LOS). In feedforward configurations, these transducers can also be fundamental to the stabilization process. When designing an ISP, a trade-off must be made between key performance parameters like accuracy and resolution, considering constraints such as size and cost. Accuracy is crucial for controlling the ISP's aim point in a pointing loop configuration, while resolution is vital when the LOS stability or aimpoint jitter is influenced by the transducer. Figure 11 show the feedback loop after an encoder is incorporated to the system design.

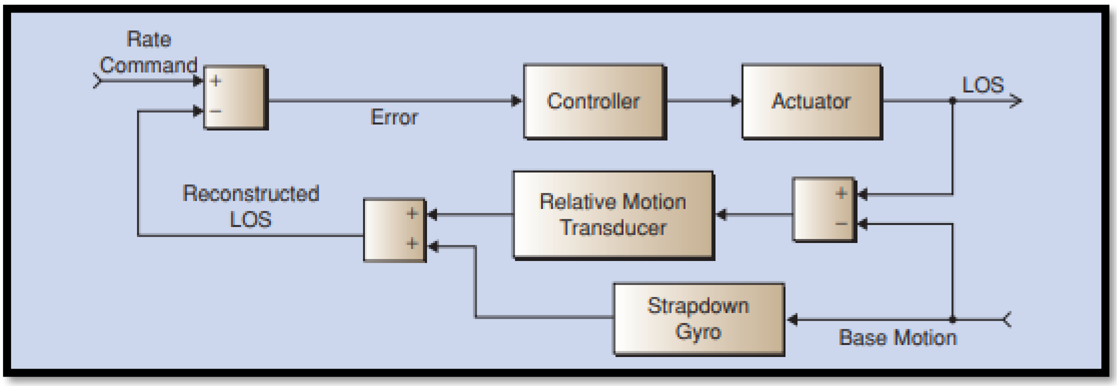


Figure 13 The feedforward approach. When IMU's cannot be mounted to provide a direct measurement of the line-of-sight (LOS) motion, a combination of sensors can often be used to reconstructed a signal that can then be used to control the LOS motion. This approach is called feedforward because the gyro output, which now measures the base motion, is fed forward to the loop similar to an input command and thus is not embedded in a feedback loop.

2.4 Operating principles

The first major category of inertially stabilized platforms is known as *platform*-stabilized systems. In this approach, the entire sensor payload is stabilized by a rotating gimbal assembly that controls the sensor's line of sight (LOS). When the host vehicle rotates, the gimbals counter this motion by rotating the sensor payload in the opposite direction, thereby maintaining a consistent LOS. Consequently, the gimbal's movement directly influences the sensor's LOS. In such a mass-stabilized setup, the number of orthogonal gimbals in the electro-mechanical assembly matches the number of axes requiring inertial control.

In line with all Inertially Stabilized Platforms (ISPs), the objective of a mass-stabilized system is to maintain the sensor payload in a fixed position in inertial space. According to Newton's 2nd Law, in an ideal, frictionless mass-stabilized ISP, the Line-of-Sight (LOS) remains in its initial inertial orientation. When extended to rotational dynamics, Newton's 2nd Law posits that a body with a moment of inertia (J) will experience an angular acceleration (α) when subjected to an unbalanced torque (T).

$$\sum T = Ja$$

In a perfect mass-stabilized direct-drive system devoid of friction, cable flexure, imbalance, kinematic coupling, or other disturbances, the sensor maintains its initial orientation due to Newton's laws. Therefore, the challenge in controlling such a mass-stabilized direct-drive system lies in optimizing the assembly design to minimize the impact of any disturbances on the ISP. Hence, stabilization aims to nullify the net torque exerted on the sensor payload. An optimal system is balanced in a way that the net internal moment around each axis is zero. If friction between the axes of rotation and other internal disturbance torques can be minimized, the system will maintain stability and remain at rest, even when subjected to external disturbances. In a practical system, however, various sources contribute to internal disturbances, such as imbalance, assembly flexure, cable flexure, kinematic and geometric coupling, and friction. The main design challenge is to create a system that minimizes these disturbance effects on the sensor.

Kinematic disturbances in an ISP arise from the dynamic interplay between the assembly's inertial properties and the angular motion of the gimbal assembly. On the other hand, geometric coupling disturbances are induced by the gimbal assembly's geometry. Rotating one axis could unexpectedly cause rotation around another axis solely due to the system's geometric configuration. In mass-stabilized systems, minimizing kinematic disturbances can be achieved by suspending the gimbals along their principal axes, a crucial design consideration for ISP development.

Actuation of gimbals is essential because merely stabilizing the sensor is usually not enough; control over the Line of Sight (LOS) between the sensor and the target is often required. To achieve this, gimbals are commonly actuated using DC motors, known for their high torque and precision, to accurately move the gimbal assembly. These motors can either be directly mounted on the gimbal axes or connected through gear or belt linkages, often situated at the assembly's base. However, geared or belt-linked systems have the drawback of inherently transmitting the host vehicle's base motion to the gimbal assembly and, consequently, to the sensor payload. As a result, even in an ideal, frictionless setup, active control of the sensor's LOS is necessary to compensate for the host vehicle's rotation. (Rue, 1974)

While directly coupled DC motors come closest to being an ideal direct torquer, no electro-mechanical actuator can fully achieve this due to inherent viscous damping within the system. In electric motors, back EMF leads to viscous damping, while in hydraulic drives, flow feedback within the assemblies causes damping. These damping factors introduce additional torque disturbances into the ISP system that must be mitigated. A prevalent approach to minimize these torques involves the use of current or pressure feedback minor loops. (Rue, 1974)

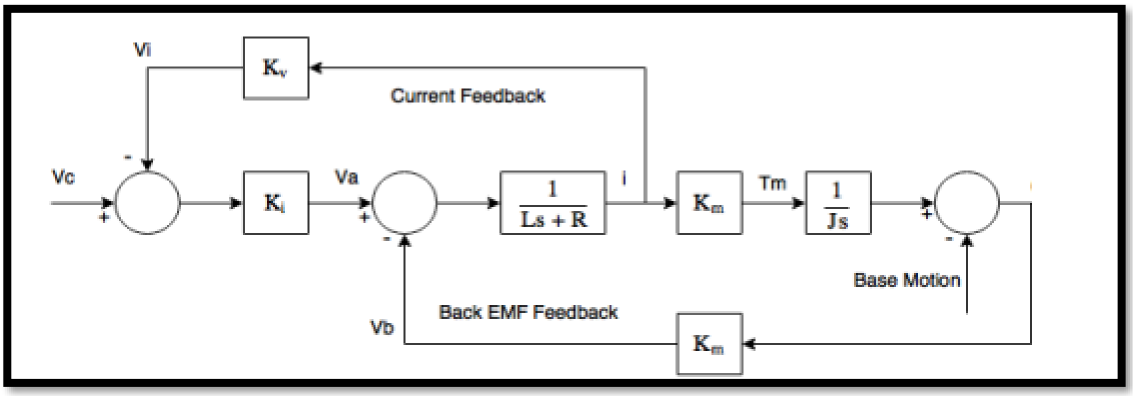


Figure 14 Current feedback loop

The block diagram model in Figure 5 illustrates a DC motor controlled by a command voltage V_c. Current feedback is enabled through the scaling block K_V and the minor loop controller gain K_i. These closed loops possess high gains and bandwidths, making them effective in mitigating the impact of viscous damping at low frequencies. Consequently, disturbance torques arising from viscous damping are also reduced.

In summary, the Line-of-Sight (LOS) rates in a mass-stabilized system are determined by the interplay between the inertial rates of the gimbal assembly and the sensor payload, and these are further influenced by the system's geometry. These inertial rates are regulated by the correlation between the gimbal assembly's inertial attributes and the total net torque exerted on each axis of the ISP, which includes both disturbance and actuator-applied torques.

In Figure 4, platform stabilization is illustrated, where the entire payload rotates within a gimbal assembly to adjust the sensor's line of sight (LOS) relative to the host vehicle. This rotation can be achieved either by a direct-drive motor mounted on the gimbal axes or by a motor connected through a geartrain or other mechanical linkages like a belt or chain. Often referred to as mass stabilization, this approach aims to stabilize the entire mass of the payload. The LOS orientation is governed by the angular movements of the gimbal assemblies. When the host vehicle manoeuvres or experiences vibrations, the gimbals, if functioning correctly, rotate in the counter direction to maintain a stable LOS relative to inertial space. As a result, gimbal movements directly dictate the LOS direction and image jitter. (Masten, 2008)

The basic functioning of a single gimbal in a mass-stabilized direct-drive system is depicted in the free-body diagram shown in Figure 12. The direct-drive motor is integrated into the gimbal, allowing the control torque to induce acceleration of the payload in inertial space. The entire movable payload, along with its supporting structure, is represented by a single inertia term, J, which is included in the rotational dynamics (Masten, 2008).

$$J\left(\frac{d^2\theta_L}{dt^2}\right) = T_M + T_D$$

Where θ_L is the angular orientation of the sensor line of sight, T_M is the torque acted on the gimbal axis by the direct drive motor, and T_D is the torque acted by all the disturbances.

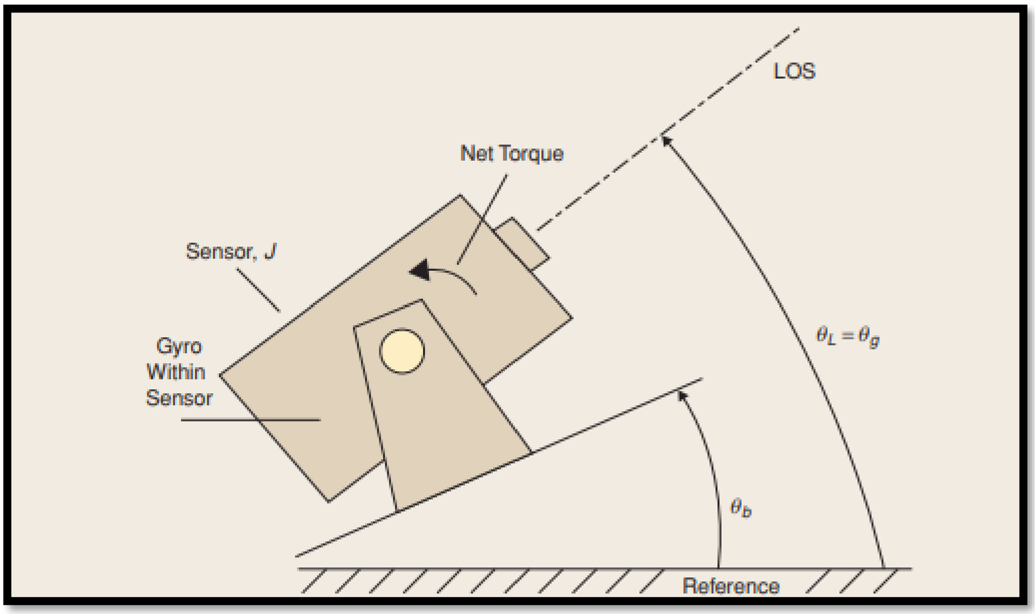


Figure 15 Mass-stabilized direct drive system. The actuator is mounted directly on the gimbal's axis of rotation

The disturbance torque, denoted as T_D, serves as a torque-equivalent representation of all potential disturbances that could affect the gimbal system's performance. As outlined in the section "Torque Disturbances," these disturbances encompass internal friction within the gimbal axes, flexural forces from electrical cables crossing the gimbal axes, imbalance effects, inter-gimbal coupling, host-vehicle motion coupling, and internal sensor disturbances. The control torque T_m generated by the drive motor is dictated by the control loop chosen by the system designer. Taking the Laplace transform and rearranging equation (1) yields the LOS rate where s is the Laplace variable.

$$\dot{\theta}_L(s) = \frac{T_m + T_D}{Js}$$

The equation is depicted in the block diagram shown in Figure 12 (b). The control system is comprised of a gyro that gauges the Line-of-Sight (LOS) rate, and a combined compensation/drive motor that generates the command torque T_m. This command torque is subsequently determined by the controller's compensation, which is in response to the amalgamated command input and LOS inertial rate feedback. (Masten, 2008)

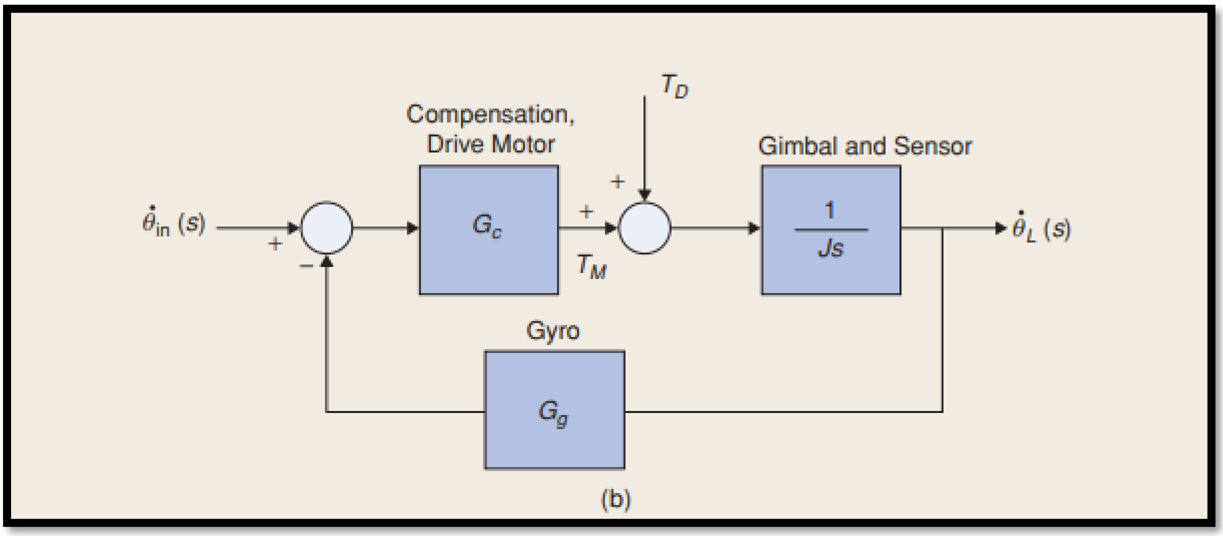


Figure 16 Mass-stabilized Direct-drive system block diagram.

The rate command input $\dot{\theta}_{in}(s)$ in the control loop depicted in Figure 15 governs the orientation of the gimbal assembly, thereby facilitating the Line-of-Sight (LOS) to either track a target or reorient the LOS. As can be inferred from Figure 15, the closed-loop behaviour of the LOS is dictated by

$$\dot{\theta}_L(s) = \frac{G_c}{Js + G_c G_g}\dot{\theta}_{in}(s) + \frac{T_D}{Js + G_c G_g}$$

in which G_g is the transfer function of the gyro that measures LOS angular velocity and G_c is the feedback error-over-torque transfer function for the combined compensation/drive motor. The goal of the control system is to manage the output Line-of-Sight (LOS) rate while mitigating the impact of external disturbances. Although this model overlooks imperfections in the gyro and motor, as well as electronic noise, it still highlights the core control objective: to adhere to the rate-command inputs while negating disturbances.

2.5 Causes of disturbances

In the mathematical modelling of Inertial Stabilization Platforms (ISPs), disturbances emanating from various sources can be collectively represented by an equivalent torque disturbance, denoted as T_D. This simplification serves as a pivotal metric for evaluating the performance of an ISP, specifically in the context of torque disturbance rejection Figure 17. However, it is worth noting that analytical models often fall short in accurately predicting these disturbances, particularly for ISPs designed for ultra-low Line-of-Sight (LOS) jitter performance.

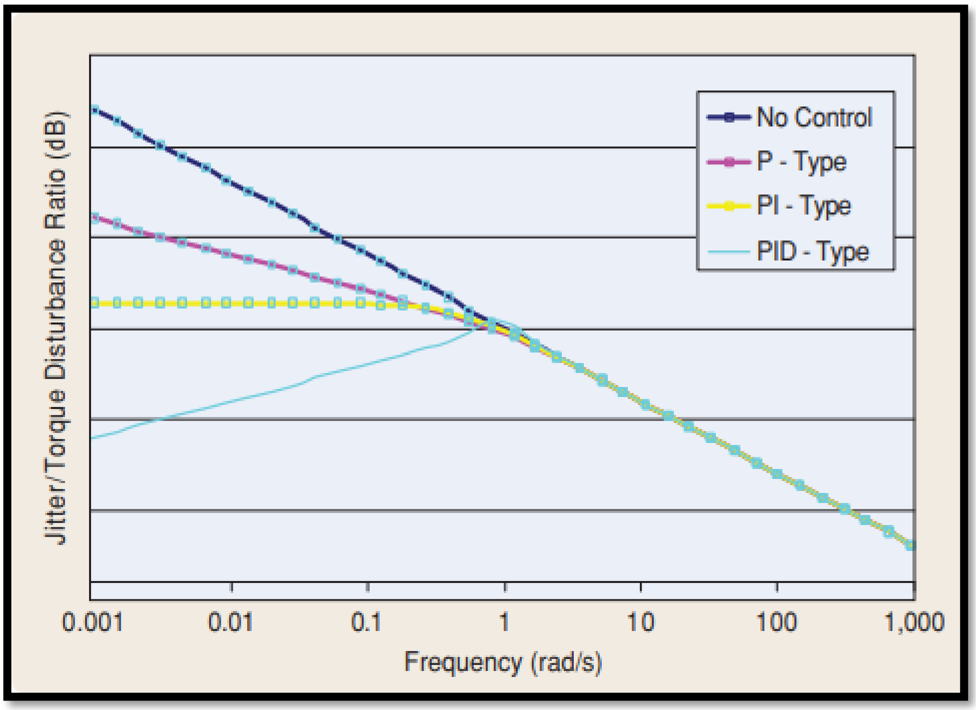


Figure 17 Line-of-sight jitter-to-torque disturbance transfer function. Suppressing a LOS motion in response to torque disturbances is the more dire spec of an ISP. PID controllers operate better than P or PI controllers on low frequency disturbances. (Masten, 2008)

Among the array of disturbances, Coulomb friction within the electromechanical assemblies frequently emerges as the predominant factor. This friction is generated due to surface interactions occurring within the rotating bearings of the gimbals, as well as from environmental and electromagnetic interference seals and brush contact in brush-type motors. Analogous phenomena can be observed in hydraulic or pneumatic actuators.

