ELE 401 - GRADUATION PROJECT I
FIRST INTERIM REPORT

HACETTEPE UNIVERSITY
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

PROJECT TITLE: STAR TRACKER

PROJECT GROUP MEMBERS: SUDE SAYIN (2200357001)
MEHMET YASİN ARIK (2200357070)

PROJECT SUPERVISOR: ASSOC. PROF. DR. ŞÖLEN KUMBAY YILDIZ

SUBMISSION DATE: 21.03.2025

SPRING 2024-2025

TABLE OF CONTENTS

1. INTRODUCTION

This project involves the design and development of a star tracker by a student group using camera and FPGA technology with the support of TÜBİTAK Uzay.

The successful execution of space missions, reliable communication with spacecraft, and precise position determination all depend on accurate attitude control. One of the systems used to determine precise attitude is the star tracker. Compared to other sensors, Star Trackers provide long-term accuracy by continuously tracking star patterns and comparing them to onboard star catalogs. The purpose of this project is to design a system that efficiently captures and processes star images, extracts relevant features, and matches them with a predefined star database to calculate the orientation of a satellite or high-altitude vehicle. In this project, an optimal balance between power consumption, accuracy, and processing speed will be pursued. By leveraging hardware acceleration and optimized image processing algorithms, this project seeks to improve real-time performance and enhance the reliability of star tracker systems. This report provides information on the project's description, components, algorithms, working principles, engineering standards, and design constraints. Additionally, it discusses sustainable development goals, provides background information, and concludes with final remarks.

2. PROJECT DESCRIPTION

A star tracker is an optical navigation device used in spacecraft, satellites, and some high-altitude aircraft to determine their orientation in space by identifying star patterns. Figure 1 shows an example of a star tracker image. It is a critical component of attitude determination and control systems (ADCS). Spacecraft relies on celestial objects, primarily stars, for attitude determination in deep space.

The working principle can be explained as follows:

1. Image Capture: A Star Tracker’s camera (typically CCD or CMOS) captures an image of the stars visible in space.

2. Star Detection & Pattern Recognition: The system processes the image to detect bright points (stars) and matches their pattern against a reference database of known star positions.

3. Attitude Calculation: Once the stars are identified, their relative positions are used to compute the spacecraft’s orientation (roll, pitch, yaw) using algorithms such as triangulation or quaternion-based attitude determination.

4. Real-time Feedback: The computed orientation is continuously updated and sent to the spacecraft’s navigation system for course corrections and stability control.

The expected design constraints and the requirements of the project are:

- The selected camera and sensor must be compatible with the FPGA board, with image data transfer rates of at least 2 FPS to ensure smooth real-time operation.
- The star tracker is required to maintain tracking accuracy within ±6 degrees for angular position detection, considering the resolution limits of a 400 x 400 pixel camera and the processing power of the FPGA.
- The image processing algorithm must execute within 50 ms per frame to ensure real-time tracking capabilities, constrained by the 40 MHz clock speed of the FPGA.
- The FPGA board is limited to 2 MB of onboard memory, constraining the size of image frames and requiring efficient data processing and storage management to avoid overflow during real-time operation.

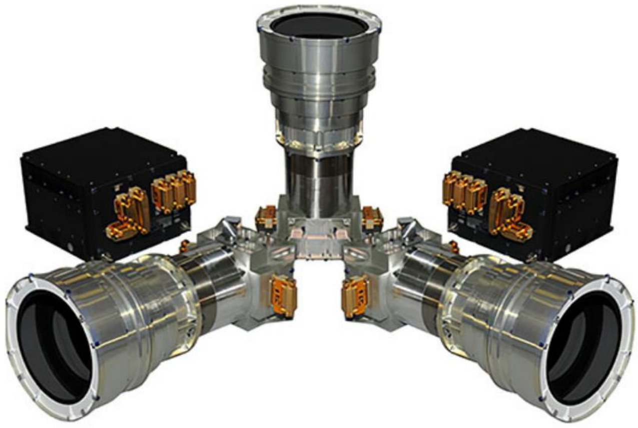

Figure 1: Example of a star tracker image [1]

2.1. STAR TRACKER PARTS

These are the camera unit and data processing unit:

2.1.1. CAMERA UNIT

The camera unit captures star images while minimizing stray light from bright celestial objects such as the Sun, Earth, Moon, and other planets. This function is achieved through a baffle, which is coated with low-reflectivity black material to absorb unwanted light. Several optical parameters are crucial for sensor design, including Field of View (FOV), F-number, focal length, and pixel properties. FOV selection requires optimization: a smaller FOV reduces stray light interference but limits the number of visible stars, whereas a wider FOV increases the number of detectable stars but also admits more stray light [2].

