Software Requirement Specification Document for Espacio: Detection, Tracking and Collision Prediction of Space Debris

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Table 1: Document version history

Version	**Date**	**Reason for Change**
1.0	25-Oct-2020	SRS First version's specifications are defined.
1.1	2-Dec-2020	....
1.3	5-Dec-2020	....

GitHub: https://github.com/jasminehegazy64/Space-Debris-Project.

Contents

Abstract

Decades of space exploration have provided us with a valuable knowledge of Earth, Solar System, and beyond. But, it has also led us to an unintended consequence – orbital space debris. Space debris has become a major concern for space stations and organizations worldwide due to the increasing number of debris generated from man-made objects such as defunct satellites, rockets, mission tool and fragments as small as paint chips. Debris comes in various shapes and sizes, according to the European space agency (ESA) there are 29,000 pieces greater than 10 centimeters, 670,000 pieces larger than 1 centimeter and above 170 million pieces larger than 1 millimeter. Since the velocity of the debris while orbiting the earth averages 10 km/sec the effect of an impact could be catastrophic and could lead to something like the Kessler syndrome, A domino effect of space debris collisions leading to a self-sustaining proliferation, posing a significant threat to orbital activities. So, in our project, detection, tracking and collision prediction of small space debris, we propose an approach to address this issue by using machine learning methods for debris detection, building a tracking model that combines Algorithms and AI-based techniques for predicting future positions of the debris and employing a collision prediction algorithm to evaluate the likelihood of potential collisions. The results should enhance space situational awareness and aid in developing effective mitigation strategies to reduce space debris.

1 Introduction

1.1 Purpose of this document

The Software Requirements Specification (SRS) document aims to illustrate the proposed system's features, explain its objectives, and set guidelines for the developers while working on it. This document is intended for the developers and stakeholders of the application.

1.2 Scope of this document

This document covers the application's detailed description, functional and non-functional requirements, basic interface and data designs, and an analysis of the classes needed and the relations between them.

1.3 Business Context

Space exploring has rapidly increased in the last couple of years with the advancement of technology. The pollution that the space debris caused and is still causing in our earth orbit creates a significant threat to functional satellites and space environment. And with the increase of debris the number of space missions and satellites that are being launched in orbit is also increasing. The need for a comprehensive system to manage and prevent risks that are related to space debris becomes of prime importance.

2 Similar Systems

2.1 Academic

- **Bin Li, Jian Huang, Yanming Feng, Fuhong Wang, and Jizhang Sang** view a machine learning-based approach that leverages the spatial and temporal distribution of tracking arcs to improve OP accuracy. The proposed approach contains training a Gradient Boosting Regression Tree(GBRT) model on a data set of simulated debris objects with known orbits and generating the model to predict the orbits of real debris objects. The authors reveal that their chosen approach outperforms the traditional methods considering accuracy and computational efficiency and test the performance of the approach using a real data set containing real debris objects and compare it with the traditional methods of OP. This machine learning-based approach leverages the spatial and temporal distribution of tracking arcs to better OP accuracy and efficiency. The authors illustrate the effect of their approach using a real data set and highlight its potential applications in the field. Some of the few limitations can be the size and representative's of the data sets in hand, the performance metrics chosen for evaluation, and the generic findings to other satellite orbits and prediction scenarios. Moreover, the study may have been restricted by the specific machine learning algorithms and techniques in use, and other approaches may conduct different results. These limitations could be addressed in future extended research studies. [1]

- **Yaobing and Ersoy, Xi Jiangbo and Xiang, Cong and Okan K, Junkai, Gu and Xin, Ming and Wei** propose a method for detection of space debris by feature learning of candidate regions. The optical image sequences in hand are first processed to withdraw any flicker noise or hot pixels. As well as the removal of the nonuniform background information by the explained one dimensional mean iteration method. Then, the feature learning of candidate regions (FLCR) method is proposed to extract the candidate regions and to detect the debris. The candidate regions containing space debris are specifically extracted and then classified by a pre-trained deep learning network. The feature learning model is trained using a vast amount of simulated space debris objects using numerous signal to noise ratios (SNRs) and motion parameters, rather than using real space debris, which hardens the extraction of a sufficient amount of real space debris with diverse parameters in optical image sequences. Lastly, the candidate regions are precisely placed in the optical image sequences and then the experiment executes using the acquired image sequences and simulated data in hand. The results reveal that this method has an exquisite performance when estimating and removing background, and it can detect low SNR space debris with a high detection probability. [2]

- **Zhenwei Li, Yigao Ding, Zhe Kang, Mingguo Sun, Chengzhi Liu,Long Chen and Jiannan Sun** tend to assess the impact on orbit prediction accuracy due to different atmospheric density models and to compare the pros and cons of the models concerning orbit determination of space debris. The researchers contribute to solving the obstacle by performing orbit determination of space targets using satellite laser ranging data. The used satellite laser ranging data is generated by the International Laser Ranging Service(ILRS) for orbit determination. They use numerous space targets to represent retired satellites and experiment the effect of different density atmospheres. They also analyze the necessity of atmospheric drag using the models and then compare the orbital prediction errors to study the impact thoroughly. This study reveals that the atmospheric drag is the most significant non-conservative force perturbation for debris in LEO. Overall, it provides valuable and beneficial information concerning the improvement of orbit prediction and mitigation efforts. [3]

2.2 Business Applications

- **NASA Seeks Solutions to Detect, Track, Clean Up Small Space Debris :** This is a challenge conducted by NASA [4] in 2023 to join in the efforts of all enthusiast to help tackle the problem of small sized space debris.

- **Astrometrica:** This a software developed for automatic image acquisition, it focuses on detecting objects and classifying them to whether they are exoplanets, stars or space debris. [5]

3 System Description

3.1 Problem Statement

Detecting and monitoring small debris pieces through the current surveillance network has proven to be ineffective. These extremely small space debris pose a significant threat due to their exceptionally high speeds, ranging from 7 to 10 km/s in LEO[6]. This poses a substantial collision risk to operational satellites and valuable assets. The high relative velocity of the objects makes their tracking incredibly challenging, while the sheer number of such objects raises noteworthy scalability concerns. Moreover, with the increasing congestion of space, the number of expected collisions with small and extremely small space debris will probably multiply tenfold in ten years. The most concerning aspect is that a collision between space debris and operational satellites can lead to the generation of additional debris fragments, initiating a catastrophic chain reaction known as the "Kessler syndrome".Thus, Clean Space aims to decrease the overall mass of existing trash, including robotic satellite recovery, in addition to reducing the amount of junk produced by upcoming ESA missions. Given that the amount of junk in the low orbit has increased by 50% over the past five years, the task is critical[7]. Minor enhancements to the existing methods may not be adequate to track the small debris objects. Thus, it is essential to find innovative solutions promptly that can detect, characterize, track, and remediate small debris to attain the safety and sustainability of space operations. The solution demands robust strategies carefully designed to address the unique physical challenges associated with the problem at hand.