Spring torques, induced by the flexure, compression, or stretching of electrical cables connecting the payload to the host vehicle, constitute another category of disturbances. This is further complicated when payloads necessitate additional connections such as coolant lines or electrical or mechanical links to the host vehicle. Imbalance-related LOS jitter is another concern, occurring when the payload's centre of gravity is not aligned with a gimbal's axis of rotation.

Kinematic coupling due to vehicle motion is another significant disturbance. Manoeuvres executed by the host vehicle in pitch, yaw, or roll dimensions can couple into the gimbal mechanisms, necessitating adjustments in the ISP orientation relative to the host vehicle. These adjustments can be quantified by transforming the vehicle manoeuvres into equivalent torque disturbances impacting the gimbal mechanisms.

Intergimbal coupling is another complex disturbance, occurring when cross-products of inertia in one gimbal induce disturbances in another. Gyroscopic torques, a form of inter-axis coupling, also contribute to disturbances. Internal disturbances, such as noise in control loop components—actuators, electronics, and gyros—can similarly be represented by an equivalent torque disturbance.

Structural flexure, resulting from external disturbances or vibrations causing deformation in the payload or gimbal assembly, is another source of jitter. While gyros typically measure this jitter, leading to control actions to mitigate its effects, structural flexure can also manifest in components not directly measured by the gyro.

Environmental disturbances can have both direct and indirect impacts. Direct interactions occur when the ISP and payload are exposed to aerodynamic wind streams from the vehicle, leading to buffeting. Indirect disturbances include temperature variations and ice buildup, which can further enlarge and exacerbate other disturbances like friction or inter-gimbal coupling. (Masten, 2008)

The structural dynamics of the electromechanical assembly introduce additional disturbance torques that are integral to the overall performance of the Inertial Stabilization Platform (ISP) (Hilkert, 2008) (Masten, 2008). These dynamics serve as a limiting factor for the control system's bandwidth, thereby affecting its performance capabilities. As such, meticulous mechanical design is imperative for achieving high-bandwidth stabilization by minimizing the structural compliance of the assembly. (Hilkert, 2008)

Moreover, the influence of structural dynamics on ISP performance is not to be underestimated. To precisely delineate the torque requirements of the system, it is essential to consider not only the aforementioned disturbances but also external loading and noise. These factors collectively contribute to the complexity of the system and necessitate a comprehensive approach to mechanical and control design.

2.6 Structural Considerations

The structural components of Inertial Stabilization Platform (ISP) design often present the most formidable challenges and can significantly influence overall system performance. Structural design interacts with the ISP system through three distinct and separate effects. These effects, each impacting different facets of the design, are sometimes either conflated or, regrettably, overlooked until issues manifest. Initially, it is crucial to understand the fundamental characteristics of structural dynamics and associated analytical methods before delving into the aforementioned effects.

The structural dynamics of an Inertial Stabilization Platform (ISP) encompass all components affixed to the system, including the payload's structural attributes as well as the gimbal and supporting framework. Given that objects requiring stabilization—such as optical sights, antennas, and weaponry—are often structurally and geometrically intricate, the structural dynamics of these entities in conjunction with their gimbal systems are typically complex. They consist of virtually an infinite array of interactive response modes. A structural mode can be conceptualized as a specific shape (Figure 19) a corresponding frequency at which this shape resonates. While the shape and frequency of a mode are predominantly determined by structural stiffness, damping, and mass distribution, the amplitude of the response is contingent upon the amplitude and spectrum of the vibrational input or force eliciting the mode's reaction.

Figure 18 illustrates the initial set of bending and torsional modes present in a beam structure. The first bending mode, also known as the first resonance, is activated by a force or motion input that aligns with the frequency of this mode. Although all modes are responsive to inputs across frequencies, the reaction is notably amplified when the input frequency matches a modal frequency. As the frequency escalates, subsequent bending modes are activated, and this pattern continues indefinitely. When the excitation encompasses a wide frequency spectrum, multiple modes are simultaneously activated. Should a torque be applied to the beam, torsional modes respond in a similar fashion. In instances where the beam lacks symmetry, which is often the case in real-world structures, a blend of bending and torsional modes may be triggered by either a force or torque applied at any point along the beam. (Hilkert, 2008)

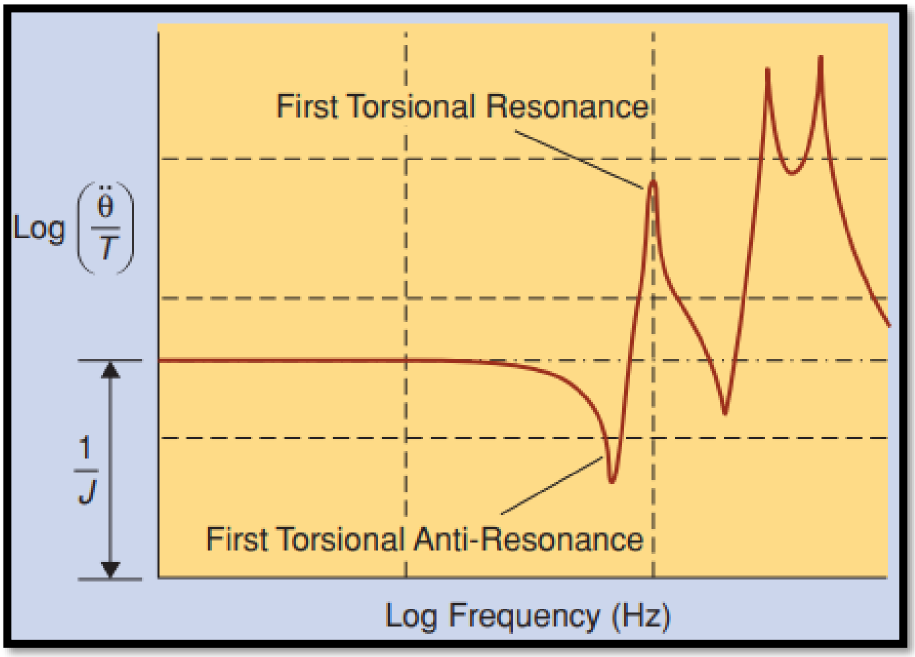


Figure 18 Standard structural transfer function. This graph shows the response of the angular acceleration to a torque excitation T over the first few resonances and antiresonances. Resonances in structures, which commonly have amplifications of 20 or more, are a major concern in the control system for ISPs. (Hilkert, 2008) (Rivin, 1999)

The frequency response shows the ratio between the amplitude and phase of the structural response at a designated point and orientation, in relation to the amplitude of the applied force at a separate point and orientation. This is essentially a measure of the structure's reactivity to different frequencies. To further clarify this interaction, a transfer function can be formulated. This function describes how rotational motion at a specific point on the gimbal is affected by an applied force or displacement at a different point. The frequency response delineates all participating modes at a specific point, encompassing both bending and torsional modes in the direction under consideration. Peaks in the frequency response signify the resonant frequencies at a particular structural point, while valleys, often termed antiresonances, indicate frequencies at which minimal or no response is observed at that specific point. The amplitude of the frequency response at each modal frequency is contingent upon the structural damping and the extent to which that mode contributes to the response elicited by the excitation. Metallic structural materials generally exhibit low damping, and resonant amplification factors ranging from 15 to 25 are not uncommon. Consequently, if an ISP system experiences 1g of vibration and the vibration input spectrum aligns with a resonant mode's frequency, response accelerations on the order of 15 to 25g can be anticipated. (Hilkert, 2008)

Finite element analysis acts as a potent instrument for the meticulous estimation of a range of transfer functions and structural behaviours integral to a design. This method is inherently iterative, necessitating periodic refinements to the mechanical design until an optimal configuration is attained. In instances where the structure, or a part thereof, is already constructed, the analytical model can be enriched with data from experimental modal testing. Such supplementary testing yields invaluable insights into specific areas that might warrant further modifications. Conventionally, this blend of analytical and experimental methodologies culminates in vibration testing to corroborate the system's performance.

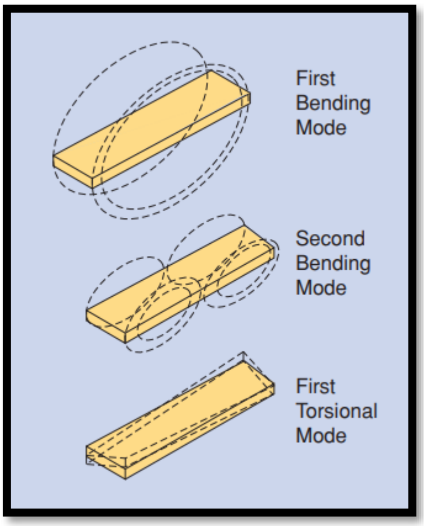


Figure 19 Structural Modes. A mode is defined by a shape and a frequency (Hilkert, 2008). There is an infinite number of modes on any given structure or system. The figure displays the first two bending modes and the first torsional mode of the most simple mechanical structure, a beam.

In order to rigorously assess the structure, it's essential to employ realistic forcing functions, whether the approach is analytical, experimental, or a hybrid of both. This evaluation must fully account for the six-degree-of-freedom (6DOF) translational and rotational dynamic environment in which the system is intended to operate. The shortcomings in the performance of many ISP designs can frequently be traced back to either a lack of thorough assessment of this dynamic 6DOF environment or a misunderstanding in the interpretation and application of the structural findings.

In this section, we delve into the various factors that encompass the structural considerations applicable to the majority of ISP system designs. These distinct categories necessitate the evaluation of diverse transfer functions and responses, each of which imparts unique effects on the overall system dynamics.

2.6.1 Part bending

We begin our discussion by analyzing the displacement of the Line of Sight (LOS), which is influenced by bending in both the gimbal and payload, as illustrated in Figure 20. Such displacement can be attributed to a variety of factors, including base-motion-induced vibrations, on-gimbal shaking forces, and even torsional responses elicited by gimbal actuators. A thorough analysis of this phenomenon necessitates meticulous identification of pivotal points within the system that accurately represent critical motion. It's important to note that optical components have the capability to either amplify or modify the direction of structural motion. Therefore, it becomes imperative to define specific coefficients for each optical element involved.

Interestingly, gyros often fail to detect LOS displacement caused by structural bending. However, they are capable of sensing certain aspects of the motion, usually those occurring at frequencies that exceed the effective operational range of the servo. The initial strategy to mitigate LOS displacement due to bending typically involves structural reinforcement. Yet, given the inherent design limitations, merely stiffening the structure is often inadequate, necessitating the exploration of alternative design methodologies. (Hilkert, 2008)

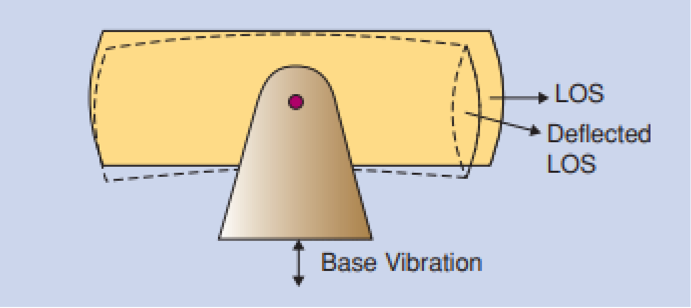


Figure 20 Part bending illustrated on an ISP. When torque excitations are applied on the structure the Line of Sight moves away from the focused area with the frequency of excitation due to the bending occurring on the parts of the stabilized payload.

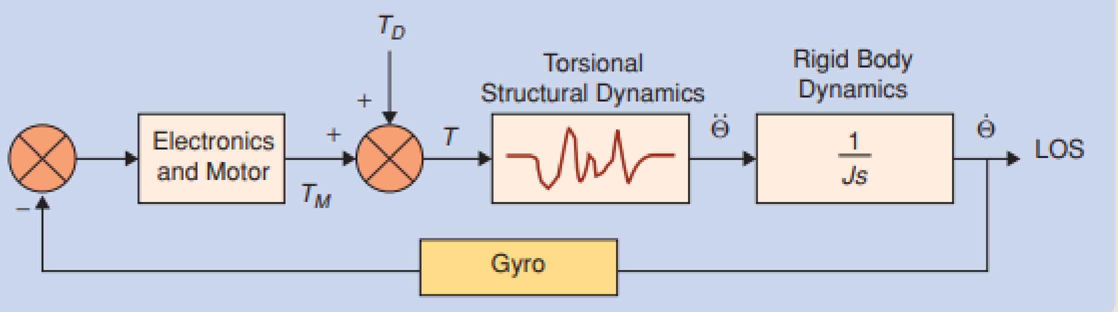
In the context of high-precision optical ISP systems, specialized devices like electronic autocollimators and fast-steering mirrors are employed to measure and subsequently compensate for the displacement. For satellites functioning as ISPs, the primary source of vibration is often the servo actuators themselves. To mitigate this, precision reaction wheels are utilized to inhibit the actuators from exerting adverse forces on the sensitive structural components.

When the primary issue is base-motion vibration, the prevalent solution is the deployment of either an active or passive vibration isolation system to dampen the vibrational effects. However, meticulous care must be exercised during the design and implementation of such systems to prevent the inadvertent introduction of additional rotational motion. Furthermore, interactions with other measurement and control systems within the broader framework must be carefully managed. This is because any motion between the gimbal and the base, aimed at attenuating vibration, can introduce complexities in the measurements from the gimbal to the base.

2.6.2 Torsional interactions

One crucial aspect to consider is the interaction between the structure and the stabilization control system. This interaction, which remains unaffected by the dynamic environment, significantly constrains the system's performance by limiting the bandwidth of the control system. A key element in this context is the torsional response, specifically the rotation at the feedback gyro relative to the torque motor or actuator, as illustrated in Figure 20. These resonances often exhibit substantial peaking, with factors reaching up to 15–25, thereby reducing the loop bandwidth to as little as one-tenth of the primary resonant frequency. (Hilkert, 2008).

Initially, the prevalent approach to mitigate this issue is to increase the structure's rigidity to alter the pertinent structural transfer functions. However, achieving adequate stiffening is often impractical, necessitating the integration of one or more notch filters into the feedback control system. These filters serve to dampen the loop gain around the resonance. It's worth noting, however, that the introduction of notch filters adds phase lag to the loop, consequently limiting the system bandwidth to less than one-third of the first torsional resonance, despite the filtering. Additionally, the modes in gimbal systems can shift as the gimbals rotate, compromising the filter's efficacy.



Various techniques, such as input shaping and flexure control, exist for managing torsional modes in structures. However, their implementation becomes complex when addressing the intricate and high-frequency modes commonly found in ISPs (Hilkert, 2008).

2.6.3 Mounting Stiffness

The final structural consideration pertains to the interplay between the control system and the structure upon which it is affixed. While this effect bears similarities to the preceding one, it does not necessarily exert an influence on the design or operational efficacy of the inertial stabilization control system. However, it can substantially curtail the bandwidth of any positioning or pointing system that is contingent upon sensor feedback measuring the relative motion between the gimbal and the foundational structure.

Figure S5 elucidates how gimbal actuators interact with the structure to which they are mounted, causing a deflection that is subsequently sensed by gimbal transducers. This interaction is particularly pronounced when the system is situated on vibration isolators or a flexible mounting framework. Several strategies exist for ameliorating this interaction. These include enhancing the torsional response of the mounting structure to increase its rigidity, adding mass to the stationary gimbal structure, and utilizing notch filters in the pointing servo system.

If the system's flexibility is attributable to the isolators, their positioning can occasionally be modified to elevate the torsional resonant frequency of the system, while preserving the requisite low lateral frequencies for isolation. For precision ground-mounted systems, another viable technique involves the synergistic use of a gyro and a relative motion gimbal transducer to furnish feedback, thereby enhancing both precision and accuracy.