The camera unit can utilize two types of cameras:

2.1.1.1. CCD (Charge-Coupled Device)

In CCD image sensors, photoelectrons generated by incoming light are transferred to the readout node through vertical and horizontal CCD shift registers. At this stage, charge-to-voltage conversion is performed, and the signal is amplified by a buffer circuit before being sent to the signal processing unit. Throughout this process, the timing sequence of the transfer gates and shift registers must be precisely controlled to prevent signal loss. [3]

2.1.1.2. CMOS (Complementary Metal-Oxide-Semiconductor)

In CMOS image sensors, each pixel contains a photodiode and a set of transistors that perform charge-to-voltage conversion, amplification, and signal readout. Unlike CCD sensors, where charges are transferred across multiple stages to a single readout node, CMOS sensors process signals within each individual pixel. This architecture enables faster readout, lower power consumption, and random pixel access. The decentralized readout mechanism reduces the risk of charge transfer inefficiencies and enhances radiation resistance, making CMOS sensors widely preferred in modern imaging applications. [3]

As shown in FIGURE 2, CCD and CMOS sensors have a different architecture [4],[5].

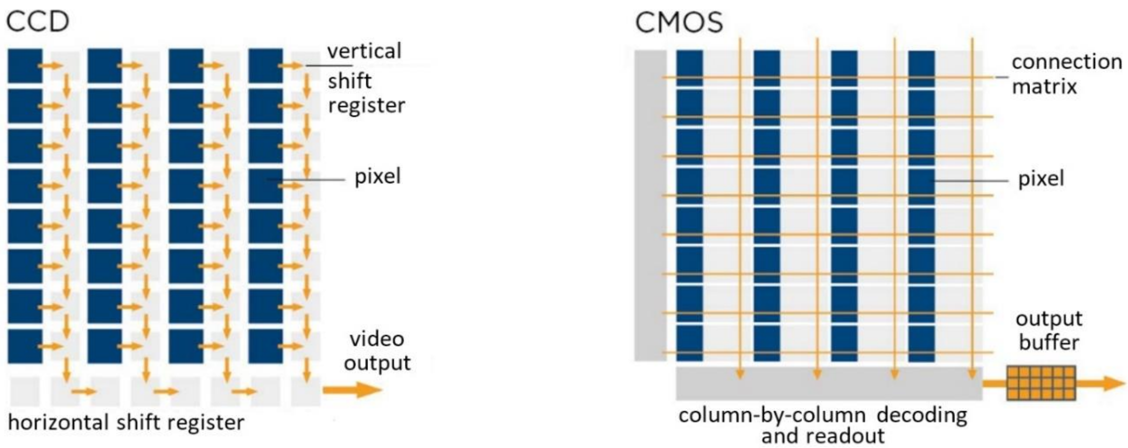

FIGURE 2: Working principles of a CCD and a CMOS sensor [4],[5]

Comparisons of CCD and CMOS sensors:

- **Sensitivity**: CCD sensors generally offer higher sensitivity and better low-light performance compared to CMOS sensors. However, newer CMOS sensors have made significant improvements in low-light performance, narrowing the gap between the two technologies.
- **Noise**: CCD sensors have lower noise levels due to more controlled signal processing, while CMOS sensors typically exhibit higher noise levels. However, advanced CMOS designs have significantly reduced this issue over time.
- **Dynamic Range:** CCD sensors typically offer a wider dynamic range, enabling them to capture more details in both bright and dark areas. However, CMOS sensors have made significant improvements in dynamic range with recent technological advancements.
- **Radiation Resistance:** CCD sensors are more sensitive to radiation, which can affect their performance in space applications. In contrast, CMOS sensors are more resistant to radiation, making them more reliable in harsh environments.
- **Speed:** CCD sensors are slower due to the sequential charge transfer process, while CMOS sensors are faster because they can process data in parallel.
- **Power Consumption:** CCD sensors consume more power because all charges are processed at a single point, whereas CMOS sensors consume less power as each pixel processes data independently.
- **Manufacturing Cost:** CCD sensors are more expensive due to their complex manufacturing process, while CMOS sensors are cheaper as they use standard semiconductor fabrication techniques.
- **Reliability:** Both CMOS and CCD sensors are reliable in most applications, but CMOS sensors are generally more reliable due to the integration of all circuit functions on a single chip, reducing the number of leads and solder joints.