3.2 System Overview

As illustrated in figure 1, the system workflow can be modeled in 5 main steps.

3.2.1 Importing data

The user is prompted to add their satellites' or radars' Flexible Image Transport System (FITS) data.

3.2.2 Converting data

FITS data will be turned into images, processed, cleaned, and analyzed to enable us to build a tracking system to identify the orbit, from it we will be able to use different algorithms to predict whether the mission would have the risk of collision or not.

3.2.3 Debris detection and recognition

By using computer vision techniques, the system would identify the debris in real time. The system is trained using a dataset coming from a satellite called Near Earth Orbit Surveillance Satellite (NEOSsat). The data is captured as images and encrypted to a FITS file. FITS files are organized into header units and data units. Each HDU contains header information, which describes the data in the subsequent data array, so it is turned to an image easily.

3.2.4 Debris tracking

The user will be able to monitor the detected debris, tracing the movement of it in space. The system will achieve this by calculating the precise orbits of detected debris objects.

3.2.5 Collision predictions

Lastly the system will provide warnings about potential risks. By analyzing different paths and calculate conjunction parameters to know if there is a close risk or what is called time of closest approach (TCA), creating thresholds for risk to know the difference between collisions, and adding a warning system, and using Monte Carlo simulations to get the probability of a potential crash whilst considering uncertainties as debris orbit parameters, the gravitational drag and other different factors.

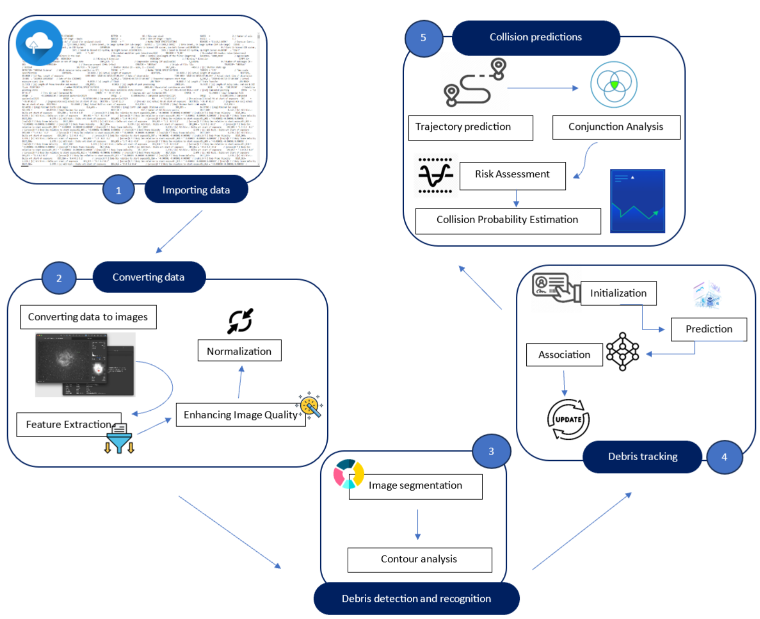

Figure 1: System Overview

3.3 System Scope

The proposed system focuses its attention on utilizing information extracted from an encrypted Flexible Image Transport System (FITS) file to identify the debris within the Lower Earth Orbit (LEO). The system will contribute to the advancement of space debris management, providing valuable insights into LEO debris behavior. The system shall address the following:

- The system shall be able to detect space debris by utilizing the capabilities of specialized satellites and telescopes.
- The system shall utilize computer vision techniques for space debris identification and classification.
- The system shall monitor and track the trajectory of identified debris going beyond mere identification to provide a comprehensive understanding of debris behavior.
- The system shall identify potential risks of collisions.
- The system shall perform risk assessment implementing a warning system.
- The system shall utilize Monte Carlo simulations to estimate collision probability, accounting for uncertainties in debris orbit parameters, gravitational drag, and other relevant factors.
- The system shall generate alerts or notifications when overlaps are detected, enabling timely responses and interventions to mitigate potential risks or collisions.

3.4 System Context

Figure 2 illustrates the processes within the proposed system and their alignment with both functional and non-functional requirements. Upon user initiation, where the user imports datasets acquired from satellites and telescopes in FITS format, the system utilizes the previously imported and gathered data. Subsequently, the system engages in data processing and cleaning, extracting pertinent information crucial for detection purposes. Employing advanced computer vision techniques, the system efficiently identifies debris within the dataset. Users are then granted the ability to visualize and monitor the trajectory of the identified debris, taking into consideration various spatial dynamics. Lastly, users can access comprehensive risk warnings and have the option to dismiss any warning alert.