2.7 Kinematics

In this chapter we delve into the intricacies of gimbal kinematics, a pivotal aspect in the design and operation of inertially stabilized platforms (ISPs) for UAVs. Kinematics, the branch of mechanics that deals with the motion of objects without considering the forces that cause the motion, is particularly crucial in understanding how gimbals achieve their primary function of stabilization. In UAV applications, especially in defense sectors, the gimbal must perform precise rotations to counteract the movements of the UAV, ensuring that the payload remains stable. This chapter aims to dissect the mathematical models and equations of motion that govern these rotational movements.

Understanding gimbal kinematics is not merely an academic exercise but a practical necessity. The kinematic equations provide the foundation for control algorithms, directly affecting the gimbal's performance metrics such as tracking accuracy, stabilization error, and response time. Therefore, a comprehensive grasp of gimbal kinematics is indispensable for the design, optimization, and ultimately, the successful deployment of ISPs in UAVs for defense applications. This chapter will explore the various types of gimbals, their degrees of freedom, and the coordinate transformations involved, all underpinned by rigorous mathematical formulations.

The gimbal assembly's role is critical in linking the system's base to its line-of-sight angular motion. The evaluation of system performance is incomplete without thoroughly assessing the different mechanisms that connect the system's base to its line of sight. The gimbal assembly, serving as the crucial interface between the two, plays a pivotal role in this evaluation. Angular rate coupling is influenced by gimbal geometry, while torque coupling arises from kinematic interactions between the gimbal and base motions. The impact of these factors varies depending on the base motion environment, operational modes, and gimbal design. Therefore, a comprehensive evaluation is essential for accurate performance assessment. (Rue, 1974)

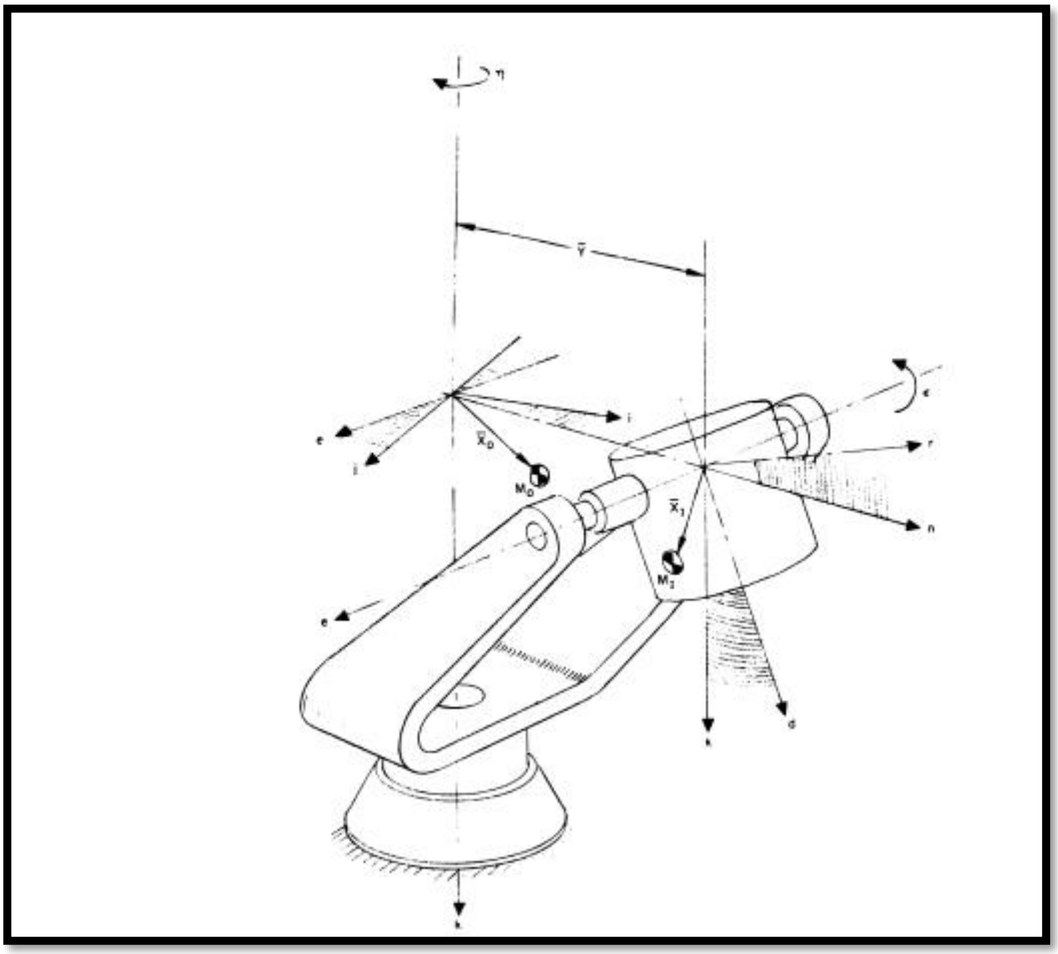


Figure 21 Gimbal systems and the frames axes. (Rue, 1974)

In Figure 13, we see a model of a gimbal system with two main parts: an outer gimbal for turning side to side (azimuth) and an inner gimbal for moving up and down (elevation). These gimbals work together to stabilize the camera or sensor they're holding.

The model uses three sets of axes to describe the system. The *I , j, k* axes are fixed to the base, giving us a main point of reference. The *n, e, k* axes are tied to the outer gimbal, and the *r, e, d* axes are linked to the inner gimbal. The outer gimbal rotates around the *k* axis, and its angle is marked as *−q*. The inner gimbal rotates around the *e* axis, with its angle marked as *e*.

This setup helps us understand how the gimbals move and what could go wrong, like if there's too much shake or if the motors aren't strong enough. It's a basic guide for anyone who needs to work on the gimbal system, whether they're designing it, fixing it, or trying to make it better.

In a conventional setup, the rotational axes of the outer and inner gimbals are not coplanar, and their centres of mass do not align with these axes. The coordinate systems i, j, k and n, e, k are designed such that their origins intersect where the k and n axes meet, provided that the r axis is also aligned with the i and n axes. For both the outer and inner gimbals, the e axes are considered coplanar and parallel. The origin of the r, e, and d coordinate system for the inner gimbal is set at the intersection of the n and inner gimbal e axes. When defined this way, the vector displacement 'y' between the rotational axes of the outer and inner gimbals is parallel to the n axis, and its e and k components are zero. The vector distances from the coordinate system origins to the centres of mass for the outer and inner gimbals are denoted as xo and SI, respectively. The mass values for the outer and inner gimbals are represented by M_o and M_I, respectively.

In matrix notation, the moments and products of inertia for the outer and inner gimbals are denoted as JoJo and JIJI, relative to their respective coordinate reference systems, extending beyond the previously mentioned symbols. The matrices are: (Rue, 1974)

$$\bar{J}_0 = \begin{bmatrix} B_N & B_{ne} & B_{nk} \\ B_{ne} & B_E & B_{ke} \\ B_{nk} & B_{ke} & B_K \end{bmatrix} \quad \text{and}$$

$$\bar{J}_i = \begin{bmatrix} A_R & A_{re} & A_{rd} \\ A_{re} & A_E & A_{de} \\ A_{rd} & A_{de} & A_D \end{bmatrix}$$

Utilizing these conventions implies that the negative signs linked with the products of inertia are inherently associated with each specific term. (Goldstein, 1950)

2.8 Drivetrain

The principle of a drivetrain, also termed as power transmission, is a foundational concept in engineering that has been rigorously researched and applied across multiple industries. It functions as the key system for channeling mechanical energy from an originating source, such as an electric motor or hydraulic pump, to a designated endpoint or load. Within the drivetrain, various components like gears, belts, shafts, and couplings are integrated, each subject to unique design parameters, efficiencies, and constraints. This literature review aims to present an exhaustive analysis of current research and advancements in drivetrain technologies, specifically focusing on their role in inertially stabilized platforms (ISPs). The review will explore the mechanics, material choices, efficiency optimization, and reliability factors that affect the design and performance of drivetrains in ISPs.

Figure 22 A belt and pulley transmission system

Drivetrains are categorized into distinct types based on design and application needs, including gear-driven, belt-driven, chain-driven, and direct-drive systems. Gear-driven systems use a series of gears for power transmission and are noted for their high torque and efficiency.

Belt-driven systems employ belts and pulleys, and are often selected for their quiet operation and ease of maintenance. Chain-driven systems use chains and sprockets and are typically used in high-strength, durable applications. Direct-drive systems connect the motor directly to the load, eliminating the need for intermediate transmission components, and offer advantages in efficiency and control. The choice of drivetrain type is highly dependent on specific application requirements, such as in inertially stabilized platforms where weight, efficiency, and reliability are critical factors.

2.8.1 Types of drive systems

Gear-driven systems

Gear-driven systems are characterized by their high torque capabilities and mechanical efficiency. They employ a series of gears for power transmission from the source to the load. These systems are commonly utilized in applications demanding high precision and durability. However, their complexity often leads to the need for regular maintenance to maintain optimal performance. (workbook, n.d.).

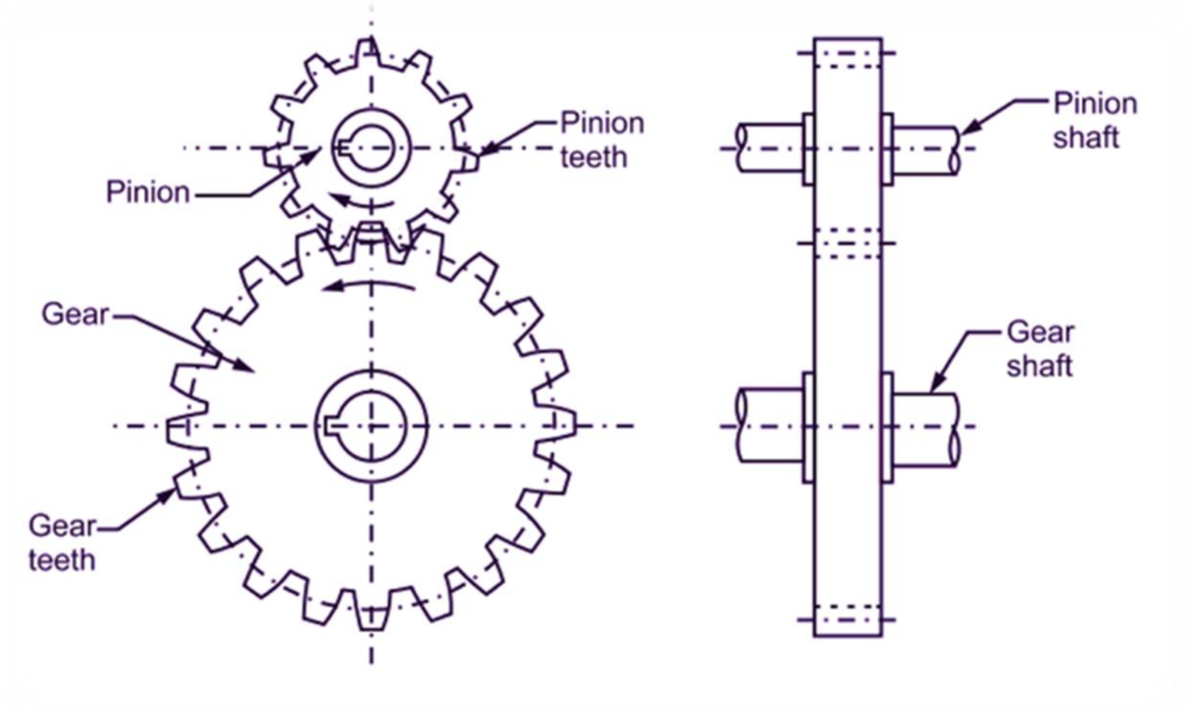


Figure 23 Gear-driven system assembly consisting of a drive gear (pinion) and a driven gear

It is essential to recognize that the engaged gears in a gear-driven system always rotate in opposite directions. The gear drive comprises two wheels: the smaller wheel is termed the pinion, and the larger wheel is referred to as the gear. In such systems, slip is notably absent, resulting in an exact and uniform velocity ratio. Owing to its capabilities for maximum power transmission and precise velocity ratio, the gear drive is classified as a perfect positive drive.

Belt and Pulley

Belt-driven systems are another form of mechanical power transmission that utilize belts, usually made of rubber or other flexible materials, to transfer motion and force between pulleys. These systems are particularly advantageous for applications where direct mechanical linkage is impractical due to distance or the need for variable speed and torque. A belt drive is a frictional mechanism that transfers power between two or more shafts using pulleys and an elastic belt. Generally powered by friction, it can also function as a positive drive. The system is capable of operating across a broad range of speeds and power levels, and is noted for its efficiency. (SIld, n.d.)

Figure 24 A belt driven system utilized in an engines timing

In terms of economic considerations, belt drives are less expensive than both gear and chain drives, both in installation and maintenance. Additionally, the wear experienced by belt drive pulleys is minimal compared to that of chain drive sprockets over extended use.

Unlike most gear and chain drives, belt drives can tolerate a certain degree of misalignment. However, proper alignment extends the system's lifespan. Excessive misalignment can lead to issues such as improper belt tracking, uneven pulley wear, noise, and belt edge wear, with the severity of these issues being directly proportional to the belt's width.

Although belt-driven systems are recognized for their versatility and low maintenance requirements, they do have inherent limitations. A significant issue is the potential for belt slippage, which can arise if the belt lacks proper tension or if the material is unsuitable for the application. This slippage compromises efficiency and often necessitates frequent adjustments. Additionally, belt-driven systems are generally less efficient than direct gear drives, particularly over extended distances. The materials used for belts, commonly rubber or similar composites, are also heat-sensitive and may degrade over time, requiring replacement. These constraints should be meticulously evaluated when selecting a belt-driven system for specific applications.

Epicyclic (Planetary) gears

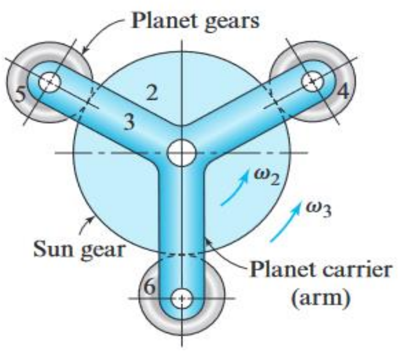


Figure 25 A common planetary gearset (John J. Uicker)0

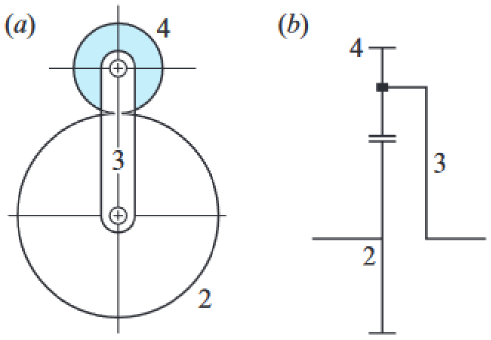


Figure 26 a) The most basic form of a planetary gear train; b) Schematic diagram (John J. Uicker)

In the terminology of gear trains, epicyclic trains are alternatively referred to as planetary or sun-and-planet gear trains. In this context, the gear labeled as '2' in Figure 26 is designated as the sun gear, while gear '4' is termed the planet gear. Crank '3' is identified as the planet carrier. Figure 25 illustrates the same gear train as Figure 26 but includes two additional planet gears for improved force balance. The incorporation of extra planet gears also allows for reduced forces via enhanced load sharing. However, it should be noted that these added planet gears do not affect the kinematic properties of the system. Therefore, even though a single planet gear is usually depicted, an actual machine is likely to be designed with multiple planet gears, often in sets of three. (John J. Uicker)

The basic configuration of an epicyclic gear train, as outlined in Figure 27, demonstrates how the motion of a planet gear can be transferred to another central gear. In this specific instance, the second central gear, designated as gear 5, is an internal gear. Figure 27 shows that internal gear 5 is stationary, but this is not a necessary condition, as indicated in Figure 27.

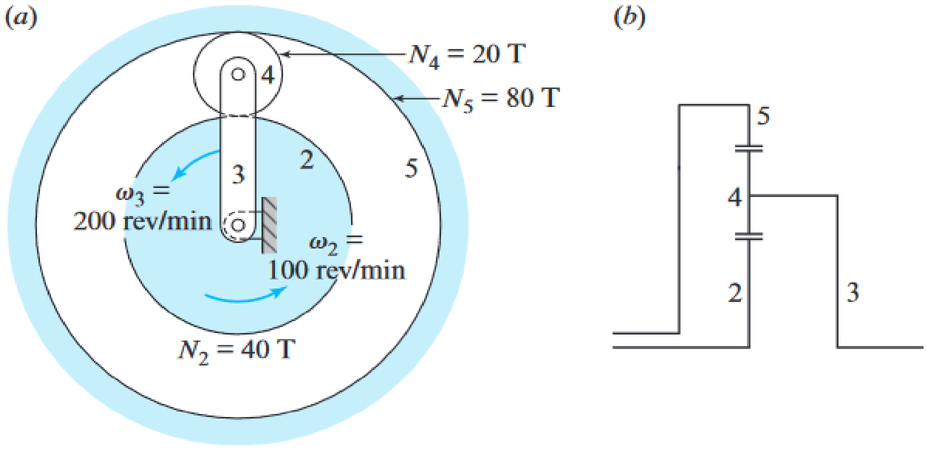


Figure 27 a) A simple planetary gear train b) its schematic diagram

Equations

The fundamental equation for epicyclic gears is derived in this form: (tec-science, n.d.)

$$n_p * d_p = n_c * (d_p + d_s) - n_s * d_s$$

In this equation, n_p denotes the rotational speed and d_p the diameter (pitch circle) of the planetary gear. For the sun gear, the speed is denoted by n_s and the diameter by d_s. The rotational speed of the carrier is denoted by n_c.