CCD sensors excel in sensitivity, low noise, dynamic range, and image quality, making them ideal for precision applications, though they consume more power and are slower. In contrast, CMOS sensors are faster, more energy-efficient, cost-effective, and radiation-resistant, making them better suited for modern consumer and industrial applications. While CCDs remain superior in specific imaging tasks, advancements in CMOS technology have significantly narrowed the performance gap. Due to their cost-effectiveness, energy efficiency, and high-speed performance, CMOS sensors have been selected for this design.

2.1.2. DATA PROCESSING UNIT

2.1.1.2. Software

Star tracker systems rely on advanced algorithms to accurately determine the orientation of a spacecraft by analyzing star patterns.

2.1.1.2.1. Center of Light Method (Simple Center of Light)

This is the simplest and most basic method. The method aims to track the light source by identifying its center. From the camera image, the position of the light source is determined and used as a reference for tracking.

Advantages:

• Simple and fast: The basic mathematical computations are minimal, making the process very fast.

• Low computational power requirements: It can efficiently work on systems like FPGA with low power consumption.

Disadvantages:

• Lower accuracy: The method may be misleading if the shape or brightness of the light source changes.

• Limited flexibility: This method may not be sufficient in complex scenarios (multiple light sources, changing environments, etc.).

2.1.1.2.2. Kalman Filters

The Kalman filter is particularly useful in systems with time-varying data (dynamic environments). This algorithm makes predictions based on the system’s previous state and measured data, minimizing the difference between the predicted and observed data. [6]

Advantages:

• Real-time updates: The Kalman filter continuously integrates new data with previous predictions.

• More accurate results: It minimizes random errors, providing more accurate tracking.

• Effective in complex systems: It can perform well even in noisy environments and changing conditions.

Disadvantages:

• Computationally intensive: It requires more complex mathematical calculations compared to other methods, which may cause performance issues on systems with limited resources like FPGA.

• Advanced knowledge required: To produce accurate results, the Kalman filter needs detailed knowledge of the system's dynamics and noise models.

2.1.1.2.3. Machine Learning

Machine learning learns from data to build models that can track the light source using various features. This method can analyze large amounts of data, making it suitable for more complex models and algorithms [7].

Advantages:

• High accuracy: Machine learning can achieve very high accuracy by training on large datasets.

• Flexibility: It can handle varying environments and situations effectively, especially dynamic and changing conditions.

Disadvantages:

• High computational power requirements: Machine learning typically requires intensive computations and is best suited for more powerful processors. This can be a limiting factor in FPGA-based systems.

• Training requirements: Machine learning models often require large amounts of data labeled and time-consuming training processes.

Most Suitable Method for FPGA-based Star Tracker:

• The Center of Light method is likely the most suitable for FPGA-based Star Tracker systems. This method requires low computational power and is highly efficient in terms of speed. FPGA's parallel processing capabilities make it ideal for such simple algorithms.

• Kalman Filters can offer more accurate results, but due to their computational complexity, they may pose challenges on FPGA-based systems with limited resources. Thus, performance issues could arise in more complex applications.

• Machine Learning provides the highest accuracy but requires significant computational power, which may not be efficient on FPGA due to the system's resource limitations.

In conclusion, the Center of Light method is the most suitable for FPGA-based Star Tracker projects due to its simplicity and efficiency. However, for more complex applications or more powerful FPGA systems, Kalman filters or machine learning could also be considered.

2.1.1.3. Hardware

Various electronic boards can be used for star tracker design. If categorized into three groups:

2.1.1.3.1. FPGA-Based Processors

If real-time image processing, low latency, and high speed are required, an FPGA (Field Programmable Gate Array)-based system should be preferred.

Advantages:

• Can process data in parallel for real-time image processing.

• Can be optimized at the hardware level.

• Suitable for low-latency computations.

Disadvantages:

• Requires FPGA programming knowledge (Verilog/VHDL).

• More expensive compared to microcontrollers.

2.1.1.3.2. Microcontroller-Based Processors

If the image processing load is low and the system only needs to perform basic orientation calculations, microcontrollers can be used.

Advantages:

• Can operate on battery power with low energy consumption.

• Easier to program (developed with C/C++).

• Cost-effective.

Disadvantages:

• May not be powerful enough for image processing.

• Can be insufficient for real-time processing requirements.

2.1.1.3.3. Embedded Linux-Based Processors

If complex image processing algorithms (e.g., star recognition, machine learning) will be used, boards capable of running Linux should be preferred.