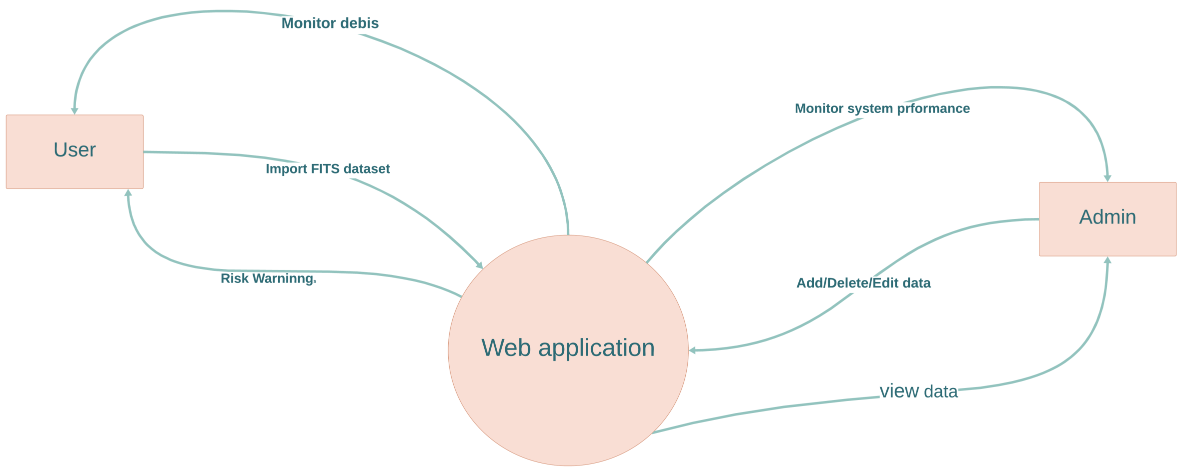

Figure 2: System Context

3.5 Objectives

- Develop a user-friendly web application to assess space organizations and help them visualize what to expect in space when launching their satellites or space stations.
- To be able to detect and recognize the existence of space debris and differentiate between stars and debris.
- To overlay detailed characterizations on debris based on gathered information such as size, shape, composition, and orbital parameters.
- Establish a robust system for real-time monitoring of space debris.
- Continuously track the position, trajectory, and movement of debris objects to predict their future paths.
- Display warnings to users to prevent incorrect satellite launches.
- Provide fully comprehensive collision predictions.
- Facilitate research and development efforts to identify effective maneuvering solutions for operational satellites to avoid collisions.

3.6 User Characteristics

The system targets space organizations to assist them in launching anything in LEO. Consequently, the system will also be used by admins to control and manipulate the users and datasets. Also, the system is designed to be user-friendly.

Admins:

- Will keep a username and password secured for the login.
- Must be capable of managing the database.
- Should be familiar with the project's fundamental design.
- Will have full authority to accept/ reject new accounts.

Users:

- Will keep a username and password secured for the login.
- Should have sufficient knowledge about space and the expected output.
- Should be familiar with the project's fundamental design.

4 Functional Requirements

4.1 System Functions

Figure 3: Use Case Diagram

1. General Requirements:

    - The system shall read raw data and if they match the specifications of .FITS data it will convert into PNG images. (GR01)
    - The system shall be able to pre-process the converted images and extracting features for easy classification. (GR02)
    - The system shall detect and recognize the difference between stars and debris using machine learning models or image processing techniques. (GR03)
    - The system shall label the detected debris when analyzing the imagery from satellites and radars. (GR04)
    - The system shall track the debris from the extracted features from the detection. (GR05)
    - The system shall monitor the trajectory of the debris and keep track of it's coordinates. (GR06)
    - The system shall do a conjunction analysis on the tracked objects. (GP07)
    - The system shall generate a warning when tracked objects are in the danger of a collision. (GR08)
    - The system shall generate reports with all potential risks. (GR09)

2. End user Module:

    - The end user shall be able to add raw data from satellites. (EUM01)
    - The end user shall be able to monitor the detected debris. (EUM02)
    - The end user shall be able to receive warnings about potential risks. (EUM03)
    - The end user shall be able to dismiss an alert. (EUM04)
    - The end use shall be able to receive a warning if the a step was done incorrectly. (EUM05)

3. Admin Module:

    - The admin shall be able to add/ delete/ edit/ view admin profiles. (AM01)
    - The admin shall be able to add/ delete/ edit/ view user profiles. (AM02)
    - The admin shall be able to add/ delete/ edit/ view sensor systems. (AM03)
    - The admin shall be able to monitor system preformance. (AM04)
    - The admin shall respond to user inquiries. (AM05)

4.2 Detailed Functional Specification

Table 2: Convert Fits to images Function Description.

Name	convert_fits_to_image
Code	GR01
Priority	Extreme
Critical	It ensures that the data is compatible with the rest of the system and due to the fact that most astronomy data comes in forms of FITS.
Description	The user selects that they want to add data in the form of FITS data type, then the function proceeds to convert the data into images.
Input	.FITS data files
Output	Folder with PNGs
Pre-Condition	The data must be .FITS.
Post-Condition	Images are in the folder.
Dependency	Depends on EUM01
Risk	Data may be corrupted or not in the same format.

Table 3: Iterative Threshold Function Description.

Name	iterative_thresholding
Code	GR03
Priority	Extreme
Critical	This is crucial due to the need of segmentation of the image to detect debris.
Description	It takes the pre-processed images and applies iterative thresholding on it, since a fixed threshold won't be sufficient, this function gets an initial threshold and then irritates on all images and tunes the threshold based on each image.
Input	Grey Scale_image, initial_threshold, max_iterations, tolerance.
Output	The threshold value sufficient for the image.
Pre-Condition	Images must be pre-processed.
Post-Condition	none
Dependency	GR02
Risk	Celestial objects could be mistaken for debris.

Table 4: Adding data Function Description.

Name	Add_data
Code	EUM01
Priority	Extreme
Critical	Essential for the system to work.
Description	This function allows the users to add his data into the system.
Input	Data file
Output	True, if the data is added successfully.
Pre-Condition	user needs to be logged in and data has to be in .FITS format.
Post-Condition	A small window indicating that the images are added successfully.
Dependency	none
Risk	User may add corrupted data. Network may fail due to large data.

Table 5: Alerts Function Description.

Name	Alert_when
Code	EUM03
Priority	Extreme
Critical	This is essential to the system to identify risks from debris.
Description	When the tracking threshold is passed, users will be sent a warning with the description of the risk, coordinates of risked clash objects.
Input	TrackedID
Output	Warning Message
Pre-Condition	User needs to have the webapp open.
Post-Condition	A window that gives the user the option to ignore or generate report.
Dependency	GR07
Risk	Alerts overriding each other.

Table 6: Accept Users Function Description.

Name	Accept_Users
Code	AM02
Priority	Extreme
Critical	There must be monitoring of users to make sure there is no malicious behavior.
Description	The admin will be allowed to accept new users requests who newly signed-up.
Input	UserRequestID
Output	True, if admin accepts users.
Pre-Condition	Admin must be signed in.
Post-Condition	An analysis page with all user profiles that are accepted.
Dependency	none
Risk	Admin might not be able to maintain with the traffic.

5 Design Constraints

5.1 Standards Compliance

- Adherence to international space traffic management standards and regulations, ensuring that the system aligns with established guidelines for space debris monitoring.[8]

5.2 Hardware Limitations

- Potential limitations in the hardware infrastructure used for processing and storing space debris data, including processing power, memory, and storage capacity.