The Willis equation is universally applicable to all forms of planetary gears. Even when the planet gears are enclosed by a ring gear, as in a traditional planetary gearbox, the established relationships among the sun gear, planet gear, and carrier remain unchanged. The only variable that needs clarification is the manner in which the motion of the planet gears is transferred to the ring gear. In this context, only a rolling motion without sliding occurs between the ring gear and the planet gear, considered as pitch cylinders. This necessitates that the velocity at the point of contact be identical. If the speed vpo, representing the motion of the planet gear's outermost point, is known, it equates to the velocity v_r of the ring gear. This eliminates the possibility of relative motion, which is incompatible with toothed wheels. The pitch circle radius r (or pitch circle diameter d) of the ring gear can then be employed to ascertain its rotational speed n, given the existing relationship between these parameters. (tec-science, n.d.)

$$v = \omega * r = \omega * \frac{d}{2} \text{ and since } \omega = 2\pi * n \text{ we derive to}$$

$$v = \pi * n * d$$

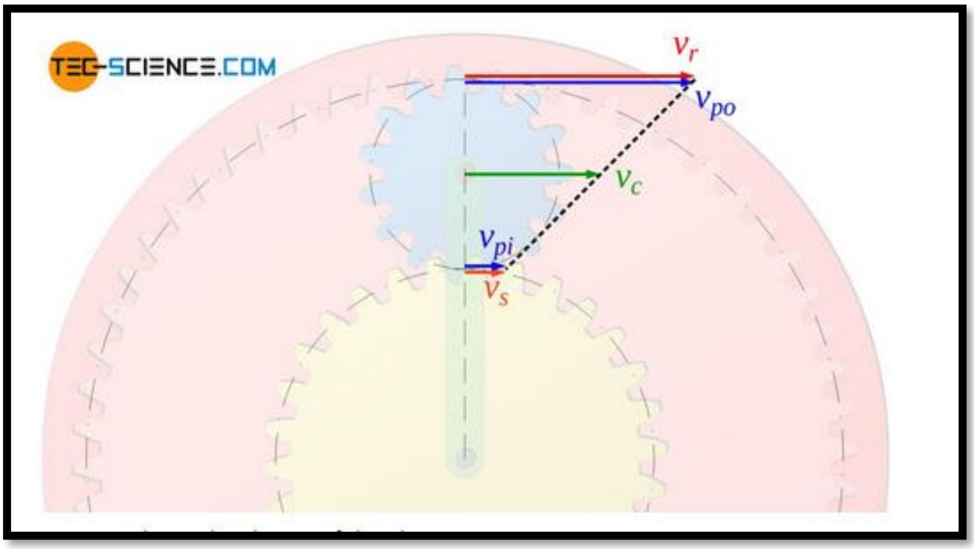


Figure 28 Velocity distribution of the planet gear

Advantages of Planetary Gears:

- High Efficiency
- Compact Construction

- High Power Density

Planetary gears are distinguished by their elevated efficiency and high power density relative to other gear types, attributes largely due to their compact form. The incorporation of an external ring gear notably diminishes both the system's volume and mass. This design also facilitates the transmission of high torque in a limited space, achieved through the use of multiple parallel tooth combinations and several orbiting wheels. The distribution of torque across multiple gears reduces tooth forces, making them less than those in other gear types. Additionally, the absence of a need for synchronisation permits gear changes without disrupting traction. The continuous meshing of all gears results in low operational noise. (SE, n.d.)

Figure 29 A planetary gearbox designed to be fitted in series with an electric motor

Disadvantages of Planetary Gears:

- Complex Construction
- Higher Power Dissipation Compared to Spur Gears
- Complex Bearings

The drawbacks of planetary gears include their intricate construction and greater power dissipation relative to spur gears. The transmission of power through at least two meshed teeth results in double the power loss compared to a simple spur gear. This gear type also necessitates complex bearings, particularly for use in three-shaft systems. (SE, n.d.)

Harmonic Drives

The Harmonic Drive, also known as Harmonic Drive gear, harmonic gear, or strain wave gearing, is a mechanical device invented in the 1950s to increase torque by reducing the gear ratio of rotary machines. It operates on a different principle than conventional speed changers. The device comprises a thin, elastic ring that rolls inside a slightly larger rigid circular ring. (Brittanica, n.d.) The basic Harmonic Drive consists of three main components: a circular spline, a flexspline, and a wave generator. The circular spline has internal teeth that mesh with the external teeth on the flexspline. The flexspline has fewer teeth and a smaller effective diameter than the circular spline. The wave generator is elliptical and contains two rollers that rotate within the flexspline, causing it to mesh with the circular spline at opposite points. When the wave generator (input) rotates clockwise and the circular spline is stationary, the flexspline (output) rotates counterclockwise inside the circular spline at a slower rate.

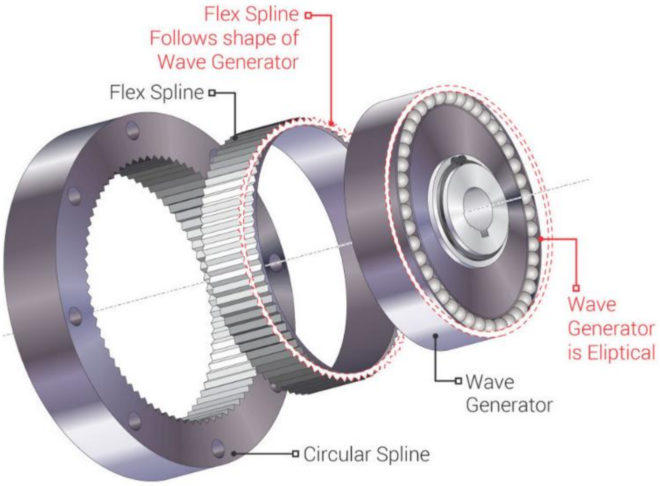


Figure 30 A breakdown of the harmonic drive with the most basic components

In contrast to traditional toothed gears, harmonic drives offer several advantages along with some limitations. Key benefits include high torque capacity, precise and repeatable positioning, compact design, absence of backlash, high single-stage reduction ratios, and strong torsional stiffness. However, they also exhibit high elasticity and nonlinear stiffness and damping. The application scope for harmonic drives is expanding. They are increasingly used in various sectors including automotive, aerospace, aviation, medicine, automation, and robotics. Additionally, they are suitable for inertially stabilized platform (ISP) applications. (P. Folega, 2012)

2.8.2 Types of Motors

In Inertially Stabilized Platforms (ISPs), motor selection critically impacts system performance, efficiency, and reliability. Various motors are utilized, each with distinct advantages and limitations. Servo motors are chosen for precision and control; stepper motors for their cost-effectiveness and simplicity; and traditional DC motors for balanced speed and torque. Axial flux motors have recently gained prominence due to their compactness and high-power density. The motor type is selected based on specific ISP requirements such as high torque, quick response, or energy efficiency. This section examines the attributes and applicability of these motor types within ISPs.

DC motors

DC motors are commonly used in Inertially Stabilized Platforms (ISPs) for their simple design, controllability, and adaptability. Operating on magnetic fields generated by direct electrical currents, they produce rotational motion. Notably, they offer high torque, especially at low speeds, making them ideal for quick and precise adjustments. They provide a wide range of speed control and can be integrated into feedback loops for better positioning accuracy. However, they require regular maintenance, such as brush replacement, and may be less efficient than other motor types like servo motors. Their performance can also be affected by temperature changes and electrical noise. Despite these limitations, DC motors remain a preferred choice for ISPs requiring robustness and extensive speed control. DC motors are further divided in two major categories:

Brushed DC motors

The Direct Current (DC) motor consists of a stationary stator and a rotating armature. The stator contains permanent magnets, while the armature has a wire coil connected to a commutator. As the commutator switches the electrical current through the coil, a rotating magnetic field is generated. This interacts with the stator's static field to produce torque, causing the armature to rotate. This mechanical energy can be utilized in various applications, including Inertially Stabilized Platforms (ISPs). Brushed DC motors employ carbon brushes for current transfer but suffer from wear and reduced efficiency due to friction between the brushes and commutator. The term "brushed" in brushed DC motors refers to the carbon brushes that deliver current to the rotating armature via the commutator. The brushes make physical contact, differentiating these motors from brushless types where current is transferred without contact. (Millett, n.d.)

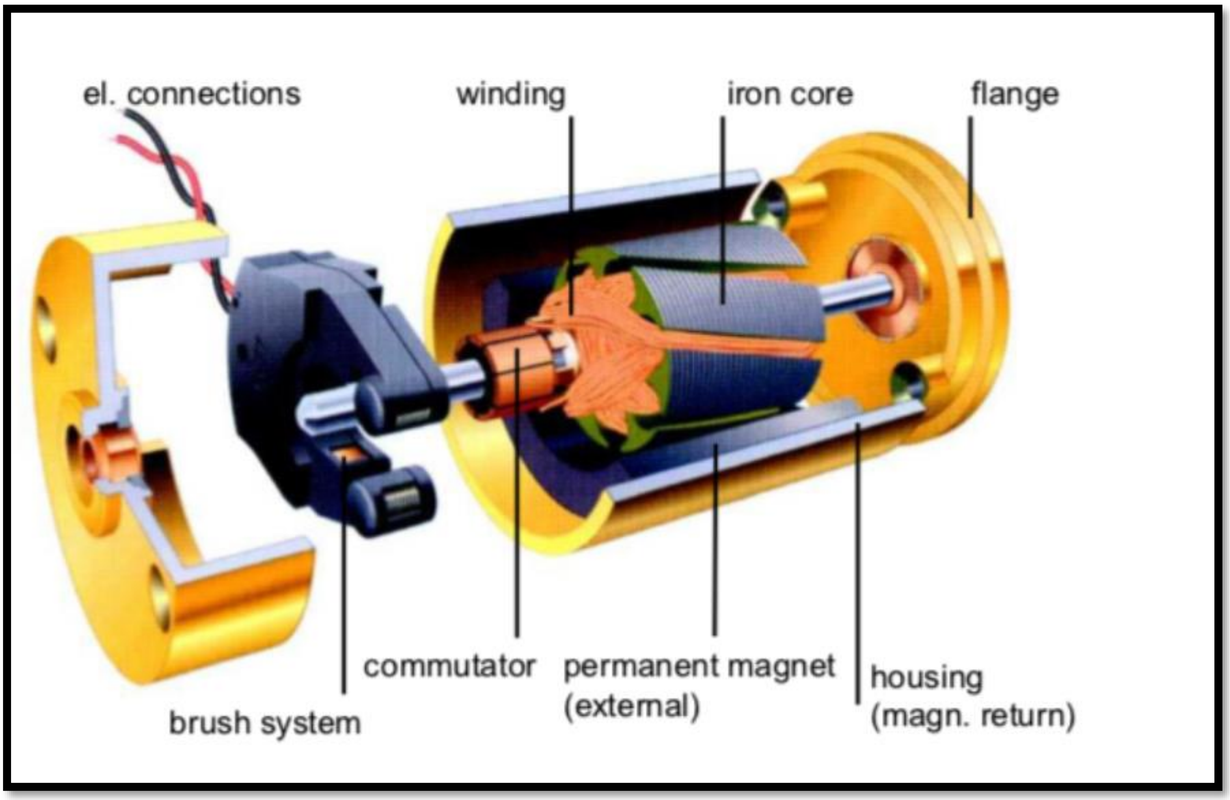


Figure 31 Break-down of a Brushed DC Motor

Brushless DC motors

Brushless DC motors operate on the same magnetic principles as brush motors but differ in construction. They employ electronic commutation to rotate the stator's magnetic field, requiring active control electronics. The rotor is fitted with permanent magnets, and the stator contains windings. These motors can have the rotor either inside or outside the windings, the latter being termed an "outrunner" motor. Typically designed with three phases, exceptions exist, such as small cooling fans with one or two phases. The windings can be connected in a "star" or "delta" configuration, with both setups using three connecting wires and identical drive techniques and waveforms. (Millett, n.d.)

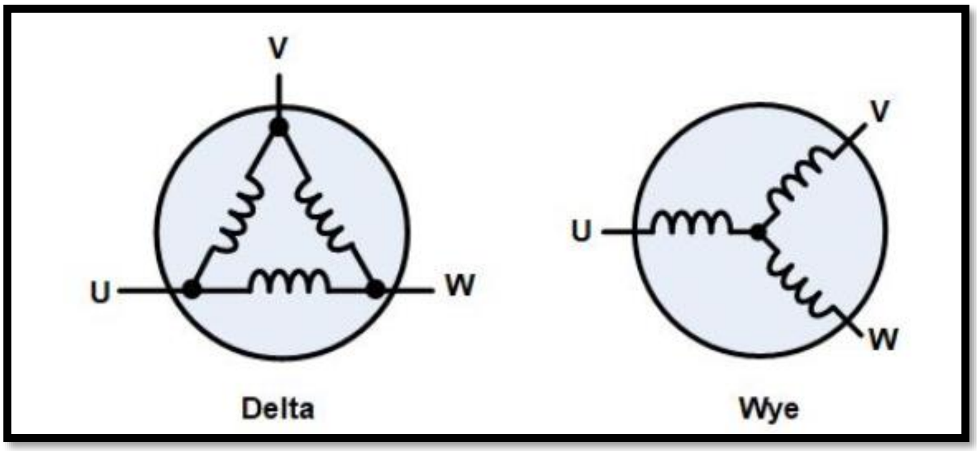


Figure 32 Common electrical configurations of BLDC motors

Three-phase brushless motors can be driven using various techniques, with trapezoidal and sine commutation being the most common. Trapezoidal commutation is simpler and resembles the method used in DC brush motors. It involves driving one phase to the supply voltage, grounding another, and leaving the third open. This method, however, results in torque ripple due to abrupt phase switching. Sine commutation is more advanced, driving sinusoidal currents through all three phases continuously, thereby minimizing torque ripple and noise. It's often used in high-performance applications.

Rotor position is crucial for proper commutation. Hall sensors mounted on the stator are commonly used to detect the rotor's magnetic field, providing feedback for phase current sequencing. While trapezoidal commutation can be implemented with simple logic, sine commutation requires more sophisticated control, often involving a microcontroller. Sensorless methods also exist, such as monitoring back EMF or using Field Oriented Control (FOC), which calculates rotor position based on currents and other parameters. FOC offers high performance but requires a powerful processor, making it costlier than simpler methods.

FEATURE	BRUSHED DC MOTOR	BRUSH-LESS DC MOTOR
LIFESPAN	Short (carbon brushes wear out)	Long (No significant mechanical wear)
SPEED AND ACCELERATION	Medium	High
EFFICIENCY	Medium	High
ELECTRICAL NOISE	High (Bush arcing)	Low
ACOUSTIC NOISE & TORQUE RIPPLE	High	Medium (Trapezoidal) or Low (Sine)
COST	Lowest	Medium (extra electronics)

Overall, the choice of drive technique impacts motor performance, noise, and cost.

DC motors, primarily because they eliminate the need for mechanical brushes that wear out and require frequent maintenance. This not only enhances durability but also reduces long-term costs. In terms of performance, BLDC motors can achieve higher speeds and quicker acceleration, as they are not limited by the brushes and commutators that restrict rotational speed in brushed motors. They can also be designed with powerful rare earth magnets, further reducing rotational inertia and enabling rapid acceleration.

Moreover, BLDC motors are quieter on both electrical and acoustic fronts. They generate less electrical noise due to the absence of arcing issues associated with brushes and commutators, making them ideal for environments with sensitive electronic circuits. Acoustically, they produce less noise due to smoother torque ripple, which minimizes vibrations and mechanical noise, especially at low speeds. While the initial cost of BLDC motors can be higher due to the need for electronic controllers, these costs are gradually declining as the technology matures, making them increasingly cost-effective for high-demand applications. (Millett, n.d.)

Axial flux Motor

Axial flux motors, particularly Axial Flux Permanent Magnet (AFPM) motors, are gaining attention for their compact structure and high torque density, making them suitable for applications like solar-powered vehicles. Unlike traditional radial flux motors, axial flux motors are designed with a disc-like structure where the magnetic flux flows along the axis of the motor. This design allows for a more compact and efficient motor. AFPM motors can also be configured without stator cores, eliminating associated losses and simplifying manufacturing. Advanced designs even incorporate multiple stator and rotor disks for enhanced performance. These motors are often analyzed using three-dimensional finite element analysis (FEA) for optimum design and efficiency.