Advantages:

• Easily programmable with pre-built libraries like Python and OpenCV.

• Supports machine learning and advanced image processing.

• More powerful processors allow execution of complex algorithms.

Disadvantages:

• Not as low latency as FPGA.

• Consumes more power (battery-powered usage may be limited).

When comparisons are made and system requirements are considered, we can see that FPGA-based processors are the most suitable option. Here are some FPGA boards that can be used in star tracker systems:

❖ Zynq 7000 SoC

Specifications:

• Processor: ARM Cortex-A9 processor (dual-core).

• FPGA: Xilinx 7 series FPGA.

• Memory: DDR3 SDRAM.

• I/O: Various I/O ports (HDMI, USB, GPIO, etc.).

• Scope: Integrated FPGA with ARM processor, enabling fast data transfer between software and hardware.

• Software Support: The Zynq 7000 can run Linux-based systems and can be easily programmed using tools such as Python and OpenCV.

Advantages:

• Combines FPGA and ARM processors for real-time data processing, offering high parallelism and fast processing capabilities.

• Provides flexibility through FPGA and ARM processor integration, allowing both software and hardware usage for complex algorithms.

• Delivers high performance for image processing and video processing, especially useful when working with high-resolution data.

• Offers more software libraries and processing power with Linux support.

Disadvantages:

• Requires a more complex programming process (both FPGA and ARM software).

• May be more expensive compared to other boards.

Suitability for Star Tracker:

• Perfect for a Star Tracker system requiring high parallel processing capabilities, real-time image processing, and software-hardware integration.

• FPGA section can provide speed and accuracy using VHDL, while the ARM processor can be used for additional algorithms.

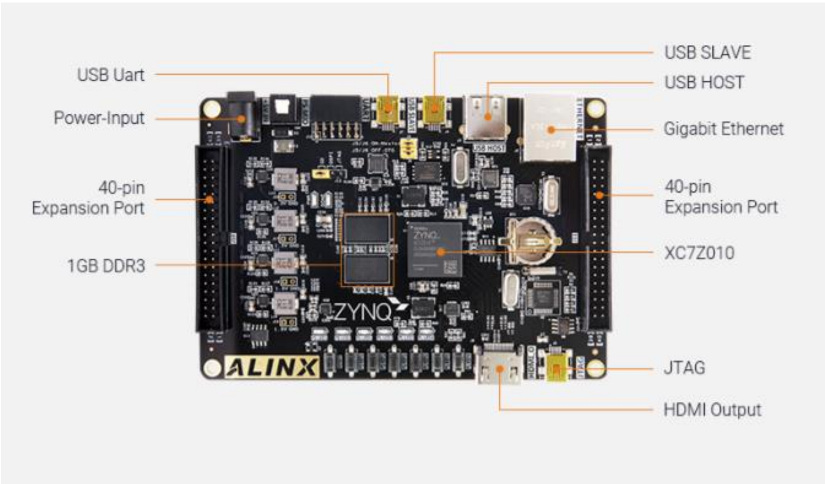

Figure 4: Zynq 7000 SoC Dev Board & Kit [8]

❖ Nexys A7: FPGA Trainer Board (Artix-7)

Specifications:

• FPGA: Artix-7 FPGA (15k to 33k LUT capacity).

• Memory: 128MB DDR3 SDRAM.

• I/O: Various I/O ports (HDMI, USB, GPIO).

• Scope: Suitable for general-purpose education and prototyping.

• Software Support: Programmable using Vivado and Xilinx SDK.

Advantages:

• Artix-7 FPGA is a high-performance, low-power FPGA, suitable for applications like image processing.

• Education-focused, making it easy for development.

• Can run complex FPGA-based algorithms with high parallelism capacity and sufficient memory.

Disadvantages:

• Memory capacity is lower compared to other boards (128MB).

• Lower processing power, relying solely on the FPGA part compared to SoCs like the Zynq 7000.

Suitability for Star Tracker:

• Suitable for parallel processing and basic image processing requirements using VHDL.

• May be limited for high-resolution data processing due to its smaller memory capacity compared to other boards.

• However, it's a good option for smaller and more cost-effective projects.

❖ Nexys Video Artix-7 FPGA (For Multimedia Applications)

Specifications:

• FPGA: Artix-7 FPGA (another version of Artix-7).

• Memory: 512MB DDR3 SDRAM.

• I/O: HDMI, VGA output, GPIO, USB, Audio, and more I/O options.

