Threats Prediction to a Satellite by Detected Asteroids

Linesh Patil
Shah & Anchor Kutchhi Engineering College, Mumbai, India

Siddhi Khanvilkar
Shah & Anchor Kutchhi Engineering College, Mumbai, India

Ashish Shethia
Shah & Anchor Kutchhi Engineering College, Mumbai, India

Tulika Jain
Shah & Anchor Kutchhi Engineering College, Mumbai, India

Vidyulatta Devmane
Shah & Anchor Kutchhi Engineering College, Mumbai, India

Srikanth Kodeboyina
Blue Eye Soft Corporation, USA

1. ABSTRACT

The term "satellite" refers to a spacecraft that is launched into orbit around Earth or another celestial body. To fulfill the demand of our technological society, the number of satellites in near-Earth space is rapidly increasing. Launching a single satellite cost between $10 million to $400 million so if a satellite gets damaged then it is a great threat to the economy and resources. These satellites are launched for a certain mission but due to the collision of an asteroid satellite may damage leading to failure of mission. The outer space surveys have obtained a valuable understanding of the celestial bodies using the satellite's observation process. Therefore, it is a necessity to protect the satellite from any threat in space. That's why the interest in the detection and tracking of asteroids has grown dramatically over the previous few decades. At the same time, technology has also been increasingly growing, enabling well-known surveys and amateur mini-surveys to decorate their solutions to attain better consequences. In light of this situation, we are making an attempt using more reliable technology for detecting asteroids and predicting collision threat for satellites. There are numerous attempts, studies, researches and software to locate asteroids based upon which we have developed a system to detected asteroid in space and predicted threats to satellites. In this paper, we have used YOLO algorithm for real time detection and astrometric calculations to gain more accurate risk factor.

2. INTRODUCTION

Asteroids are small rocky objects orbiting the sun that are too small to be considered planets. These asteroids have peculiar shapes because they were produced by the collision of two gas clouds or planets. The asteroid count in space currently is 1,113,527 ranging between the size of 329 miles to 10 meters [1]. These asteroids revolve around the sun in their orbits but due to movements and forces of other planets and stars many times asteroid is pulled out from their orbit and then they interrupt other orbits and become threat to other space bodies. Now-a-days technology is getting more advanced day by day. Hence to know more about space movements and surface activities, artificial satellites are launched to keep an eye on all these movements. An artificial satellite is a man-made object that is sent into orbit using rockets. Currently, there are over a thousand operational satellites circling the Earth. A satellite's size, altitude, and design are determined by its mission.

A satellite is best viewed as a projectile, or an object that is solely subject to one gravitational force [2]. People have been able to use these satellites to make the world better by knowing the various forecast report. The globe is a secure and convenient place as with the help of satellite observations future earth movement can be predicted. Satellites enable in-flight device interactions aboard aircraft and are frequently used as the primary source of voice activation in rural areas when phone connections have been destroyed as a result of a disaster. Satellites are also the major source of timing for smart phones and landlines. This shows that satellite plays a vital role in the improvement and advancements of technology, so it’s a need to safeguard our launched satellites. Countries are enhancing their capacities for detecting, classifying, recognizing, and identifying (DCRI) unknown space objects as small and agile space objects continue to proliferate [3]. Numerous ASAT systems will entail testing, which will exacerbate an already severe debris problem. The following are some typical threats to satellites in space: First one is space weather, while space appears to be an empty and vacuum void, it is extremely complicated. Our solar system is blasted with cosmic rays and solar storm salvos of energetic particles, all of which may enter a satellite, wreak havoc on its electronics and in extreme circumstances render it inoperable. The second issue is space congestion. Currently, nearly 3,000 operational satellites orbit the Earth, and this number is growing due to an abundance of small satellite launch opportunities, primarily into low-Earth orbit (LEO), which increases the probability of accidents.

There are two types of collisions possibility with the artificial satellites that are intentional collisions and unintentional collisions. Intentional collisions are designed to destroy satellites, either to test anti-satellite weapons or to destroy satellites that could pose a risk if they reenter the atmosphere intact. The USA, Russia, China and India are the only countries who got success in destroying satellite by designing intentional collision [4]. In September 1985, U.S. Solwind P78-1 satellite was destroyed while testing USA ASM-135 anti-satellite missile [5]. On 27 March 2019, India tested anti-satellite weapon under Mission Shakti to destroy an Indian telecom satellite [6].

Unintentional collisions are the unpredicted collisions between satellites or orbital space bodies like asteroids. In August 1996, French microsatellite Cerise collided with space debris of Ariane rocket, and reported first case of active satellite and orbital debris collision [7]. On February 10, 2009, at a height of 776 kilometers, a privately owned communications satellite from the United States, Iridium 33, collided with a Russian Strela-2M military communications satellite, Cosmos 2251, in the first ever unintentional in-orbit collision between two spacecraft resulting loss to our economy and resources [8]. The debris of Chinese satellite Fengyun FY-1C destroyed in 2007 under ASAT test got collided with Russian BLITS nano-satellite on 22 January 2013 [9]. The most recent incident of such collision was reported on 18 March 2021, the debris of rocket Zenit-2 which was used to launched Tselina-2 in 1996 collided the Chinese satellite Yunhai-1 02 [10]. From the above cases, we observe that in collisions not only two colliding bodies are damaged but also creates havoc in space and increases threat to other space bodies. A single collision can create thousands of space debris which also orbit in space at high velocity for hundreds of years disturbing space stability and makes space more and more contested. Hence, protecting space assets becomes increasingly necessary.