5.3 Other Constraints as appropriate

- Data Sensitivity and Privacy
- Real-time Processing and Updates
- Scalability
- Integration with Space Surveillance Network (SSN)
- Notification Latency
- Public Access and Outreach

6 Non-functional Requirements

1. **Performance**

- Response Time: Specify the maximum time for the system to respond to user inputs or generate predictions.
- Throughput: Define the number of images or data points the system should be able to process per unit of time.

2. **Reliability**

    - Availability: Specify the required percentage of time that the system must be available for use.
    - Fault Tolerance: Describe the system's ability to continue functioning in the presence of errors or component failures.

3. **Scalability**

    - Define how well the system can handle increased data volume or user load, especially as the amount of space debris data grows.

4. **Usability**

    - Training Requirements: Define the level of expertise or training users should have to operate the system effectively.

5. **Security**

    - Data Encryption: Specify encryption standards for securing sensitive data during transmission and storage.

6. **Compatibility**

    - Specify compatibility requirements with different operating systems, browsers, or other relevant software and hardware.

7. **Maintainability**

    - Define guidelines and standards for code readability, documentation, and future system updates.

8. **Reliability**

    - Specify error-handling mechanisms and reporting procedures.

9. **Interoperability**

    - Specify requirements for the system to work seamlessly with other relevant systems and data sources in the space monitoring ecosystem.

7 Data Design

7.1 Dataset

An initial dataset, as shown in the below figure, is coming from a satellite called Near Earth Orbit Surveillance Satellite (NEOSsat) [9]. The data is captured as images and encrypted to FITS. FITS is a standard digital file format used in astronomy for storing scientific data, including images, tables, and metadata. FITS files are commonly used to store data from telescopes, satellites, and other astronomical instruments. FITS files are organized into HDU. To turn a FITS file into an image, you need to extract the data from the HDU containing the image array. The process involves reading the FITS file, extracting the relevant information from the header, and interpreting the data array as an image. We will be extracting from the HDU the important information that we need. As an example, we have extracted from it the exposure time as it's an important information[10]. The dataset consists of folders, every folder is focused on the same part of the space capturing same debris with their features, capturing this part in different time intervals which will help us in tracking. In the figures below there are 2 different parts, every part has 4 images with sequential time intervals. After calculating the difference between the time intervals in all the parts, we concluded that the time intervals are almost constant which is 65 seconds for each consecutive image.