• Scope: Optimized for multimedia applications, especially strong for video processing.

• Software Support: Programmable with Vivado and Xilinx SDK.

Advantages:

• Designed for multimedia processing, it has a strong FPGA capacity capable of processing high-resolution video.

• Provides high memory capacity (512MB DDR3) and fast data transfer.

• Supports output such as HDMI and VGA for working with video signals, making it ideal for image processing applications.

Disadvantages:

• May be more expensive due to additional hardware for multimedia features.

• Lacks an ARM processor, meaning you'll only rely on FPGA-based processing, which can make some algorithmic parts more difficult to implement in software.

Suitability for Star Tracker:

• Very strong for projects involving image processing and video signals.

• Suitable for image processing and data parallelism with VHDL, but there may be limitations in cold computation and algorithm processing.

• The increased memory capacity is beneficial when working with high-resolution data.

• Multimedia features like HDMI output might be unnecessary, making it less useful for a Star Tracker project. [9]

Conclusion:

The Zynq 7000 SoC is the most suitable option for Star Tracker projects. The ARM processor allows for high parallel processing power, and integrating image processing algorithms with the FPGA makes it a powerful solution. Additionally, Linux support and the ARM processor provide a flexible software development environment.

The Nexys A7, using Artix-7 FPGA, could be suitable for smaller, low-cost projects that don't require parallel processing, but it may not be sufficient for higher resolution and more complex processing requirements.

The Nexys Video is the most suitable board for video and multimedia applications. Due to its high memory capacity and video capabilities, it is strong for video signal processing, but it may struggle to efficiently run the necessary image processing algorithms for a Star Tracker.

Overall, the Zynq 7000 SoC is the most flexible and powerful option, making it the best choice for Star Tracker projects.

TABLE 1 A GANTT CHART EXAMPLE

Project Timeline	2025-2026													
Task List	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Background research														
Selection of Tools and Methods														
Comparing methods														
Hardware Initialization														
Implementation														

3. ENGINEERING STANDARDS AND DESIGN CONSTRAINTS

The design of the star tracker system must adhere to established engineering standards while meeting multiple realistic constraints. These standards and constraints ensure the system's reliability, accuracy, and efficiency.

3.1. ENGINEERING STANDARDS

To ensure the reliability and performance of the star tracker, relevant international and industry standards must be followed. The following standards apply to this project:

IEEE 12207: Software Life Cycle Processes

• Relevance to Project: This standard governs the software development processes for mission-critical applications. Since the star tracker relies on real-time image processing algorithms and star-matching techniques, adherence to IEEE 12207 ensures the software's quality, maintainability, and reliability.

• Implementation in Design: The software development for image processing and attitude determination will follow a structured life cycle, including requirements analysis, design, coding, testing, and validation.

ISO 21348: Space Environment (Natural and Artificial) – Definition of Solar Irradiance Spectral Categories

• Relevance to Project: Space-based optical sensors, such as the star tracker, must consider the effects of solar radiation and stray light. ISO 21348 defines the solar spectral categories that help in designing optical filters and image processing algorithms to reduce interference from the Sun and other celestial bodies.

• Implementation in Design: The optical system will incorporate spectral filtering techniques, and the image processing algorithm will employ filtering methods to minimize the impact of stray light.

ANSI/VITA 57.1: FPGA Mezzanine Card Standard

• Relevance to Project: The star tracker relies on an FPGA-based data processing unit. The ANSI/VITA 57.1 standard ensures compatibility between FPGA hardware and peripheral devices, such as image sensors.

• Implementation in Design: The FPGA board selection will consider compatibility with high-speed image sensors and memory modules in line with this standard.

NASA-STD-5001: Structural Design and Test Factors of Safety for Spaceflight Hardware

• Relevance to Project: The mechanical design of the star tracker housing and mounting system must comply with space-grade structural requirements to withstand launch vibrations and thermal cycling.

• Implementation in Design: The star tracker housing will be designed using lightweight and rigid materials, and Finite Element Analysis (FEA) will be conducted to verify mechanical integrity under expected space conditions.

3.2. DESIGN CONSTRAINTS

In designing the Star Tracker, several constraints must be considered to ensure functionality, reliability, and feasibility. These constraints impact the design choices and must be carefully addressed. Below are the design constraints categorized into different aspects:

3.2.1. Economy

• Budget limitations: The cost of components (FPGA, sensors, optics) must stay within the allocated budget.

• Cost of similar products on the market: Commercial star trackers are expensive, so this project aims to be a cost-effective alternative.