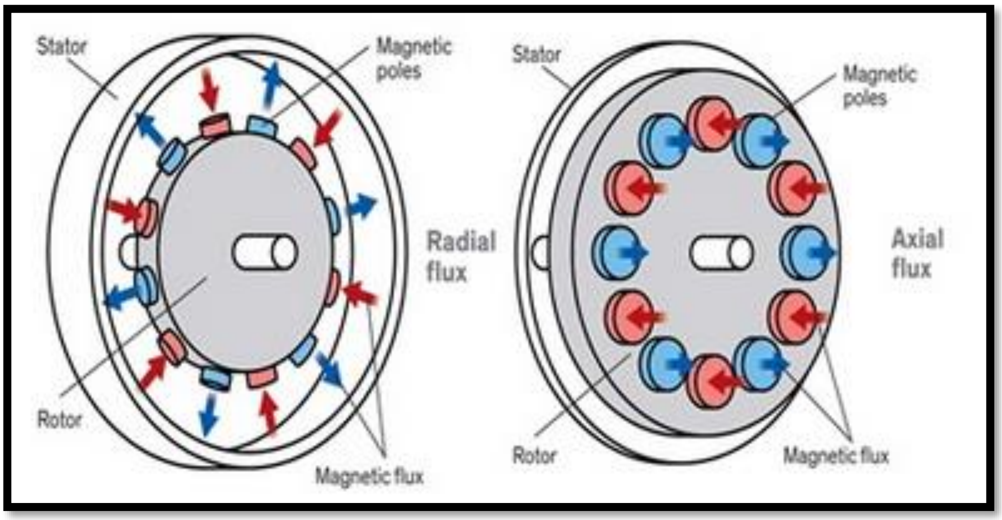


Figure 33 Breakdown of an axial flux motor

Axial flux permanent magnet (AFPM) machines are increasingly utilized in diverse applications, attributed to their high specific torque, compact pancake-shaped profiles, and adaptable topology. In a configuration featuring dual rotors with facing permanent magnets of opposite polarity, the magnetic flux directly

transfers from one rotor to the other, negating the need for circumferential passage through the stator core. This design eliminates associated losses and cogging torque but increases the electromagnetic air-gap. Furthermore, axial flux machines have an important advantage compared to radial machine in term of winding. It has a higher active winding copper and less overhang which means more ability to increase the number of turns and less heat caused by end effect. Moreover, winding can be in contact with aluminium which is good heat conductor. This means an easier cooling system. The heat in a radial machine should be evacuated through the stator core made of steel that has a low thermal conductivity. In conclusion axial flux motors appear to be an excellent choice for Inertial Stabilization Platforms (ISPs) due to their high torque density, compact form factor, and efficiency. Their unique disc-like structure allows for a reduced size and weight, which is crucial in applications where space and weight are at a premium. Moreover, the absence of a stator core in some designs eliminates core losses, contributing to higher efficiency. These features make axial flux motors particularly well-suited for ISPs, where high performance, reliability, and efficiency are essential. Overall, their advanced design and capabilities make them a compelling option for next-generation ISPs.

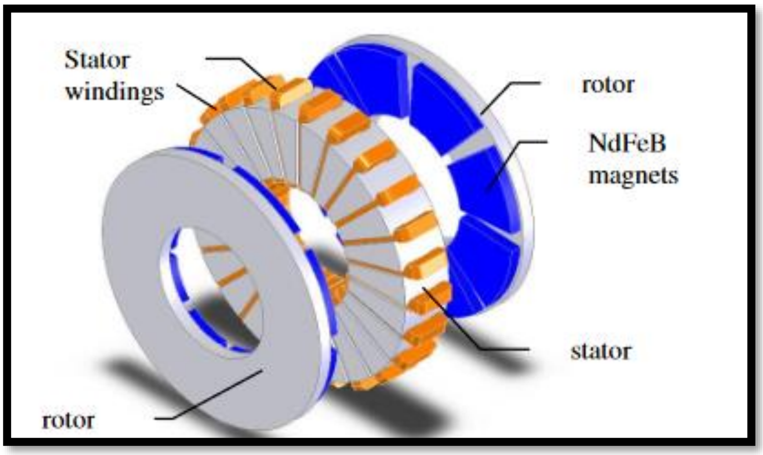


Figure 34 a 24-slot 8-pole dual-rotor single-stator AFPM

2.9 Conclusion

In conclusion, this literature review has provided a comprehensive overview of the various components and considerations involved in gimbal systems, with a particular focus on Inertial Stabilization Platforms (ISPs). Starting from an overview of gimbals, we delved into the essential components such as the gimbal payload, IMU, bearings, motors, and encoders. The operating principles were discussed to understand the mechanics of gimbal systems, followed by an examination of the causes of disturbances that could affect performance. Structural considerations like part bending, torsional interactions, and mounting stiffness were also explored to understand their impact on system integrity. The literature review also delved into the kinematics of gimbal systems and offered a detailed analysis of drivetrains, encompassing a range of drive systems and motor types. This body of knowledge serves as a cornerstone for those engaged in the engineering, functioning, and fine-tuning of gimbal mechanisms, especially within the scope of Inertial Stabilization Platforms.

3. Gimbal Specifications

The literature review outlined in Chapter 2 was instrumental in formulating a detailed set of system specifications for the project. Originating from a collection of qualitative performance criteria, these quantitative specifications were designed to meet the project's initial objectives.

Upon revising the project to more closely approximate its initial aims via a cost-effective system amenable to future expansion, these specifications evolved into aspirational design goals. These goals subsequently guided the design choices elaborated in Chapters 4 through 7. To preserve the coherence of this document, only the finalized specifications are included here.

3.1 Purpose of the product

The initial objectives of this project focused on the design, simulation, implementation, and testing of a robust multi-axis ISP (Image Stabilization Platform) to enable precise c tracking of celestial objects via an optical telescope mounted on a drone. The project encompassed the development of all associated subsystems, including the electro-mechanical assembly of the ISP, the control algorithms, and the electronic interfaces.

The system's primary function is to facilitate automatic tracking of celestial bodies using an optical telescope mounted on the drone. The aim is to ensure high-quality celestial observations by mitigating the disturbance torques imparted on the imaging sensor due to the drone's motion. Accordingly, the subsequent specifications outline the performance criteria required for the ISP to fulfil this purpose.

3.2 System specifications

The system specifications of the product are largely determined by what is already on the market. Since the product targets to enter a highly competitive and high-end market, the specifications should at least match the most important performance parameters. Due to the focus on being a cheaper alternative to already established products, some parameters might be compromised in order to save some cost.

Table 3-1 will show the typical specifications for a product already on the market.

System specifications of OCTOPUS EPSILON 180 Z

Sensors	MWIR Thermal imager, Day camera, LRF
System type	2 axis mechanical stab. / 3 axis electronical stab.
Az. Coverage	360°
El. Coverage	+80° to -10°
Slew rate	
Encoder resolution	0.01°
Stabilization bandwidth	100Hz
Gyro noise	6 uRad
Stabilization	<50 uRad RMS
Motors	Direct drive
Rating	IP 67
Operating temperature	-40°C to 55°C
Consumption	40W typical / 160W peak
Size	Ø180 mm x 215 mm height
Weight	3,9kg

Table 1 System specifications

The aforementioned specifications directly affect the mechanical design of the ISP system. The payload sensors as well as the mechanical stabilization axes directly affect the size and the weight of the whole system while the rest of the specifications largely contribute to the design being complicated. While Azimuth coverage is 360°, Elevation coverage does not need to have that wide a coverage since directly looking up to the carrier is of no use. Encoder resolution directly affects the choice of angle encoders for the whole system and the motors used by the system are directly coupled to each axis without a gearbox in-between. The most important specifications which have the biggest gravity when it comes to the choice of product is its size and weight. While size does not directly affect the functionality of the product, it indirectly contributes to the increase of weight on a system due to the packaging components needing to be larger.

Figure 35 Octopus Epsilon 180 Z, with its size dimensions.

The mass of an Inertially Stabilized Platform (ISP) holds considerable importance as it directly wields influence over its functionality, particularly in contexts like UAVs where weight is a critical factor. A heavier ISP not only engrosses a larger share of the available payload capacity but also demands more energy for its operations and stabilization, thus impacting the system's overall energy efficiency and potentially diminishing its flight endurance. This additional weight can also hamper the platform's ability to swiftly respond, a crucial aspect for rapid target acquisition and tracking. Furthermore, increased weight introduces elevated levels of vibration and noise, which can adversely affect the quality of collected data or imagery. It also imposes additional mechanical strain on crucial components like bearings, motors, and actuators, potentially shortening their operational life and reliability.

Moreover, the ISP's weight extends its influence to other facets of the entire system. For instance, a heavier ISP might compromise the manoeuvrability of the airborne vehicle, making it less agile and more challenging to control. It also perturbs the system's equilibrium and centre of gravity, factors of utmost importance for maintaining stable flight conditions. Additionally, bulkier ISPs may necessitate more robust cooling mechanisms, further augmenting the system's mass and intricacy. The financial implications are substantial as well, as the utilization of heavier materials and the need for additional power resources can inflate the overall cost of the system. Hence, strategies for weight reduction, such as the incorporation of lightweight materials and the application of advanced design algorithms, are typically integral components of the ISP design process.

4. Components selection

In Chapter 2.3, the foundational elements of an Inertially Stabilized Platform (ISP) were examined, elucidating their roles and functionalities within the system. As the discussion progresses to Chapter 4, attention is redirected towards the critical task of component selection, a phase that has a substantial impact on the ISP's performance, reliability, and cost-effectiveness. This chapter aims to navigate the reader through the various factors and considerations essential for selecting appropriate ISP components, such as motors, bearings, sensors, and actuators.

The choice of each component is not an isolated act but is inherently connected to the overarching system requirements, which include weight limitations, power usage, response time, and environmental conditions. This chapter offers a thorough methodology for component selection, underpinned by analytical models and empirical evidence. The objective is to ensure that the selected components not only meet individual specifications but also function cohesively to optimize the overall system performance. The chapter aims to provide the reader with the requisite knowledge and tools for making informed decisions in the intricate task of ISP component selection.

Regarding the mechanical design of the product, some of the components have a critical role in the implementation of the whole system. The most important parts include machine elements like bearings, the actuator assembly as in the motor and its suitable reduction, as well as electronical components such as the controller and the angle encoder. Some of the performance specifications of the target product boil down directly to the performance of the components chosen (such as the angle resolution of the encoder), while some others depend on the whole assembly performance parameters such as weight, stiffness, dimensions, inertia and so on. The selection of those components is based on a feedback loop with the whole design of the system, as while the system evolves and changes parameters the elements have to be verified again to confirm their selection.

In the forthcoming component selection phase, initial attention will be given to components not strictly governed by overarching system parameters. This strategy affords greater flexibility, facilitating the identification of components that perform optimally across diverse system configurations. These initial choices will subsequently act as the basis for selecting more constrained components, thereby contributing to an efficient and cohesive system design.

4.1 Controller

The controller functions as the central hub of the inertially stabilized platform (ISP), coordinating the complex interactions among various components to achieve the targeted system performance. It is instrumental in ensuring that the gimbal system responds both accurately and efficiently to external stimuli and disturbances. The architecture and algorithms of the controller directly affect the system's capabilities in maintaining a stable line-of-sight, tracking targets, and correcting errors, thereby significantly influencing the ISP's overall effectiveness in mission-critical operations.

Given the controller's central role, its selection transcends a mere technical requirement and becomes a strategic decision with considerable impact on the system's operational capabilities. The type of controller selected dictates the range of algorithms and control strategies that can be employed, effectively setting the performance ceiling for the system. This section will examine the criteria for controller selection, considering factors such as computational power, latency, and component compatibility, to ensure the controller is optimally suited for the specific application requirements.

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Figure 36 [redacted], standard controller for UAV gimbals (Electronics, n.d.)

The [redacted] controller provides a comprehensive feature set, making it a suitable choice for advanced gimbal systems. A key feature is its high-power motor drivers, capable of delivering up to 13A per motor. This enables the use of robust motors that can accommodate camera systems weighing between 5 to 50 kg, enhancing the controller's versatility across applications. The controller also integrates DC regulated power supplies at both 5V and selectable 12V or 14.8V, simplifying power management for additional video equipment such as cameras, transmitters, and converters. Additionally, it incorporates protection mechanisms like overcurrent, short-circuit, over-temperature, and under-voltage safeguards, ensuring reliable and safe operation.

The modular design of the controller, which includes a power board, logic board, and interface board, allows for significant customization flexibility. This adaptability enables the controller to be fine-tuned according to specific product needs. These features, along with its current and voltage sensing capabilities for precise power monitoring, make [redacted] controller a robust and adaptable option for an advanced inertially stabilized platform.

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Figure 37 Top view of logic board of the [redacted] *(Electronics, n.d.)*

From the logic board diagram in Figure 24 and Figure 25, it can be deduced that this particular controller gives many opportunities and liberties to the designer. By having a separate interface for the IMU instead of having it integrated in the design it gives the ability to the system to take a strapdown configuration as discussed in 2.3.5 by directly communicating with the IMU of the given carrier vehicle. Furthermore, the controller is compatible with SPI communication-based encoders. SPI (Serial Peripheral Interface) is favoured in gimbal control systems due to its high data transfer rates, full-duplex communication, and robust noise immunity. Its capability for simultaneous data transmission and reception enables real-time control and rapid sensor data acquisition, essential for the precise and stable operation of gimbals. The simple hardware interface and separate slave select lines for each device further simplify system design and troubleshooting. As can be seen inFigure 39 Power supply unit of the [redacted] controller Figure 26 the controller also has room for 3 motors which gives some flexibility in the design phase as more than one control motors can be used in any of the mechanically stabilized axes.

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Figure 38 Bottom view of the Logic board of [redacted] *(Electronics, n.d.)*

[redacted]

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Figure 39 Power supply unit of the [redacted] *controller*

To summarize, the [redacted] controller is a strategically sound choice for the inertially stabilized platform (ISP) due to its robust and adaptable features, as well as its compatibility with sophisticated control algorithms. The controller is equipped with high-power motor drivers and integrated DC power supplies, making it a reliable and versatile option for diverse applications. Its modular structure allows for extensive customization, aligning well with the specific needs of the ISP. The controller's support for SPI communication and a dedicated interface for the IMU enable real-time control and quick data acquisition, both crucial for optimal system performance. The ability to support multiple motors adds another layer of design flexibility. Overall, the BaseCamBGC Pro controller not only meets but could exceed the technical requirements for an advanced ISP, making it a strong candidate for achieving the desired system performance.

4.2 Angle Encoder

Angle encoders, as already introduced in 2.3.5, are critical devices that measure the angular position of a rotating shaft and convert this data into an electrical signal for a control system. They are essential in high-precision, fast-response applications like robotics, aerospace, and ISPs. Available in various types such as optical, magnetic, and inductive, each with its own pros and cons, these encoders are vital for the accurate control and stabilization of ISPs. They act as specialized sensors, converting angular positions into digital or analog signals for the control system. Their accuracy and resolution are key factors in an ISP's ability to maintain stable orientation, particularly when subjected to external disturbances like wind.

In ISPs, angle encoders are commonly used in gimbal systems for feedback control. They maintain the orientation of payloads like cameras or sensors by providing real-time angular data to the controller. This enables the controller to adjust motor positions to counter undesired movements, forming a closed-loop control system. This mechanism is crucial for ISPs in applications such as aerial photography and surveillance. Therefore, the choice of angle encoder is not just a component selection but a strategic decision affecting latency, accuracy, and power consumption in ISP design and performance optimization.

4.2.1 Types of angle encoders

Optical encoders

The optical encoder is a commonly used transducer for gauging rotational motion. It features a shaft linked to a circular disc that has one or more tracks with alternating transparent and opaque segments. A light source and an optical sensor are situated on opposite sides of each track. As the shaft rotates, the sensor produces a series of pulses when the light from the source is interrupted by the disc's pattern. This output signal is directly compatible with digital circuitry. Given that the number of output pulses for each disc rotation is known, these pulses can be directly converted to the shaft's rotational speed in rotations per second. Optical encoders are frequently used in applications for controlling motor speed. Figure 19 illustrates a basic, single-track encoder wheel. (Austerlitz, 2003)

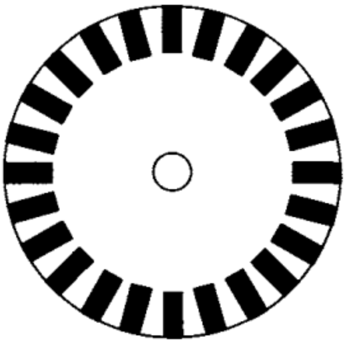

Figure 41 Simple one-track optical encoder wheel (24 positions = 360/24 =15° Resolution) (Austerlitz, 2003)

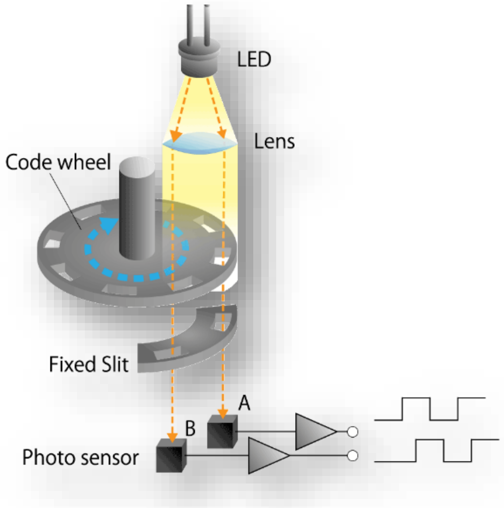

Figure 40 Operation principle of optical encoder (KASEI, n.d.)