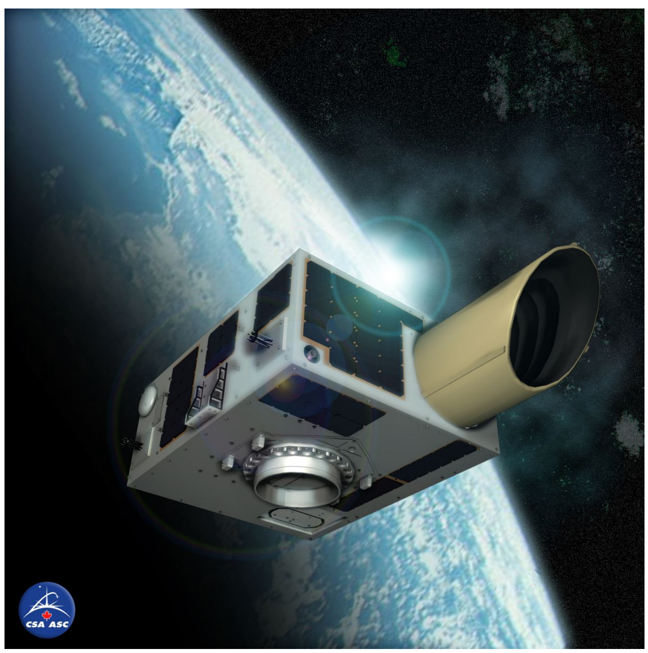

Figure 4: NEOS Satellite

Figure 5: Part 1 - Image 1 : Captured at 2023-01-21T20:07:04.275

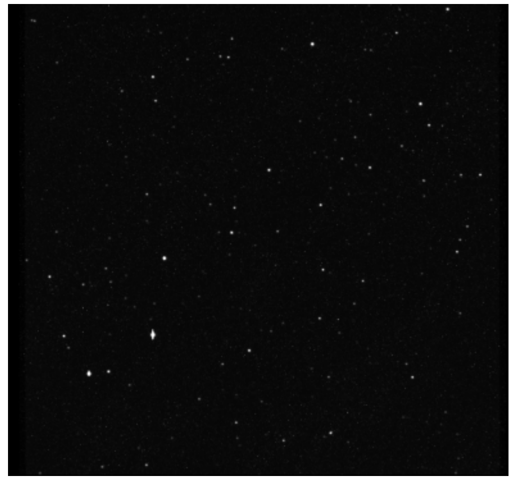

Figure 6: Part 1 - Image 2 : Captured at 2023-01-21T20:08:09.277

Figure 7: Part 1 - Image 3 : Captured at 2023-01-21T20:09:14.286

Figure 8: Part 1 - Image 4 : Captured at 2023-01-21T20:10:19.276

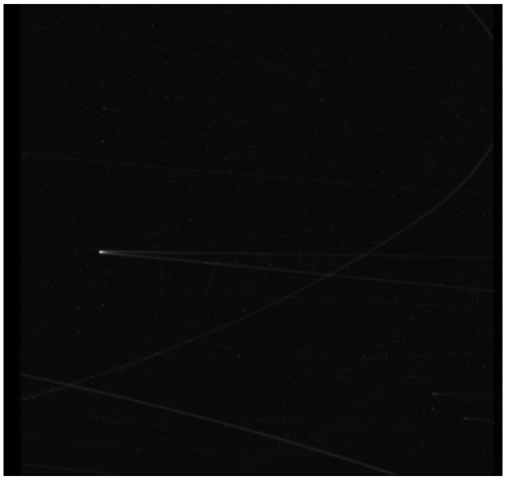

Figure 9: Part 2 - Image 5 : Captured at 2023-01-21T21:37:39.027

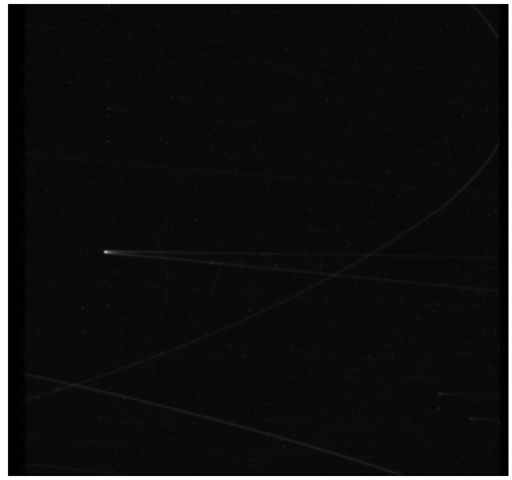

Figure 10: Part 2 - Image 6 : Captured at 2023-01-21T21:38:34.060

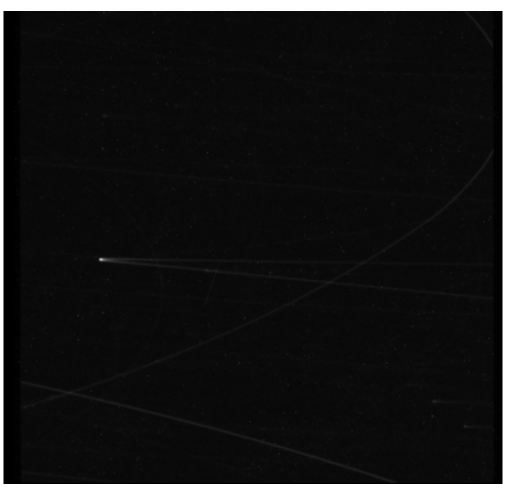

Figure 11: Part 2 - Image 7 : Captured at 2023-01-21T21:39:29.092

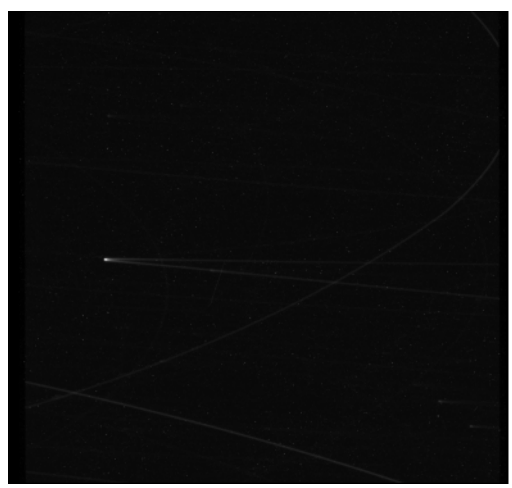

Figure 12: Part 2 - Image 8 : Captured at 2023-01-21T21:40:24.125

7.2 Schema

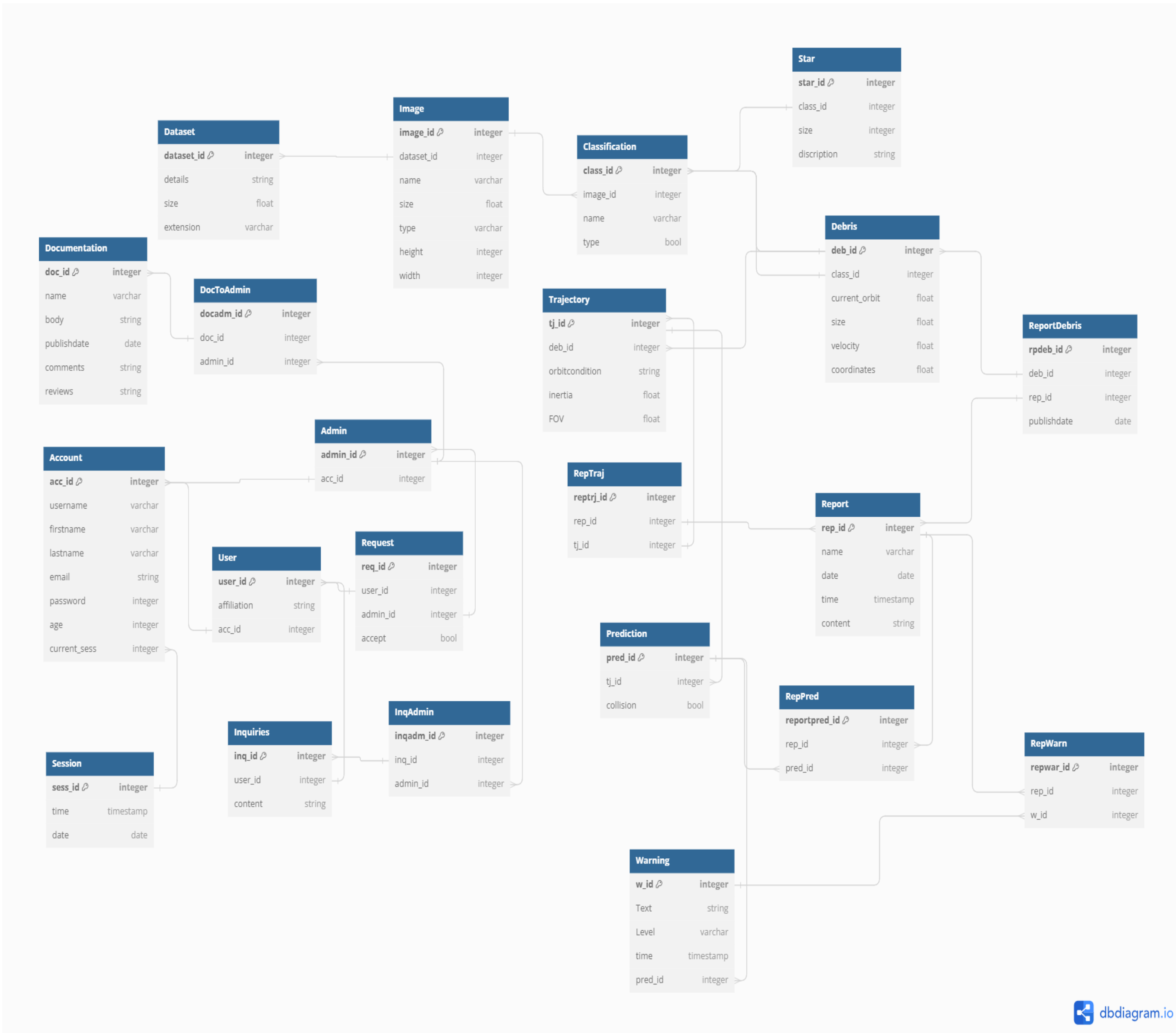

Figure 13: Schema

7.3 Database

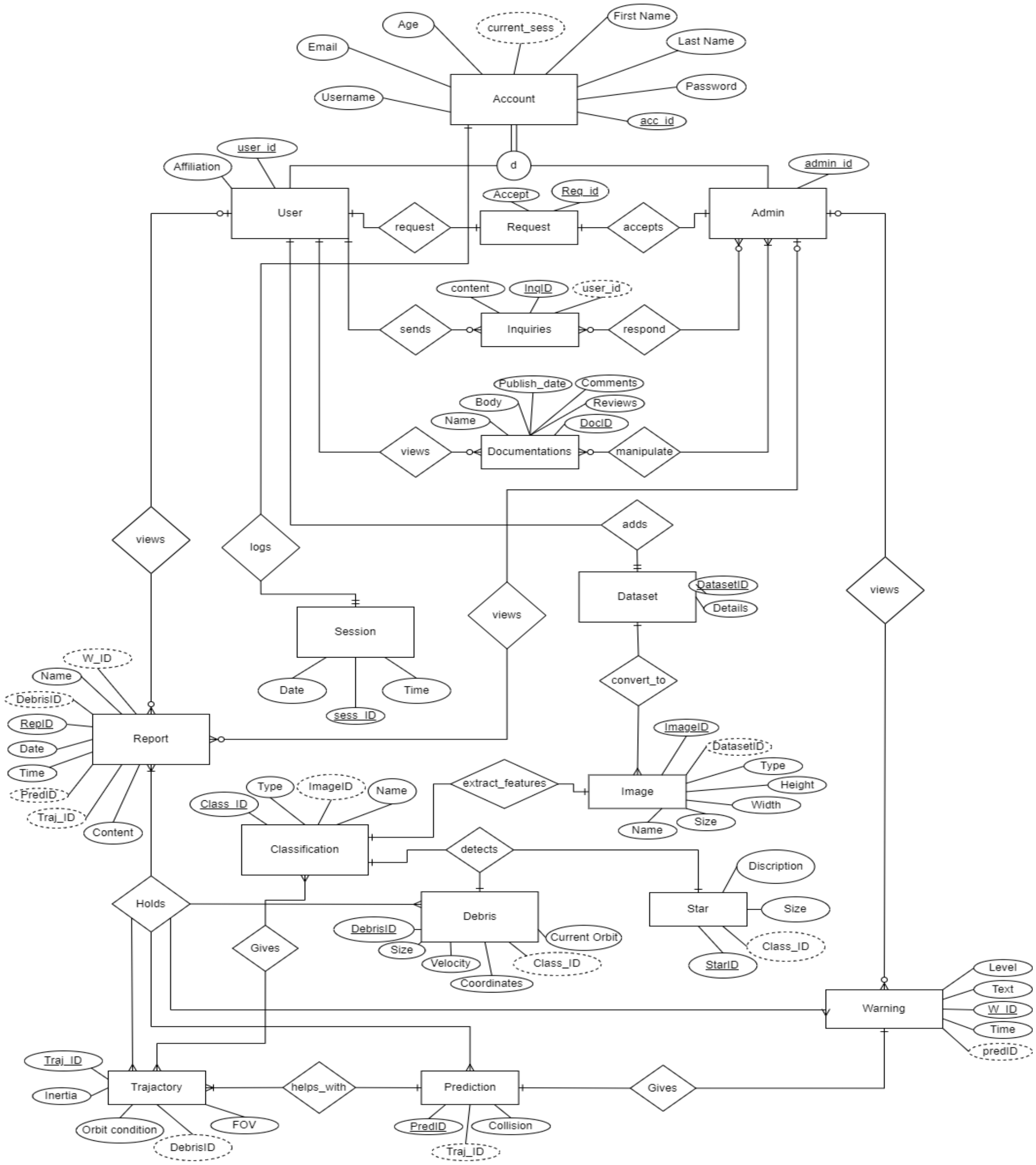

Figure 14: Database

8 Preliminary Object-Oriented Domain Analysis

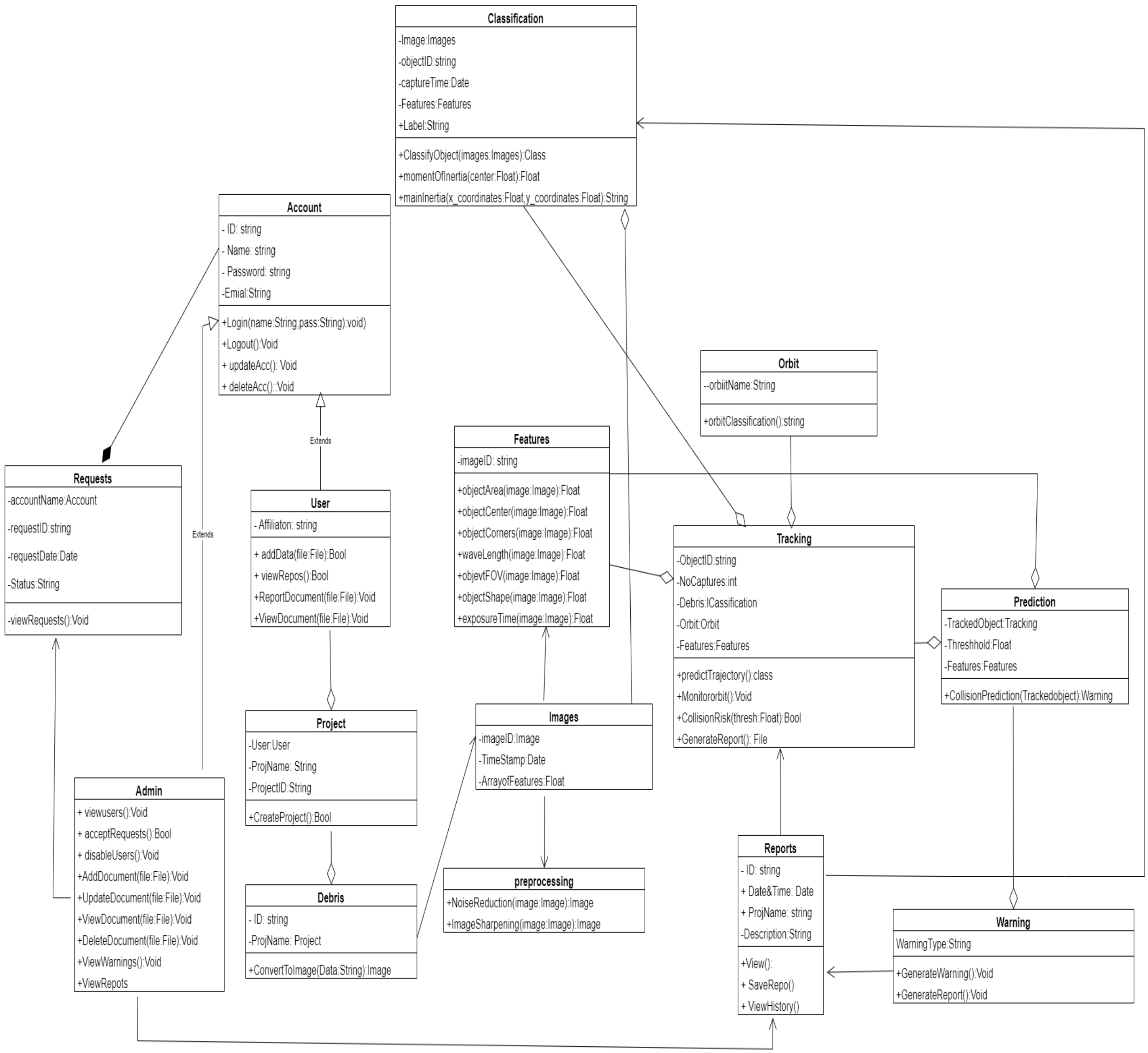

Figure 15: Class Diagram

9 Operational Scenarios

Scenario 1: User adds data

Initial assumption: The user has an account and he is logged in to that account. User has data that is made up of .FITS.