• Maintenance cost: The system should require minimal maintenance after deployment.

3.2.2. Environment

• Power consumption: The tracker must operate with low power due to spacecraft energy constraints.

• Electromagnetic radiation issues: The system must comply with EMC standards to avoid interference with other spacecraft systems.

• Environment-friendly power sources: If applicable, the design should support energy-efficient processing methods.

• Noise pollution: The star tracker should not generate unwanted electrical noise that affects other onboard instruments.

3.2.3. Society

• Assisted living for the disabled and elderly: The system is not directly related, but advancements in image processing may benefit accessibility applications.

• Information security and privacy: Spacecraft orientation data should be encrypted to prevent cyber threats.

• Social networking and communication: Not directly relevant but could support open-source space research.

3.2.4. Politics

• Gender and race equality in design: The project should promote inclusive engineering practices.

• National security: The tracker should comply with export regulations (ITAR, EAR).

• Solving international and national problems: Space-based navigation helps with global positioning, climate monitoring, and disaster response.

3.2.5. Ethics

• Safety and health considerations: The system must not pose any risk to operators or users.

• Intellectual property rights: The design should respect existing patents and algorithms.

• Privacy issues: Data collected must be secured against unauthorized access.

• Honesty, truthfulness, and openness: Performance should be reported accurately in research and documentation.

3.2.6. Health and Safety

• Public safety: The tracker should operate without causing hazards to spacecraft and ground stations.

• Consumer safety: The design should ensure electrical and mechanical safety.

• Worker safety: Assembly and testing must follow safe engineering practices.

3.2.7. Manufacturability

• Compatibility with current manufacturing technology: The system should be produced using existing PCB and optical fabrication methods.

• Physical implementation: The tracker must be compact, lightweight, and easy to integrate into spacecraft.

3.2.8. Sustainability

• Reliability and durability: The system must operate in extreme space conditions (vacuum, radiation, temperature variations).

• Future upgrades: FPGA-based processing should allow software updates and algorithm improvements.

• Environmental resilience: The design should function under different mission conditions (LEO, deep space).

4. SUSTAINABLE DEVELOPMENT GOALS

The Sustainable Development Goals (SDGs), established by the United Nations in 2015, provide a global framework for addressing various social, economic, and environmental challenges. The Star Tracker project aligns with several SDGs by contributing to scientific advancements, technological innovation, and environmental sustainability. The following SDGs are particularly relevant to this project:

Goal 9: Industry, Innovation, and Infrastructure

The Star Tracker project directly supports technological innovation by improving the accuracy and efficiency of satellite orientation systems. This enhances the reliability of space infrastructure, which is crucial for satellite communication, Earth observation, and scientific research. By developing advanced algorithms and hardware solutions, the project contributes to advancements in aerospace technology and strengthens global research and development capabilities.

Goal 12: Responsible Consumption and Production

The design of the Star Tracker emphasizes power efficiency and optimal resource utilization. By selecting energy-efficient components and implementing optimized algorithms, the project aims to minimize power consumption, extend the lifespan of satellites and reduce space debris. Responsible production practices, such as selecting sustainable materials and ensuring minimal electronic waste, align with this goal.

Goal 13: Climate Action

Star trackers play a crucial role in Earth observation satellites that monitor climate change, deforestation, and natural disasters. By improving the accuracy and reliability of these satellites, the project indirectly supports climate action initiatives by enabling better data collection for environmental monitoring and policymaking.

Goal 17: Partnerships for the Goals

The development of the Star Tracker involves collaboration between researchers, engineers, and academic institutions. By fostering international partnerships and knowledge sharing, the project aligns with SDG 17, which emphasizes global cooperation to achieve technological advancements and sustainability.

In summary, the Star Tracker project significantly contributes to global sustainability by promoting innovation, responsible resource usage, environmental monitoring, and international collaboration. These efforts help advance scientific knowledge and ensure that space technologies continue to support the broader goals of sustainable development.

5. BACKGROUND

5.1. BACKGROUND ACQUIRED IN EARLIER COURSE WORK

ELE120 – Computers and Programming

This course provides a fundamental understanding of high-level programming languages, focusing on problem modeling and algorithm development. It enables proficiency in solving real-world problems using structured programming techniques and efficient algorithmic approaches.

The knowledge gained in this course is essential for implementing the software components of the star tracker system, including image processing, star identification, and real-time data analysis.