These sensors typically have high resolution, which is defined by the number of signals emitted during one complete axis rotation. They are also highly accurate, with the accuracy being determined by the tolerance level for each emitted signal. Additionally, they possess quick response times. Optical position sensors are particularly useful in applications requiring high accuracy, such as the production of electrical components or medical analysis equipment. (Choosing the right position sensor, n.d.)

Inductive encoders

The inductive encoder's role is to detect linear or rotational movement relative to a target. This sensor responds to ferromagnetic or electrically conductive metals in the target. It includes a transmitting coil and four receiver coils, generating an electromagnetic field. When a copper object enters this field, the receiver coils detect the change and convert it into a digital output signal representing movement. The encoder moves over a target with copper markings in a specific pattern: each marking is two-thirds the width of the following gap, defining the period length. This movement is converted into an analog signal, shaped like sine and cosine waves, and then digitized into a square wave. Interpolation refines the large period step of 1.2 mm into smaller digital steps, achieving resolutions even smaller than 1 µm with an inductive encoder.

Inductive encoders offer several advantages that make them a suitable choice for various applications, whether rotary or linear. Their compact design, with a maximum length of 11 mm and thickness of 0.9 mm, allows for easy integration into space-constrained designs. They provide high-accuracy measurements down to the micrometer level, thanks to their high resolution, which can be further enhanced through interpolation. The encoders are also resistant to external electromagnetic interference due to their differential receiver coils, making them ideal for use in electric motors. They operate effectively in a wide temperature range from -40 to 125°C, eliminating the need for additional protective measures against heat. Furthermore, their insensitivity to contaminants like dust, moisture, and oil makes them robust and versatile, especially in polluted environments.

Figure 42 Operation principle of inductive encoders

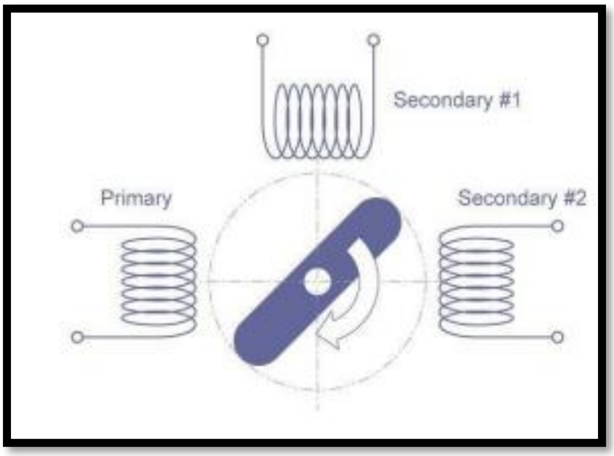

Figure 43 Incoders, Inductive Encoders by Zettlex

Hall effect encoder

Hall effect encoders utilize magnetic phased arrays with hall sensor elements aligned to a magnetic wheel. When the sensor crosses the magnetic field, a signal is generated and then interpolated to the desired resolution. The technology is now integrated into a single IC chip, reducing component count and simplifying board design.

Magnetic Hall Phased Array technology is currently the forefront of magnetic encoder technology. These encoders are notably robust due to their inductive nature, eliminating the need for bearings and thus a potential failure point. The internal electronics are encapsulated, making them resilient to environmental factors like dust and moisture. Therefore, they can operate in harsh conditions without additional protection.

These encoders are specifically designed to meet the rigorous demands of applications requiring broad operational temperature ranges, high resistance to shock and vibration, and strong protection against contaminants. The primary design objective is to maintain reliable and accurate output signals, even under challenging conditions. As a result, these encoders are particularly well-suited for industries operating in extreme environments, such as construction sites with heavy machinery, agricultural areas with varied terrains, and mining locations that are often remote and harsh. They are also ideal for forestry settings where equipment is exposed to the elements and for the food and beverage sector, which often requires washdowns or involves corrosive chemicals. In all these industries, the encoders go beyond basic functionality to offer enhanced durability, reliability, and reduced maintenance downtime. (Dynapar, n.d.)

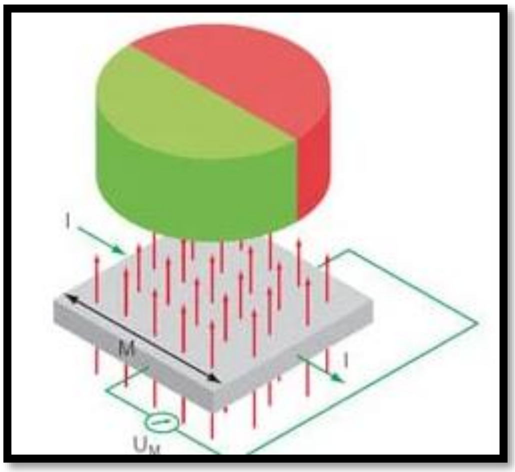

Figure 44 Magnetic hall effect encoder. (Dynapar, n.d.)

Encoder Requirements

The selection criteria for an angle encoder in our inertially stabilized platform (ISP) are primarily dictated by the objectives specified in Table 1**3.2**. The encoder must provide a resolution that aligns with the system's performance targets, ensuring precise and reliable angular measurements. Given the weight considerations of ISPs, especially when used on aerial platforms, a lightweight encoder is preferred. A compact design is also advantageous to reduce the encoder's spatial footprint within the gimbal assembly. These criteria are designed to enhance the encoder's role in overall system performance while complying with design constraints.

As mentioned in Table 1 the target encoder resolution is 0.01°. Most high-end encoders measure their resolutions in bits of information in a circle, or in other words number of divisions in 360°. Thus, the target resolution is

$$\frac{360^o}{0.01^o} = 36{,}000\ divisions$$

A bit, short for "binary digit," is the most basic unit of information in computing and digital communications. It can have one of two values, commonly represented as 0 or 1. In the context of digital systems, bits are used to represent a variety of data types and are fundamental to processes such as encoding, encryption, and data compression. Since bits have two states, either 0 or 1, a bit can give 2 pieces of information, or rather 2 division of a circle. Two bits can give 2 * 2 bits of information, so 4 divisions and so on. In order to have at least 36000 divisions

$$2^x \geq 36000 => x \geq \log_2(36000)$$

$$x \geq 15.136\ , \qquad x \in \mathbb{N}$$

$$x = 16\ bits$$

So the target encoder resolution should be at least 16 bits.

Constraints

Constraints in this case take form of geometrical constraints. Due to the nature of the encoders, their mountings can only be done in a way so that they directly measure the rotation between two bodies in a given axis. This means that the encoder should be coaxial to the rotational axis. Encoders can come either with an inner diameter if clearance or just in the form of a disc rotation without an internal clearance. However, seeing as the wiring for the whole system can only go through the axis of rotation, there has to be enough clearance for the wires to pass through. For conceptual reasons, after revising the wires that will connect to the controller as well as all the wires of the optical payload, 15mm of clearance should be taken as the initial minimum dimension given to the Inner Diameter of each component that is part of the area of interest.

Candidate encoders

Out of the various angle encoders reviewed in the market, a specific choice was made to focus on encoders that are explicitly designed for low-profile and high-accuracy applications. These specialized encoders are engineered to meet the stringent requirements of systems that demand both compact form factors and exceptional resolution. The decision to concentrate on this subset of encoders aligns with the project's objectives, ensuring that the selected encoder will be optimally suited for the unique challenges posed by our application. This targeted approach to encoder selection is crucial for achieving the desired system performance while adhering to the design constraints. These candidate encoders are shown in

Manuf.	*Model*	***OD (mm)***	***ID (mm)***	***Width (mm)***	***Weight (grams)***	***Resolution (bits)***

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Table 2 Angle encoders

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[redacted] are manufacturers that offer encoders meeting the project's criteria for low profile and high accuracy. The [redacted] (Inductive encoder) series from [redacted] and various encoder options from [redacted] have been identified for further evaluation. These encoders align with the project's specific requirements and will be central to the forthcoming selection process.

Technical review table

A technical review table is an organized framework designed for the systematic assessment and comparison of various products, components, or solutions, based on established criteria. The table is structured with rows and columns, where each row signifies a specific product or component under evaluation, and each column represents an attribute or feature considered important for the project. The table incorporates a numerical scoring system to quantify the performance of each product or component in relation to each feature. The inclusion of weighting coefficients to the scores serves to emphasize the varying significance of each feature. This structured approach provides an objective basis for comparison, allowing decision-makers to make empirically informed choices. (Stergiou, 2003)

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Figure 45 [redacted]

Figure 46 [redacted]

The initial pool of encoders was filtered by using the two most important criteria, them being high resolution and a relatively compact size. First, only models with a resolution equal to or greater than 16 bits were considered. Second, encoders with an outer diameter (OD) exceeding 100 mm were excluded. These initial filters ensured that the encoders that would be reviewed would certainly be fit for the application while also excluding encoders that would seem perfect for the application but they would require a compromise in the design.

In the forthcoming technical review table Table 4, each essential attribute of the angle encoders under consideration will be given an importance coefficient. This numerical value quantifies the relative importance of each feature in relation to the specific needs of our application. The encoders will be assessed based on these weighted attributes, offering a holistic evaluation that extends beyond basic technical specifications. This systematic methodology allows for a detailed comparison, incorporating multiple factors such as resolution, weight, profile, and cost-effectiveness. The table is designed to provide a structured framework for encoder selection, ensuring that the chosen encoder satisfies both the technical criteria and the broader objectives of the overall system.

Manuf.	*Model*	***OD (mm)***	***ID (mm)***	***Width (mm)***	***Weight (grams)***	***Resolution (bits)***

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Table 3 Candidate encoders. These are encoders that are specifically manufactured for low profile and high accuracy applications and marketed towards gimbals

Feature	Importance	Optimal
OD	4	Lowest
ID	2	Highest
Width	5	Lowest
Weight	5	Lowest
Resolution	Not Needed	Highest

Table 4 Feature Gravity/Importance table

The gravity G assigned to each feature of the encoder is not derived from a mathematical equation but is empirically determined on a scale of 1 to 5. This relative importance level serves as a weightage factor, indicating how crucial a particular feature is in deeming an encoder suitable for the project. The higher the importance level, the more influence that feature will have in the overall evaluation and selection process. Furthermore, each encoder will undergo a thorough review to assess its performance in each designated feature. Based on this evaluation, a composite score will be calculated that takes into account the weighted importance of each feature. This approach will culminate in a comprehensive diagram that visually represents the overall effectiveness of each encoder, factoring in its performance across the weighted features. This diagram will serve as a valuable tool for making an informed selection.

During the encoder selection process, various attributes were evaluated based on their relevance to the project's goals. These attributes were assigned weight values determined empirically. Specifically, Outer Diameter (OD) was given a weight of 4, Inner Diameter (ID) a weight of 2, and both Width and Weight were assigned the highest weight of 5. The rationale for these weight assignments is as follows: OD and Width directly affect the available space for other components, potentially requiring an increase in the gimbal's overall size. ID is less critical, as it only needs to be sufficient to accommodate wiring. Weight is of the highest importance, as it directly impacts the payload and, consequently, the gimbal system's performance. To assess each encoder's suitability, a technical review table will be constructed. In this table, each encoder will be scored based on its performance in each attribute, considering the weighted importance of that attribute. These scores will be aggregated to provide an overall performance metric for each encoder, allowing for a nuanced comparison and facilitating an informed selection process.

Now to give each encoder a scoring, their performance in each feature also needs to be evaluated. Taking the Outer diameter of each encoder for instance, firstly we understand which encoder is best at this feature. The lower the OD the better therefore [redacted] and [redacted] perform the best in this regard with 60mm each. On the other hand [redacted] and [redacted] perform the worst. Now these measurements need to be processed into a dimensionless scoring number again out of 5 for simplicity's purpose. The worst performing product will receive a score of 1 and the best a scoring of 5. To do this process the measurements need to be linearly interpolated:

Example.

Product	OD (mm)	Scoring
[redacted] (Minimum OD)	60	5
[redacted]	70	Y
[redacted] (Maximum OD)	100	1

$$Y = Score_{max} + \frac{(OD - OD_{min})}{OD_{max} - OD_{min}}(Score_{min} - Score_{max}) = 5 - 4 * \frac{10}{40} = 4$$

$$Y = 4$$

Product	OD score	ID score	Width score	Weight score	Overall
Gravity	4	2	5	5	-
[redacted]	4,0	1,6	3,5	4,2	3,6
[redacted]	2,0	4,1	3,5	4,0	3,4
[redacted]	5,0	1,3	3,5	4,4	3,9
[redacted]	1,0	5,0	3,5	2,2	2,7

[redacted]	5,0	1,0	5,0	5,0	4,5
[redacted]	3,0	2,3	4,8	4,9	4,0
[redacted]	3,5	1,0	1,0	2,1	2,0
[redacted]	2,0	2,9	1,0	1,6	1,7
[redacted]	1,0	4,1	1,0	1,0	1,4

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Figure 47 [redacted]

Figure 48 [redacted]

The technical review table has revealed that [redacted] series of encoders emerge as the most suitable candidates for our specific application requirements. These encoders not only meet but exceed the performance criteria set forth, particularly excelling in areas such as resolution, low profile, and weight, which are critical for the success of our project. The [redacted] series also aligns well with the system parameters and design constraints, offering a level of compatibility that significantly simplifies the integration process. Given these advantages, the decision has been made to proceed with [redacted] encoders for the subsequent phases of the design and development. This choice is not merely a technical requirement but a strategic decision that is expected to positively impact the overall performance and reliability of the inertially stabilized platform. Therefore, all future design considerations, component selections, and system optimizations will be conducted with the integration of [redacted] encoders in mind.

Product	Overall
[redacted]	4,5

[redacted]	4,0
[redacted]	3,9
[redacted]	3,6
[redacted]	3,4
[redacted]	2,7
[redacted]	2,0
[redacted]	1,7
[redacted]	1,4

Table 5 Technical review table

5. Drivetrain

The drivetrain, also known as the power transmission system, is a key assembly in mechanical systems, responsible for channeling energy from its source to a designated endpoint where it performs useful work. Composed of gears, belts, shafts, and couplings, the drivetrain functions as the medium for transmitting mechanical power and torque. It is meticulously engineered to maximize the efficiency and accuracy of energy transfer under diverse operational conditions. The drivetrain's components and configuration are specifically tailored to fulfil particular performance criteria, including rotational speed, torque, and directional control. The design of this system is critical for the overall efficiency and effectiveness of any mechanical system, and this is especially true for inertially stabilized platforms (ISPs), where precision control and reliability are paramount.

5.1 Existing technologies

In the context of Inertially Stabilized Platforms (ISPs), the primary criterion for drivetrain selection is having enough torque to mitigate the torque disturbances. Torque is a critical variable that directly influences both performance and efficiency. Therefore, it is essential to choose a drivetrain capable of delivering the requisite torque for optimal system functionality. Too little torque and the system becomes unstable, too much of it means that size can be cut down.

Another crucial factor is the minimization of drivetrain weight and volume. A lighter, more compact design is particularly beneficial in ISP applications where space is constrained or portability is required. Reducing these dimensions can also improve overall system efficiency by lowering the energy needed to move the components. However, while torque, weight, and volume are important, they should not overshadow the need for accuracy. Precision is often

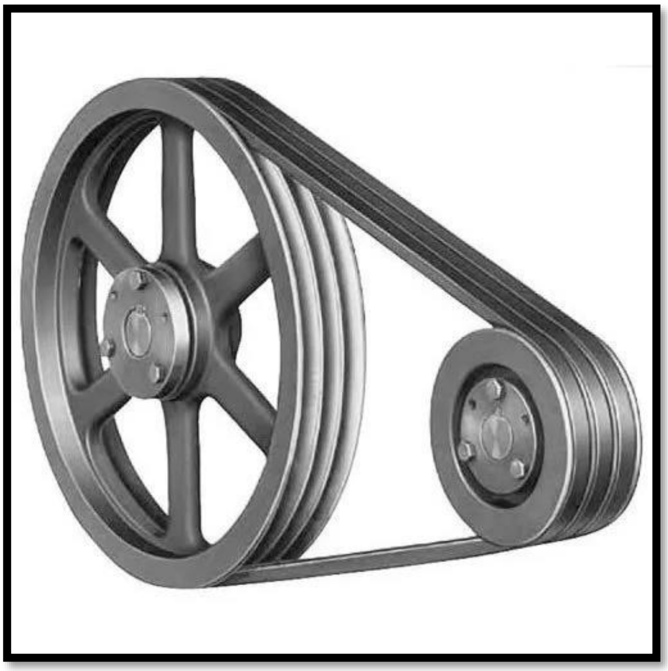

Figure 49 A power transmission assembly consisting of a belt and a pulley system of two sprockets`

vital in ISP applications, and the selected drivetrain must offer the necessary accuracy to ensure the system performs as intended.

To identify the most suitable drivetrain configurations for our application, it's essential to conduct a comparative analysis based on the criteria outlined in Chapter 2.8. Specifically, we need to evaluate various drivetrain options in terms of torque density, accuracy, weight, and other relevant factors. By doing so, we can ensure that the chosen drivetrain not only meets the torque requirements but also aligns with other critical considerations such as weight limitations and the need for precision. This comprehensive approach will enable us to select a drivetrain that offers the best balance of these key attributes, thereby optimizing the overall performance and efficiency of the system.