Normal: The user taps on “ Add Data” button from the home screen. The system will launch and a form-like page will show, The user should fill the form with the information related to the data like name, size, source, etc. If data is verified to fit the required specifications, the user will be redirected to generate reports page and can access the results from his data and if requirements are not met the user will see a warning on the screen.

What can go wrong :

- Data can be corrupted.
- Session can crash due to the size of the data.

Scenario 2: A user request to monitor the space debris

Initial assumption: The user has already created an account, and imported his own dataset.

Normal: The user opens the web application. The user chooses to view the debris detected by the system. The system then activates, utilizing the dataset provided by the user. It undergoes preprocessing, processing, and analysis of the dataset. Once the process concludes, the user is directed to the generated reports. The identified debris is then presented to the user in GIF format for visualization.

What can go wrong :

- Dataset not sufficient.

Scenario 3: The system generates reports

Initial assumption: The user has already registered to the website, and uploaded his dataset.

Normal: The user tabs on "Generate reports " from the home screen. The user chooses one of the 3 options, which are: 1. Detected debris, 2. Path of the detected debris, 3. Predicted collisions. After choosing the needed option the website generates a report with the details needed.

What can go wrong :

- Data is not in the right extension, so the system can’t read it and generate reports for it.

Scenario 4: Admin adds new user

Initial assumption: The admin opened the website and successfully logged in with the pre-saved username and password. The admin is directed to homepage.

Normal: The admin taps on "Add new User" from the homepage. The form to be filled is viewed. The admin fills the empty text areas with first name, last name and email. The admin taps on “Add” to finalize and add successfully. The website will add data received into the users’ database and show an alert to show successful or faulty adding process. The admin will be redirected to homepage for any needed further transactions.

What can go wrong :

- Adding new user can be unsuccessful and give a failure alert.
- Network failure mid process of filling in user's information.

Scenario 5: Admin respond to user requests
Initial assumption: The admin is logged in in his account and the user requested to contact the admin.
Normal: The admin opens the web application and directed to his home page. Where he can view the number of requests. The admin chooses to view the requests submitted and is automatically redirected to the mail associated with the system.
What can go wrong :

- Incorrect contact information.
- Undelivered email.
- Request notification not delivered.