ELE230, ELE315 - Electronics

These courses cover the operation and application of fundamental electronic components such as diodes and transistors. Topics include AC/DC circuit analysis, frequency response analysis, and the design of voltage rectifiers, voltage regulators, and transistor amplifiers (BJT or FET) based on gain, input-output impedance, and frequency response specifications. Additionally, concepts related to feedback circuits, differential and operational amplifiers, power amplifiers, oscillators, signal generators, and digital logic circuits are explored.

For the star tracker project, the knowledge acquired from these courses is essential in designing and optimizing the electronic hardware. This includes signal amplification, power management, and efficient processing of signals from the image sensor, ensuring accurate and reliable star identification and tracking.

ELE225 - Fundamentals of Digital Systems

This course provides the fundamental principles of digital systems, including the analysis and design of combinational and synchronous sequential logic circuits. Key topics covered include the operation and implementation of flip-flops, registers, and counters, as well as memory devices such as RAM, ROM, PLA, and PAL.

For the star tracker project, the concepts from this course are crucial in designing digital logic circuits for efficient data processing and control. Flip-flops and registers can be used for state management in FPGA-based implementations, while memory components play a role in storing star catalog data for real-time star matching algorithms.

ELE301 - Signals and Systems

This course introduces the foundational concepts of signals and systems, focusing on their classification and behavior in both time and frequency domains. It covers the computation of system outputs for periodic and aperiodic signals, applying tools like Fourier, Laplace, and z-transforms. The course also addresses the sampling theorem, which bridges continuous-time and discrete-time signal relationships

For the star tracker project, knowledge from this course is crucial for processing the signals captured by the optical sensors and translating them into meaningful data. Fourier and Laplace transforms can be applied to analyze and filter the signals for star detection and identification. Understanding the relationship between continuous and sampled signals will also be important when working with the digitized data from the star tracker's image sensors.

ELE354 - Control Systems

This course covers the fundamental principles of feedback control systems, including system modeling, stability analysis, and control system design. Various mathematical techniques are introduced to analyze and design controllers that meet specified performance criteria. The course also includes practical applications using existing software tools for control engineering.

For the star tracker project, concepts from this course are essential in designing attitude determination and control algorithms. Stability analysis methods ensure the robustness of the star tracker's orientation estimation, while feedback control techniques can be applied to fine-tune tracking accuracy in dynamic space environments.

ELE403 - Control Systems Design

This course focuses on the design and implementation of control systems, equipping individuals with the skills to address practical challenges and physical constraints in real-world systems. The course provides the ability to analyze control problems, select appropriate techniques, and design systems that meet specific requirements.

For the star tracker project, knowledge from this course is important for the development of the attitude control system. The techniques learned can be applied to ensure that the satellite or spacecraft's orientation is controlled accurately based on star tracker data. Understanding the physical limitations and choosing the right control techniques will help optimize the tracker's performance under varying space conditions.

ELE407 - Digital Signal Processing

This course introduces individuals to the theory and techniques of signal processing, focusing on how to model and solve signal processing problems using various algorithms. It emphasizes understanding the advantages and disadvantages of these algorithms and their application in real-life scenarios.

For the star tracker project, the knowledge gained from this course is essential for designing and implementing the image processing algorithms needed to identify stars, determine their positions, and match them with known star catalogs. Digital signal processing techniques, including filtering, Fourier transforms, and other signal analysis methods, can be used to improve the accuracy and efficiency of the star tracker.

ELE432 - Advanced Digital Design

This course covers advanced topics in digital design, with a focus on synthesizable hardware description languages (HDL) such as VHDL or Verilog. It explores how to design efficient digital circuits, with an emphasis on FPGA-based systems, and develops skills in creating test circuits, generating benchmarks, and integrating Intellectual Property (IP) cores.

For the star tracker project, the knowledge gained from this course will be crucial when implementing the FPGA-based processing unit. The ability to write synthesized HDL code for hardware design will allow for real-time processing of star images, which is essential for the star tracker's performance. Additionally, the understanding of test circuit generation and benchmark creation will ensure that the FPGA-based system is verified and optimized for its task, contributing to the overall success of the project.

ELE490 - Fundamentals of Image Processing

This course provides a comprehensive understanding of image processing techniques, covering image acquisition, formation, filtering, restoration, segmentation, and compression in both spatial and frequency domains. It also includes deep learning methods for image classification and object recognition.

For the star tracker project, the skills learned in this course will be directly applicable to the image processing algorithms used for star identification and orientation determination. The ability to filter and restore images, along with performing segmentation and object recognition, will be crucial for accurately identifying stars in the captured images. The deep learning techniques will enhance the accuracy and robustness of the star-matching algorithms. Additionally, the practical programming experience will allow for efficient coding of the image processing pipeline required for the star tracker's real-time performance.