Belt drives

For our ISP application, belt drives do meet the torque requirements, making them a viable option from a performance standpoint. However, the design of belt drives necessitates additional volume, which could be a significant drawback when space is limited and ought to be exploited to maximum. This extra volume is often due to the pulleys and tensioning systems required for effective operation. Furthermore, the inclusion of these additional components not only consumes space but also adds to the overall weight of the system. This weight increase could be a critical factor, especially in applications like ISPs where payload weight is a key consideration. Therefore, while belt drives offer adequate torque, their spatial and weight demands may make them less ideal for our specific needs.

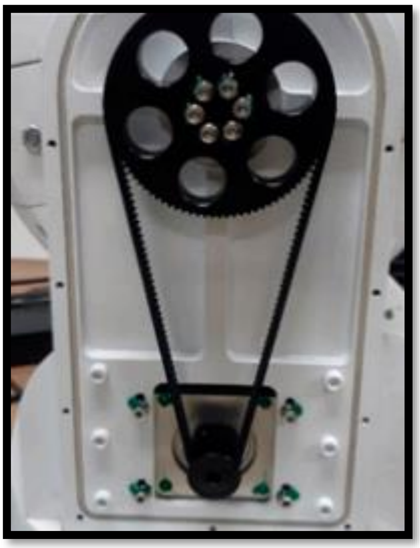

Figure 50 A belt drive system utilized in a naval applications' ISP (Hwan-Cheol Park)

Planetary Drives

A planetary gear system presents several advantages that align well with our application needs, most notably its high torque density and the ability to achieve high reduction ratios in a relatively compact form factor. This aligns well with the requirements we have set regarding the tight spaces in the system. However there are also reason to not choose a planetary gear system. The system tends to be heavier than other gear systems like direct gear coupling, which could be a concern given our weight constraints. Additionally, planetary gear systems are generally more expensive, which could impact the overall budget for the project. Another technical limitation is the presence of backlash, which could affect the system's accuracy and precision. Therefore, while a planetary gear system offers some compelling benefits, these advantages must be carefully weighed against its drawbacks in terms of weight, cost, and backlash.

Harmonic drives

Harmonic drives stand out as a potentially excellent choice for our application due to their exceptional torque-to-volume ratios. Some designs even boast ratios as high as 100:1, making them one of the most efficient options in terms of space utilization and torque output. This could be particularly beneficial for our project, where both torque requirements and spatial constraints are critical factors. Although its important to note that Harmonic drives are generally on the more expensive side, which could have budgetary implications for the project. Therefore, while they offer outstanding technical advantages, the financial aspect of using harmonic drives must be carefully considered. The geometry needed

Direct drive

While direct drive systems may not excel in torque density compared to planetary or harmonic drives, they offer unique design flexibility. Unlike other systems with fixed structures, direct drive systems allow for custom housing tailored to project-specific needs. This enables innovative design approaches and the incorporation of additional components, which may be restricted with other drive types. The adaptability of the housing also enhances space efficiency, critical in applications with volume constraints. This flexibility makes direct drive systems particularly advantageous for projects with specialized or complex design requirements, including Inertially Stabilized Platforms (ISPs).

Figure 51 Direct Drive Frameless motors made by AHS

System	Torque	Accuracy	Weight	Volume	Torque/Volume	Overall
Belt Drive	+++	++	++	+	++	++
Planetary	++++	++++	+++	++++	++++	++++
Harmonic	+++++	+++++	+++	+++++	+++++	++++
Direct Drive	+++	+++++	+++++	+++++	++++	+++++

Being frameless, the absence of a predefined housing in direct drive motors offers a distinct advantage in terms of design flexibility. This characteristic allows for greater adaptability in system configuration, potentially leading to a more compact assembly in comparison to traditional shafted motor systems. The design flexibility inherent in direct drive motors is notably advantageous in applications with spatial constraints, such as Inertially Stabilized Platforms (ISPs). Engineers have the capability to develop custom housings that are specifically aligned with the project's unique requirements and limitations, thereby enabling a more seamless incorporation of the direct drive motors into the overarching system architecture. This adaptability not only maximizes the use of available space but may also contribute to minimizing the system's overall footprint, thereby enhancing system efficiency.

In subsequent analysis, a detailed comparison matrix will be presented, evaluating various drivetrain systems against essential performance metrics such as weight, accuracy, and torque density. This matrix is designed to serve as an instrumental resource for assessing the comparative merits and limitations of each system, thereby aiding in the judicious selection of the most appropriate drivetrain for specific applications. The intent is to offer a clear, immediate understanding of each system's performance in relation to these key parameters, thereby rendering the decision-making process more efficient and grounded in empirical data.

The comparison table has been constructed based on the various drivetrain systems and key performance indicators that were previously discussed. It serves as a synthesized summary, allowing for an easy and informed comparison of each system's weight, accuracy, and torque density. This table aims to streamline the decision-making process by offering a clear, data-driven overview of how each option aligns with the project's specific requirements.

In applications where precision and compactness are not primary concerns, belt drives are frequently employed. However, for the specific requirements of this project, they present several limitations. The inclusion of a belt to connect two gears inherently results in unutilized volume within the mechanical assembly, a significant drawback in scenarios where spatial optimization is imperative. Moreover, the mass of the belt itself can contribute disproportionately to the total system weight, further compromising its efficacy for this application. Consequently, due to these constraints in volumetric utilization and weight contribution, belt drives are not the optimal choice for the current system under investigation.

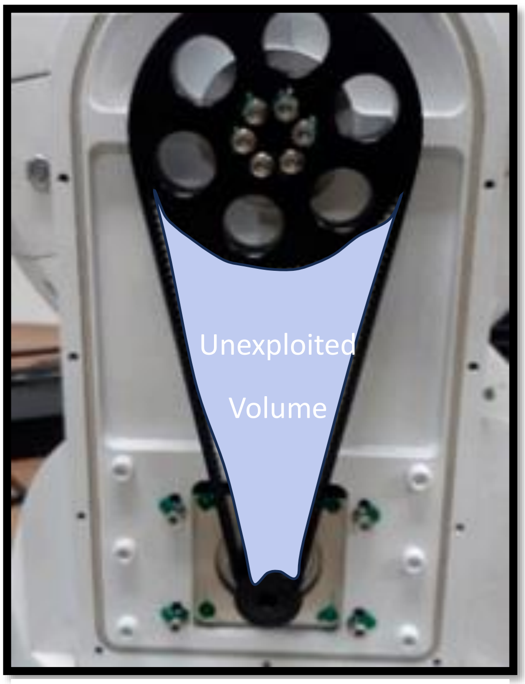

Figure 52 Belt driven gimbal

Planetary gear systems offer notable advantages, particularly in the context of torque density and reduction ratios. Their design allows for substantial torque output and high reduction ratios within a relatively compact spatial envelope. However, these systems are not without drawbacks. The intricate architecture, which necessitates the fabrication of a minimum of five distinct gears, results in elevated manufacturing costs. Additionally, the utilization of steel gears contributes to a higher overall mass, which may be a limiting factor in certain applications. Contrary to common claims of zero backlash, planetary gear systems do exhibit some degree of backlash, which compromises their suitability for applications demanding high levels of precision, such as Inertial Stabilization Platforms (ISPs).

Harmonic drives are highly versatile and can be employed in a wide array of applications that demand compact size, minimal weight, absence of backlash, exceptional precision, and robust reliability. They are commonly used in sectors ranging from aerospace and robotics to medical imaging and semiconductor manufacturing. Noteworthy historical applications include the wheels of the Apollo Lunar Rover and the winches of the Skylab space station. While harmonic drives offer numerous advantages that make them a compelling choice for our Inertial Stabilization Platform (ISP), it's important to consider that they have significant system weight and that it the high reduction rates and torque density offered by harmonic drives may be more than sufficient for mitigating torque disturbances in an (ISP).

Direct drive motors offer a favorable set of characteristics for this application. Their minimal weight is attributed to the inclusion of only essential motor components, making them highly advantageous for scenarios requiring compact solutions. The precision of these motors is closely linked to the specifications of the accompanying encoder, providing the capability for precise control. Furthermore, the absence of a housing in these motors offers considerable flexibility in design configurations. Based on these attributes, the design strategy will focus on the utilization of direct drive motors.

5.2 Choice of motors

As discussed in (Hilkert, 2008), the primary concern to have when choosing a motor is for its torque to be enough to mitigate the torque disturbances. The problem with that is that torque disturbances come from countless sources, sources that can be numericized and analysed with software like the torque applied on an axis due to eccentricity of the center of mass and a given platform acceleration, or sources that can't be taken into account before a lab experiment has been made.

Therefore, the choice of motors will be made by our set specification of the gimbal which was made in Chapter 3.2, the slew rate. The slew rate being 360°/s means the gimbal has to be able to turn a whole circle in one second, therefore we can create a rough model of the gimbal with a simple payload inside to give the system inertia in order to find the required torque to accelerate the system and stop it into position in one second. Once all components have been selected, this method can confirm that our choice was right.

Celera motion offers a freely available catalogue to their Direct Drive products therefore the initial choice will be made based on their catalogues. They manufacture three different types of direct drive motors. The [redacted] and [redacted] series are both made for mid to high torque output range, and feature an inner rotating rotor which means lower inertia. [redacted] on the other hand has the rotor on the outer ring which might mean more inertia but also means that there can be more magnets fitted on the rotor which might increase the torque density and output of the motor. In the next table we will compare the most basic features of each motor

Manufacturer	Model	OD (mm)	ID (mm)	Width (mm)	Weight (g)	St. Torque (Nm)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

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Upon examination of the comparative table, it becomes evident that the majority of motor options exhibit relatively low torque output. However, this level of torque may be sufficient for the specific requirements of the application. Weight is another critical factor to consider; motors such as [redacted] and [redacted] are eliminated from consideration due to their excessive weight. Additionally, the motor should possess an inner diameter of at least 15mm to accommodate wire clearance. Among the available options, the [redacted] motor emerges as the most viable candidate. Its design, which features an outer ring rotor, offers increased flexibility in design configurations. Therefore, based on these criteria, the [redacted] motor appears to be the most appropriate selection for this application.

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Figure 53 [redacted], the outer ring rotor direct drive motor

The utilization of an externally rotating rotor in the motor design offers several distinct advantages. Primarily, the external rotor configuration allows for the incorporation of a greater number of magnets along the rotor's circumference. This results in an enhanced torque output for a given current, thereby increasing the motor's torque density and making it more compact compared to alternative designs. Additionally, the presence of an inner ring stator provides certain benefits, such as creating a stationary interface between the rotor and the electrical wiring. This stationary interface significantly mitigates the risk of mechanical damage to the wiring, which could otherwise occur due to the relative rotational motion between the rotor and the wiring. Given these considerations, the selection of a motor with an external rotor and an inner ring stator appears to be highly advantageous for this particular application. The next phase of this study will focus on the selection of an appropriate bearing system, following which a prototype will be developed for further evaluation and testing.

5.3 Choice of bearings

In the process of selecting appropriate bearings for Inertial Stabilization Platforms (ISPs), several pivotal factors warrant meticulous consideration to assure optimal performance and reliability. Foremost among these considerations is the load-bearing capacity, which must be engineered to accommodate both static and dynamic loads exerted by the system. Additionally, it is essential that the selected bearing exhibits low frictional characteristics to mitigate energy dissipation and thermal generation, as these factors could adversely affect the system's operational efficiency and durability.

Material selection is another crucial aspect; the bearing material should exhibit high wear resistance and low coefficient of friction while being compatible with the operating environment, which may include exposure to extreme temperatures or corrosive substances. The precision and accuracy of the bearing are also vital, especially in ISPs where even minute angular misalignments can result in significant errors in stabilization and positioning.

Speed capability is another factor, as ISPs often require rapid adjustments to maintain stability. Therefore, the bearing should be capable of operating at high rotational speeds without experiencing fatigue or failure. Lubrication requirements should also be considered, as inadequate or excessive lubrication can lead to premature wear or increased friction, respectively.

Furthermore, the form factor of the bearing is essential, particularly in ISPs where space and weight are often at a premium. Compact, lightweight bearings are generally preferred to maximize the efficiency and agility of the system. Finally, cost and availability are practical considerations that can influence the choice of bearings, especially in large-scale or budget-sensitive projects.

In summary, the selection of bearings for ISPs involves a multi-faceted evaluation that considers load capacity, friction, material properties, precision, speed capability, lubrication, form factor, and cost. Each of these factors plays a critical role in determining the overall performance and reliability of the inertial stabilization system eloped for further evaluation and testing.

5.3.1 Criteria

When selecting the appropriate bearing for an Inertial Stabilization Platform (ISP), it is essential to align the bearing's radial and axial load capacities with the mechanical requirements of the system. These capacities must be robust enough to withstand both static and dynamic forces encountered during system operation. Concurrently, the design profile of the bearing is a critical factor. A low-profile bearing is preferable, as it contributes to a more compact and efficient system layout, a crucial aspect in this space-limited application. Also, low profile bearings can have be way more light than their normal counterparts and also. Therefore, both load capacity and design profile are key parameters in the bearing selection process for the system.

In table the slimmest bearings manufacturers are presented together with their slimmest product line KDN manufactures bearings that indeed have 2.5mm of width even at diameters up to 170mm

Manuf	Bearing Series	Width (mm)
[redacted]	[redacted] CONFIDENTIAL	[redacted]

[redacted]

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Figure 54 [redacted] *section bearing*

Among its [redacted] bearings, [redacted] produces three distinct categories of bearings: radial, angular contact, and four-point contact. Angular contact bearings excel in axial strength while maintaining low rolling friction, making them ideal for applications requiring robust axial support. Four-point contact bearings offer superior strength in both axial and radial directions but come with the trade-off of increased rolling friction. Radial bearings serve as a balanced option, providing moderate strength in both axial and radial directions while having normal levels of rolling friction. For our purpose, the design prototype will be made using angular contact ball bearings to minimize the friction and therefore the torque disturbances of the system.

6. Prototype design and FEM analysis

In this section, the prototype of the system will be presented, accompanied by a comprehensive static analysis of each individual component. This analysis aims to evaluate the structural integrity, load-bearing capacity, and overall performance of the components under static conditions. The objective is to ensure that each part meets the required specifications and standards for optimal functionality and reliability.

6.1 Full prototype

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Figure 55 Prototype design of the gimbal

In Figure 55 Prototype design of the gimbal the final prototype design of the gimbal is presented. In this figure the final product is seen from an outside point of view with all of its components hidden as it will be when manufactured. The design follows the market standard of a spherical payload-carrying platform being rotated in the elevation axis being supported by two arms In the next sections the prototype will be dissected and all of each main subassembly will be analysed further as well as commented upon.

The Drivetrain System of the whole gimbal comes in at a weight of 2550 grams while the Payload comes at a weight of 1700 grams. The combined weight comes at 4250 grams therefore close to the target set at chapter 3.2.

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Figure 56 Section view of the prototype

Figure 56 Section view of the prototype presents the section view of the prototype where almost every component can be seen. The Drivetrain system of the gimbal can be split into 3 different subsections.

- The pan assembly

The section of the system where all component relating to the azimuth rotation lie. Here components such as the motor, the bearing, the encoders and all parts designed to fit into the subassembly to make it functional are included.

- The tilt motor assembly

This subassembly includes the motor used to rotate the optical payload in the elevation axis, its bearing and all the fittings and components that make it functional, such as the shaft or the housing of the motor.

- The tilt encoder assembly

This subassembly includes the second rotary encoder used to measure the angular rotation of the optical equipment in the elevation axis along with its secondary bearing and of course all the fittings and components used.

6.2 Pan assembly

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Figure 57 Pan assembly

Figure presents the pan assembly. The pan assembly is responsible for the rotation and stabilization of the payload in the Azimuth axis. It consists of one Direct drive motor [redacted], an angular encoder that is [redacted] and one bearing which is [redacted] with a

70 mm inner diameter and 2,5mm width. The design for this subassembly really focused on compactness. The idea was to fit all three components stacked radially with one larger than the other and fitted over it in order for the axial displacement of the subassembly to be minimum. This would likely reduce the overall height of the system as the pan assembly directly adds to the height of the system combined with the diameter of the payload spherical cover. Stacking the components radially wasn't possible as there wasn't enough variety in regards to dimensions to some of the products like the encoder and the bearing. None the less the bearing and the motor are designed to be stacked radially and the encoder only adds 6mm plus 2 mm to either side for clearance. The overall height of the prototype comes to 259mm.

Now to explain how the system works. The whole system is coupled to the carrier vehicle via the Plastic cap by also using rubber isolators or dampers. This is to isolate the system by the UAV's vibrations. The whole system is then held up by the ground flange where the forces are transmitted through the bearing which holds up the rest of the assembly by the Chassis. Between the two rotating systems sealing is accomplished by two metal rings which rotate relative to each other with a dynamic O-ring in between, the two metal rings are manufactured with tight tolerances and four metal ribs help with the concentricity of the two parts.