10 Project Plan

10.1 Task and Time Plan

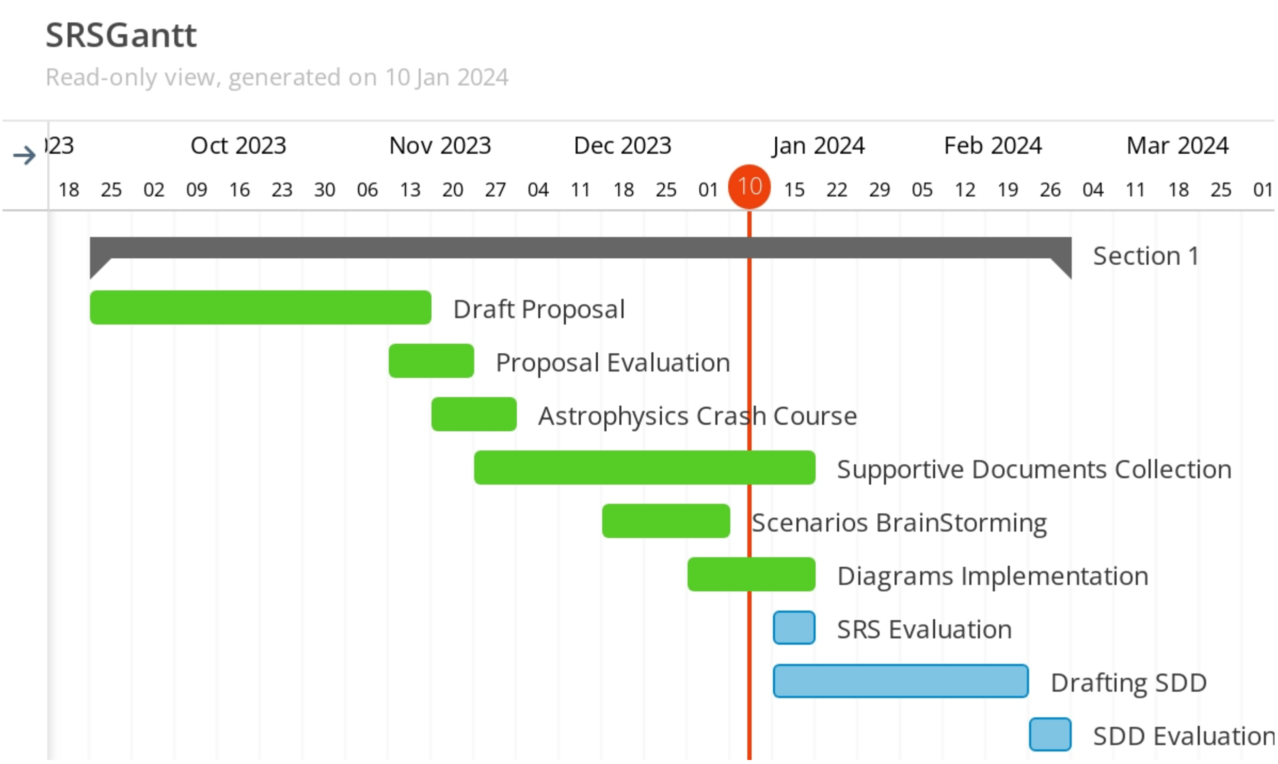

Figure 16: Gantt Chart

11 Appendices

11.1 Definitions, Acronyms, Abbreviations

LEO	Lower earth orbit
NEOSsat	Near Earth Orbit Surveillance Satellite
ESA	European Space Agency
TSA	Time of Closest Approach
SSN	Space Surveillance Network
CDD	Charge Coupled Devices
FITS	Flexible image transport system
HDU	Header-Data Units

11.2 Supportive Documents

11.2.1 Experts Opinions

The figure below represents Dr.Dalia El-Fiky, a space environment researcher, expert opinion about our project's idea and need in the market.

Dalia El fiky (Space Dep.) <delfiky@narss.sci.eg>
to me

9:57 PM (2 hours ago)

Dear Jasmine,

I trust this message finds you well. I have carefully reviewed your proposed graduation project, "Espacio: Detecting, Tracking, and Collision Prediction for Small Space Debris," and I must say it is indeed a feasible and intriguing idea.

While the project holds great potential, I want to emphasize that it involves delving into a relatively new and complex topic. Extensive research and a deep understanding of the subject matter will be crucial for its successful execution. If you are enthusiastic about undertaking the challenge and committed to thorough study, then I wholeheartedly encourage you to proceed with the project.

Addressing the market need aspect, I want to highlight that your project aligns with the current trends in space environment research. The issue of small space debris detection and collision prediction is of paramount importance globally due to its urgency and severity. By working on this project, you will be contributing in parallel with researchers from around the world while offering a valuable perspective from a local Egyptian standpoint.

Moreover, your efforts will not only add to the international discourse on the topic but also position you as one of the few individuals actively working towards a solution. Your project has the potential to provide Egypt with a standalone system, making a significant impact in addressing this critical issue.

Wishing you the very best of luck as you embark on this exciting endeavor.

If you have any questions or need further support, feel free to reach out.

Best wishes

Dalia Elfiky, PhD

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National Authority of Remote Sensing and Space Science
23 Jozif Tito, El Nozha Elgedida, Cairo, Egypt
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Email: delfiky@narss.sci.eg

Figure 17: Expert opinions

Addressing the market need aspect, I want to highlight that your project aligns with the current trends in space environment research. The issue of small space debris detection and collision prediction is of paramount importance globally due to its urgency and severity. By working on this project, you will be contributing in parallel with researchers from around the world while offering a valuable perspective from a local Egyptian standpoint.

Moreover, your efforts will not only add to the international discourse on the topic but also position you as one of the few individuals actively working towards a solution. Your project has the potential to provide Egypt with a standalone system, making a significant impact in addressing this critical issue.

Dalia Elfiky, PhD

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11.2.2 Survey

This pie chart illustrates the global awareness regarding the potential risks associated with space debris.

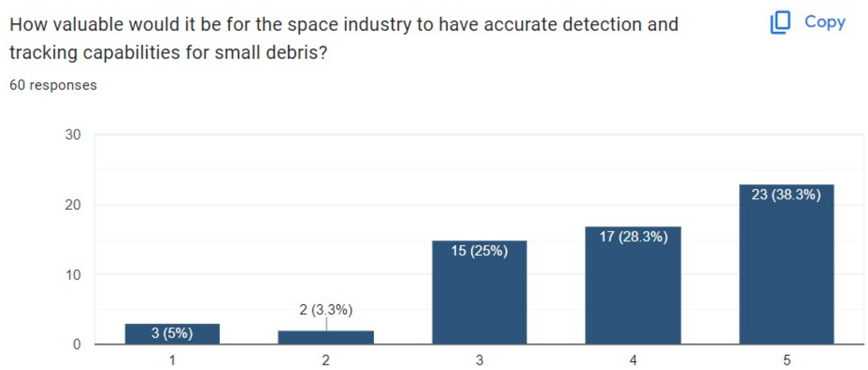

Figure 18: System Overview

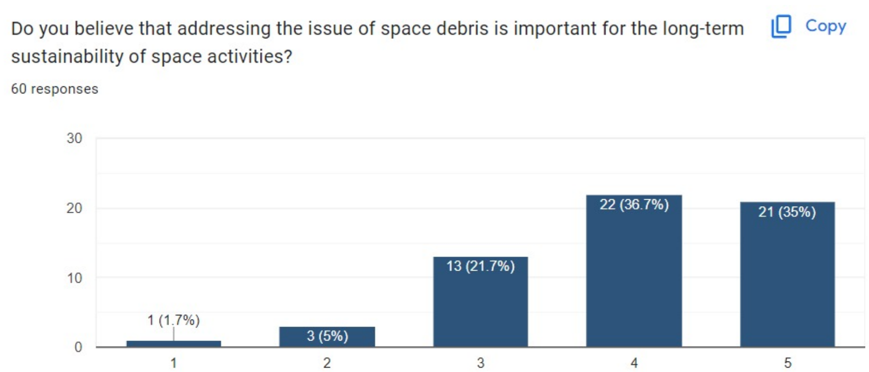

Figure 19: System Overview

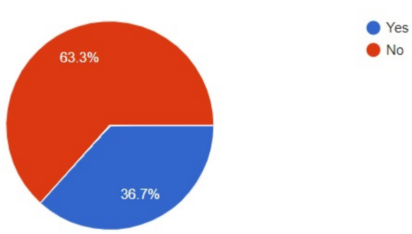

Figure 20: Aware of risk

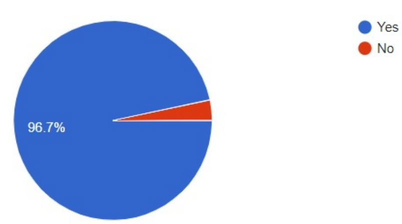

Figure 21: Is accurate collision prediction important for space traffic?

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