All these courses contribute significantly to different aspects of the Star Tracker project. ELE120, ELE225, ELE301, and DSP provide fundamental knowledge for image processing and FPGA design, while ELE354 and Control Systems Analysis are crucial for attitude control and error correction. Advanced Digital Design and Image Processing help in implementing efficient image processing algorithms on FPGA, ensuring optimal system performance

5.2. BACKGROUND ACQUIRED THROUGH ADDITIONAL RESEARCH

Astronomy and Celestial Mechanics

Astronomical concepts, such as star identification, celestial coordinates, and star catalogs (e.g., Hipparcos), are fundamental for determining spacecraft orientation using stars. Understanding how stars are positioned and move in the sky is key to accurately matching them with a star catalog.

Optics and Optical Sensors

Knowledge of optics and optical systems helps in understanding the performance of the star tracker's camera, including lens characteristics, sensor noise, and light diffraction. This is essential for designing a system that can capture clear star images under varying conditions.

Attitude Determination and Control Systems

Attitude determination algorithms, such as Triad and QUEST, along with methods like Kalman filtering, are used to calculate the spacecraft's orientation based on star positions. Understanding these algorithms is crucial for precise and real-time attitude estimation in star trackers.

Real-Time Embedded Systems

Star trackers require real-time processing to identify stars and compute orientation quickly. Knowledge of real-time operating systems (RTOS), scheduling, and low-latency computation is vital for developing efficient, fast processing systems for embedded platforms.

Sensor Integration and Calibration

Proper calibration and alignment of optical sensors are crucial for ensuring the accuracy of the star tracker. Understanding how to compensate for sensor noise and errors improves the precision of star position measurements and overall system performance.

Space Environment and Radiation Effects

Space radiation, solar radiation, and cosmic rays can degrade sensor performance or introduce errors. Understanding these environmental factors and their effects on optical sensors and electronics is essential for designing a robust star tracker that functions reliably in space.

System Integration and Testing

Integrating and testing the star tracker system ensures that all components work together as intended. Rigorous testing methods, including real-world simulations, help identify and address potential issues, ensuring the system performs reliably in various operational scenarios.

6. CONCLUSION

This project aims to develop a real-time, high-precision Star Tracker using FPGA-based image processing. The system will significantly improve space navigation accuracy, reduce power consumption, and enhance real-time processing capabilities. With rigorous testing and validation, the proposed design is expected to contribute to the future of autonomous spacecraft navigation.

REFERENCES

[1] SatCatalog, "Hydra - Star Tracker," Sodern. [Online]. Available: https://www.satcatalog.com/component/hydra/. [Accessed: Mar. 19, 2025]
[2] S. Sargıngüçlü, "Investigation of the Star Tracker Algorithms and Kalman Filter Integration," M.S. thesis, Dept. Aerosp. Eng., Middle East Technical Univ., Ankara, Turkey, 2019.
[3] L. Zhang, Y. Jin, L. Lin, J. Li, and Y. Du, "The comparison of CCD and CMOS image sensors," *in Proc. SPIE 7157*, 2008 International Conference on Optical Instruments and Technology: Advanced Sensor Technologies and Applications, Beijing, China, 2008, pp. 71570T.
[4] AstroBasics, "CCD or CMOS?," AstroBasics, [Online]. Available: https://astrobasics.de/en/components/camera/ccd-or-cmos/. [Accessed: 18-Mar-2025].
[5] Basler AG, "Moderne CMOS-Kameras als Ersatz für CCD-Kameras," White Paper, Available: https://www.baslerweb.com. [Accessed: 18-Mar-2025].
[6] M. S. Grewal and A. P. Andrews, *Kalman Filtering: Theory and Practice Using MATLAB*, 4th ed. Hoboken, NJ: Wiley, 2014.
[7] L. Zhang and J. Yang, "FPGA-based Machine Learning: A Survey," *IEEE Access*, vol. 5, pp. 12345-12355, 2017.
[8] Xilinx, "Zynq-7000 SoCs," [Online]. Available: https://www.xilinx.com/products/silicon-devices/soc/zynq-7000.html. [Accessed: Mar. 19, 2025].
[9] Digilent, "Nexys A7-50T FPGA Board," [Online]. Available: https://www.digilentinc.com/nexys-a7-50t. [Accessed: Mar. 19, 2025].