6.3 Tilt motor assembly

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Figure 58 Tilt motor assembly

The Tilt assembly is responsible for the motion and rotation of the payload on the Elevation axis. The Motor side depicted in figure presents the assembly of the motor used for this purpose. The main load bearer is the Chassis as in the Pan assembly. The bearing used in this assembly is [redacted] which is 60mm in diameter for packaging reasons and is tied to the Chassis by the Bearing cup. The Payload is rotated by a series of flanges with the main flange being the Back flange which is also used to carry the payload. A dynamic O-ring is again used for sealing between the two rotating interfaces.ψ

The motor's ID is coupled to the shaft with tight tolerances and held together with adhesive. The rotor is coupled likewise to the series of flanges therefore constituting the Cover as the frame to the frameless motor. This design decision capitalizes on the design flexibility a frameless motor has. Plastic caps encase the plastic arms depicted in pink, used as windows to access the wiring of the payload

6.4 Tilt encoder assembly

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Figure 59 Tilt encoder assembly

Figure presents the encoder side of the elevation axis assembly. This side of the rotational axis includes the second angular encoder of the system and all the parts that make it functional. This side too uses [redacted] bearing for packaging reasons. The bearing is fixed on the Encoder Bearing Cup which in turn is fixed to the chassis. The rotor of the encoder is fixed to the Encoder bearing cup with four hexagonal spacers. This makes the rotor fixed in relation to the elevation axis and the part that is rotating in place is the stator of the encoder which is mounted directly on the cover supported by metal flanges.

6.5 Miscellaneous Features

Ergonomy

Other than the three main subassemblies there are a lot of miscellaneous assemblies made both for functional reasons but also for ergonomics reasons as well. For example to simplify the work of the technician when it comes to assembling the wires, two plastic caps as seen in figure have been designed in either side of the tilt axis where the technician can guide the wires in and out of the payload sphere through the ID's of the tilt motor and encoder.

Sealing

For the sealing of the whole structure, O-rings have been utilized. Most O-rings are static in application and don't require special attention other than adequate stiffness in order to squeeze the O-ring satisfyingly. But in three cases, the O-rings are dynamic, which in effect means the two faces that are coupled with the O-ring rotate relative to each other. For some cases typical tight tolerances are enough. For the case of the pan sealing, the sealing ring is held up by a plastic cap seen in Figure. Plastic and especially additively manufactured plastic cannot retain tight tolerances and is susceptible to dimensional errors. If the ring relied on the plastic in order to dynamically seal the structure this would of course not be functional.

Therefore, concentric ribs have been designed which retain the stiffness and the tolerances of metal and correct the dimensional errors of the plastic.

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Figure 60 Motor and endcoder caps

Pressurization

The system needs to be filled with inert gas and have its humidity evacuated. This is done by an

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Figure 61 Pan sealing

evacuating fitting which is fitted in the Plastic cap seen in figure. The fitting is removed and the chamber is pressurized at 120mbar above atmospheric pressure. When the structure has been filled with inert Nitrogen gas the cap is closed and the structure then only consists of Nitrogen which doesn’t include Humidity.

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Figure 62 Pressurising valve

6.6 Final review

As a final review, the prototype managed to reach close to the requirements but was not able to surpass them. The overall mass is higher than the requirement at 4.5kg and also the overall dimensions strayed away from the criteria such as 205mm diameter instead of 180mm. That is due to having to adapt to all the components instead of having the components adapting onto our own criteria. The motor series we chose for example while being the best at having

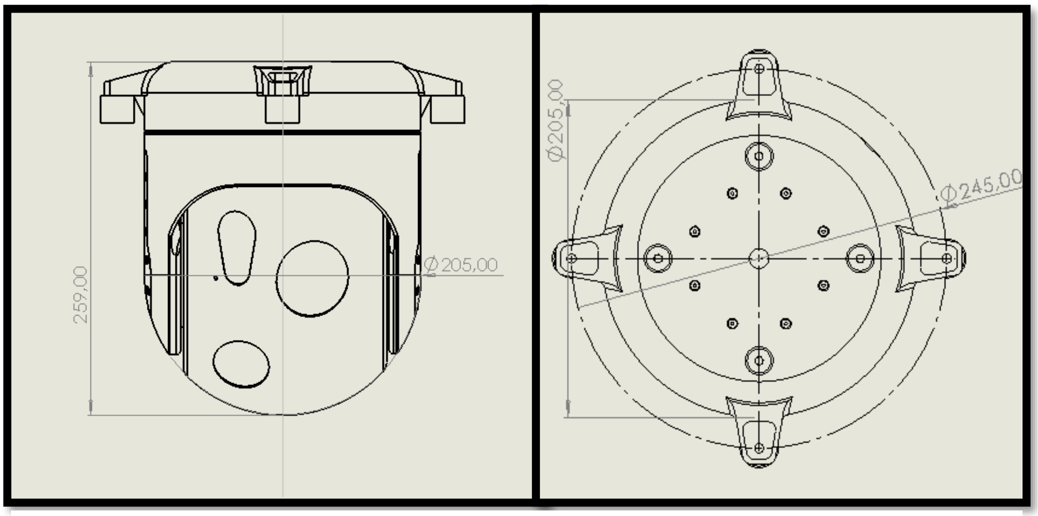

Figure 63 Dimensions

torque density and a low profile, only came in select dimensions, 20mm OD and 52mm OD. Furthermore, better choices for motors such as axial flux motors were locked behind further agreements and cooperations with the company and a very high lead time due to the custom design. Nonetheless the design is satisfactory for this level and definite improvements can be made, mainly in terms of weight and sizing.

System specifications of the Gimbal	
Sensors	MWIR Thermal imager, Day camera, LRF
System type	2 axis mechanical stab. / 3 axis electronical stab.
Az. Coverage	360°
El. Coverage	+80° to -10°
Slew rate	360°/s
Encoder resolution	0.01°
Stabilization bandwidth	N/A
Gyro noise	6 uRad
Stabilization	<50 uRad RMS
Motors	Direct drive
Rating	IP 67
Operating temperature	-40°C to 55°C
Consumption	N/A
Size	Ø205 mm x 259 mm height
Weight	4,5kg

7. Simulations and optimization

Chapter 7 undertakes an exhaustive revaluation of the system's functional elements, utilizing sophisticated computational techniques such as the Finite Element Method (FEM) and kinematic analysis. Specialized simulation software is employed to facilitate a nuanced understanding of the mechanical properties, stress distribution, and dynamic behaviour of each component under varying operational conditions. The aim extends beyond mere validation of initial design decisions; it also seeks to identify opportunities for structural enhancements that could contribute to improved performance, efficiency, and long-term reliability. This chapter serves as a critical nexus in the engineering process, bridging theoretical design with practical application and thereby guiding future phases of system development and refinement.

7.1 Structural Analysis of components

In the structural analysis of components, we will analyse emphasize on the static structural analysis of the most important components, the components that carry the main loadings. These are the chassis of the structure mainly, as well as some bearing flanges and the ground flange

7.1.1 Chassis

The chassis is the main bearer of loads. It is held but mainly by the ground flange with its bearing flange, and is responsible for keeping the payload steady.

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Figure 64 Free body diagram of chassis

The free body diagram of the Chassis is depicted in figure. The main loads of the chassis are caused by lifting the payload through the bearings. The load is transmitted through the fix points where the bearing cups are fitted depicted in red.

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Figure 65 FEM model of chassi

In the FEM model of the Chassis the fixed points are the points which are in contact with the bolts that fix it to the bearing flange, depicted in Figure 65. The bolts are countersink which have the feature of both being low profile by sinking into the body they fix, but also the bigger and more uniform contact area therefore spreading the stresses uniformly.

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Figure 66 Fixtures of the model

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Figure 67 Bearing Cup being fixed on the chassis

[redacted] CONFIDENTIAL

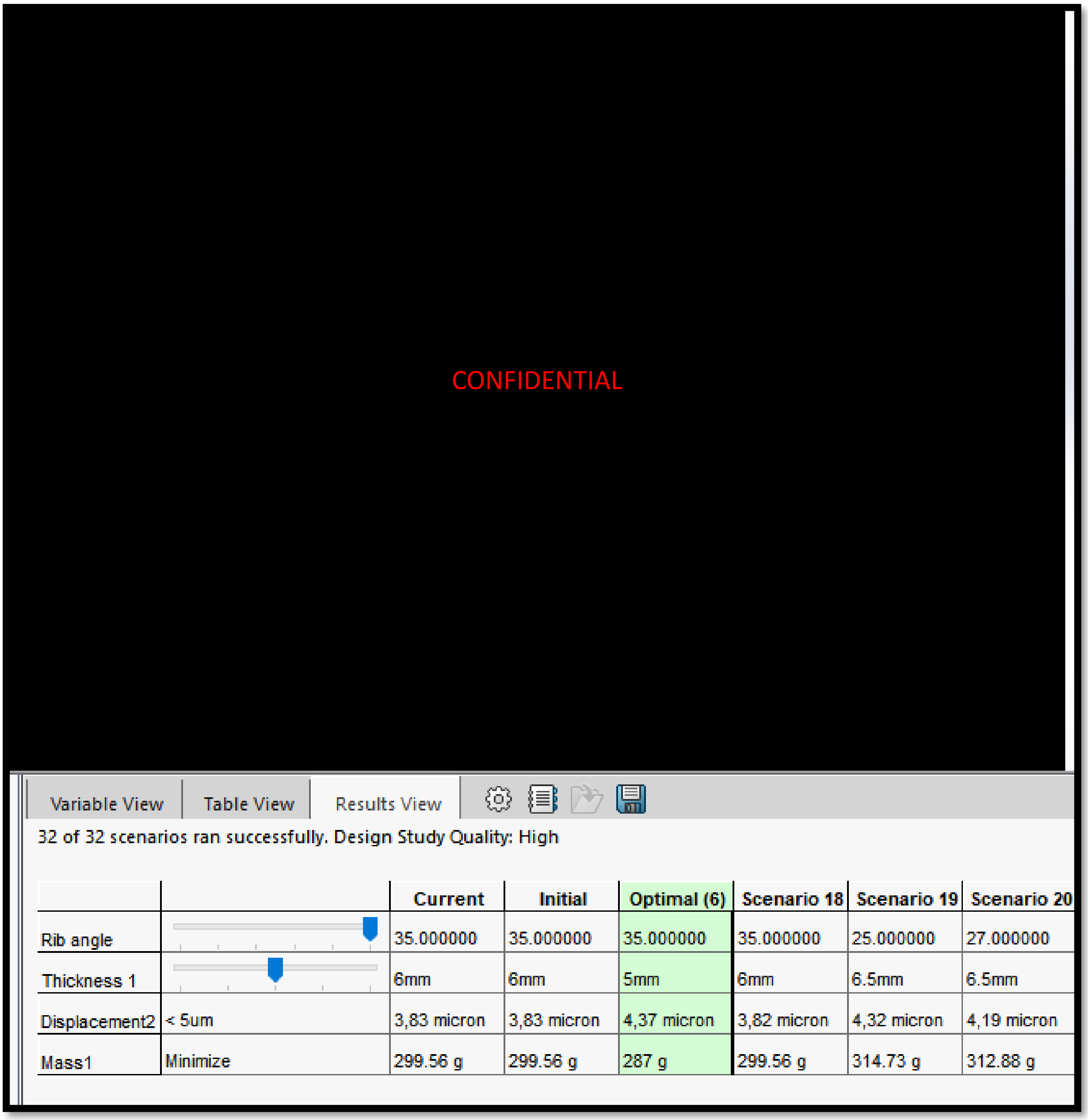
Figure 68 Results of the model

Figure 68 shows the results of the static study. The model under the normal operating conditions shown in Table 4. The material assigned is 6082-T6 for its extra light density of 2,7 g/cm^2 but very high durability with a tensile yield strength of 260 MPa.

Load name	Load Image	Load Details
Fixtures	[redacted] CONFIDENTIAL	**Entities:** 10 face(s) **Type:** Fixed Geometry
Remote Mass (Rigid connection)		**Entities:** 12 face(s) **Connection Type:** Rigid **Coordinate System:** Center of rotation axes **Remote Mass:** 2 kg
Gravity		**Reference:** Top Plane **Values:** 0 0 -9,81 **Units:** m/s^2

Table 6 Boundary conditions of the model

In order to have the most optimal geometry multiple optimization techniques were utilized. Firstly, the Design study tool provided by Solidworks was used to find the most optimal dimensions for features such as the angle of the angled mid-parts or for the thickness of the part. The goal of the study was to minimize the deformation of the part to under 5 micron at normal conditions. 5 microns were used in order to have a structure that wouldn't oscillate easily by the vibrations induced from the carrier UAV. By setting the constraints at a maximum model displacement of 5 microns its possible to find which configuration meets this requirement with the lowest amount of weight therefore finding the stiffest to weight structure.



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32 of 32 scenarios ran successfully. Design Study Quality: High

		Current	Initial	Optimal (6)	Scenario 18	Scenario 19	Scenario 20
Rib angle		35.000000	35.000000	35.000000	35.000000	25.000000	27.000000
Thickness 1		6mm	6mm	5mm	6mm	6.5mm	6.5mm
Displacement2	< 5um	3,83 micron	3,83 micron	4,37 micron	3,82 micron	4,32 micron	4,19 micron
Mass1	Minimize	299.56 g	299.56 g	287 g	299.56 g	314.73 g	312.88 g

Figure 69 Design study of 30 scenarios were the variables given were the thickness and the angle of the middle sheets.

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Figure 70 The thickness of the whole structure and the angle of the middle sheets

The design study had two variables. The angle at which the "arms" of the Chassis would go downwards in order to support the payload, and the thickness of the whole structure. The thickness had the ranges of 5mm up to 7.5mm, with 5 being the minimum in order for the part to be manufacturable, and the angle was set from 25° to 35° for packaging reasons since any higher than and space is taken away from handling the wires, which detriments the ergonomic design of the system.

7.2 Bearings

The bearings chosen have the technical data shown in Table 5

Bearing Model	Maximum Radial (N)	Maximum Axial (N)	Maximum Moment
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Table 7 bearings data

Pan bearing

For the pan axis the 70mm bearing was chosen.

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Figure 71 Forces acted on the pan bearings

- $F_{axial} = m * g = 2kg * 9{,}81 = 19{,}82N$
- $Sf = \frac{F_{axial_{max}}}{F_{axial}} = \frac{1068}{19{,}82} = 54$ *which is more than enough to satisfy functionality.*

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Figure 72 Tilt bearing loadings

Tilt motor bearing

- $F_{radial} = \frac{Mass}{2} * g = 9{,}81N < 1068N$
- $M = F_{radial} * D = 9{,}81 * 0{,}08m = 0{,}78Nm < 13Nm$

Tilt encoder bearing

- $F_{radial} = 9{,}91N < 1112N$
- $M = 9{,}81 * 0{,}08m = 0{,}78Nm < 11{,}8Nm$

Both bearings are satisfactory for this application

8. Conclusion

8.1 Introduction

This project aimed to develop a two-axis stabilised platform for camera surveillance payload which was meant to be fitted on a UAV for defence applications. Initially the project had the scope of creating an experimental jig for an ISP 2 axis system were parameters and information could be gained and tested in vivo, but due to time-sensitive goals the scope of the thesis moved to designing a working prototype immediately.

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 Chapter 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.

8.2 Payload

8.3 Motors and bearings

The motors and bearings are actuators or machine elements that are necessary for the operation of the ISP. For this project, to stabilize mechanically two axis there was a requirement for at least 2 motors and at least 2 bearings in order to allow and induce rotation about the two axes. The motor chosen was [redacted] which is suitable for the application since it is designed very compactly and also came in a configuration which allowed for freedom of design and helped bring the size of the gimbal down. But there were motors that could potentially be better than the [redacted] which weren't examined, namely axial flux motors. Companies that create low profile axial flux motors targeted at weight and size sensitive applications like this are few. Contact was made with Cierra motion, a company that designs and manufactures such motors but the motors were custom made for each application and not having designed a prototype didn't allow for the specification of the requirements of a custom motor. Other than that, a custom-made motor would also push the time frame of the project back.

The bearings chosen for the application are exactly what was needed for the application. The only manufacturer that made such low-profile bearings at such high Inner Diameters was [redacted] and therefore it was the only option. Plus having such high durability despite their given dimensions was a factor that helped with the systems overall reliability.

8.4 Design

The design of the prototype was experimental but satisfactory. The structure largely relied on aluminum as the base for most components since it is one of the stiffest to weight easily available materials, making them a prime choice for aerospace applications. Tight tolerances also must be met for the system to be functional therefore giving aluminum another reason for it to be the choice. For each part FEA analysis was conducted to each component to ensure its functionality as well as its reliability.

Due to the size constrain each component is designed to its absolute limits. A minimum thickness of 2mm is given to each component in order to make it easily manufacturable in a CNC machine. Screws are also mostly M3 size and with the shortest length available in the market in order to reduce size and weight as much as possible.

One other remark is the lack of additive manufacturing when it comes to metal parts. The plastic covers will be made by AM SLS but metal parts will all be manufactured in CNC. AM unlocks designed that are impossible or otherwise too costly for CNC machining, which allows to design utilizing topology optimization and generative design. A next revision of the project will include AM parts as well.

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