The main focus of the paper is on predicting the threat to the satellite due to the moving asteroid in space. Now-a-days many geographic decisions like weather forecasts depend on the satellite predictions, in that case satellite protection is the major issue which needs to be solved. The objective of this paper is to detect the moving asteroid using real time detection techniques and then finding if the asteroid is going to collide with a satellite or not. We have done certain astrometric calculations to get more in-depth and accurate results.

Object Detection is done using You Only Look Once (YOLO) algorithm, a smart convolutional neural network (CNN). The YOLO algorithm divides full images into regions called bounding boxes. With YOLO, a single CNN predicts several bounding boxes at the same time and provides weights as probabilities for those boxes [11]. Because of non-max suppression, YOLO has high precision and is extremely fast. The backstop of the sensor will not be used to return any of the collected samples, but it will provide the algorithm with useful information about the asteroids that impacts the Space Debris Sensor (SDS) when it is in orbit when combined with the first two layers. The proposed technology will be able to precisely assess which objects pose a danger to the satellite.

The organization of the paper is as follows. The first section describes the related work done in the field earlier. The second section is about our proposed architecture and methodology for asteroid detection and risk factor calculation. The third section of this paper explains the results obtained by our methodology and discusses it with comparison to previous work. The last section of our paper provides conclusions for our proposed research work and future improvements.

3. RELATED WORK

Zhihao Chen et al. presented work using deep learning for real-time object detection, tracking, and distance and motion estimation [12]. They devised an algorithm based on the SSD method's output bounding boxes' coordinates. The purpose is to see if a pedestrian's or a vehicle's path can lead to a dangerous situation. The entire procedure is being tested in real-world traffic conditions in Rouen's city centre, as well as footage acquired by embedded cameras along the Rouen tramway. The SSD and YOLO V3 object recognition and tracking algorithms were compared in the paper. For optimising their performance on low-consumption devices, they may need a large and appropriate dataset. Increasing the number of detection classes won't make a significant difference.

J. C. Green et al. have done great work for Developing a Comprehensive Application for Satellite Anomaly Analysis and Attribution [13]. By providing tools that bring together all of the necessary components and simplify the analysis process for end users, the paper aims to enable effective anomaly analysis and attribution. A comprehensive satellite anomaly attribution tool is being developed here. While there is little that can be done to prevent space radiation anomalies once they are in orbit, the models and tools presented here will provide real-time data for making confident decisions in the event that problems arise and will help to ensure that satellite operations remain stable in the future.

Alejandro Pastor et al. have presented the work for Satellite maneuver detection with optical survey observations [14]. During cataloguing activities, a novel method for impulsive maneuvers identification and estimation for the relationships of tracks and orbits has been presented. Results of the track-to-orbit and orbit-to-orbit methods is obtained using the simulated and real observations

L. Mugnier et al. have worked for LEO satellite imaging with adaptive optics and marginalized blind deconvolution [15]. As per paper Space Situational Awareness has emerged as a critical issue for both defence and civilian applications. The identification of potential or active threats, as well as the monitoring of critical assets and operations, are at stake. The paper discusses recent advances in image post-processing based on marginalized blind deconvolution in conjunction with parsimonious PSF modelling. However, the majority of a LEO satellite's available time of visibility is below 30°, resulting in a significant reduction in observation or link duration for optical telecommunication. Furthermore, satellite observation is limited to a few hours at night.

Geoffrey D. Reeves et al. have presented the Hazards to Satellites and how to Mitigate its Risks [16]. The paper discussed several current aspects of radiation belt research, focusing on those most relevant to space weather applications - where the term "space weather" refers to both natural and anthropogenic conditions. The most well-documented example is a large interplanetary shock event that produced an extremely intense belt of MeV electrons at L-shells where a HANE belt would be expected. The event was observed by the USAF/NASA Combined Release and Radiation Effects (CRRES) satellite in March 1991 and was still very strong when the mission ended in October of the same year.

Houman Hakima et al. have explained the Space-Object Identification Satellite (SOISat) Mission [3]. This paper describes the mission design, operational concept, and system design for the Space Object Identification Satellite, or SOISat, a Canadian Space Situational Awareness system. Simulation scenarios are included to validate SOISat's performance in detecting and tracking resident space objects of interest. Future research should look into the systems engineering of SOI payload instruments and the spacecraft bus. Furthermore, the formation-keeping maneuvers that SOISat may be required to perform during the mission should be defined, as well as the amount of propellant required.

4. METHODOLOGY

The satellite plays an important role to keep track of outer space activities. They are becoming increasingly significant in developing countries for a variety of purposes, including communication, oceanography, astronomy, and security. They assist numerous scientists in obtaining a perspective view of various items anywhere on the planet. One of the advantages of satellites is that they can capture more data faster than ground-based devices. Satellites can also look further into space than terrestrial observatories. This orbiting population's expansion now appears to be a foregone conclusion. On the one hand, the decreasing costs of access to space as a result of satellite miniaturization and lower launch costs encourages an increasing number of factors to participate in these activities, which proliferate. The accumulation of trash, exacerbated by the increasing risk of collisions between them, has resulted in an increase in the number of accidents. There are many existing software and platforms like LeoLabs which provides tracking and mapping of space debris using radar system which may be time consuming when come to predicting threat to satellite [17].

As a solution to this problem, we have tried to develop a system which will detect the asteroid in the space and based on some astrometric calculations will predict the risk factor. Below Fig. 1 show the pipeline of our proposed solution.

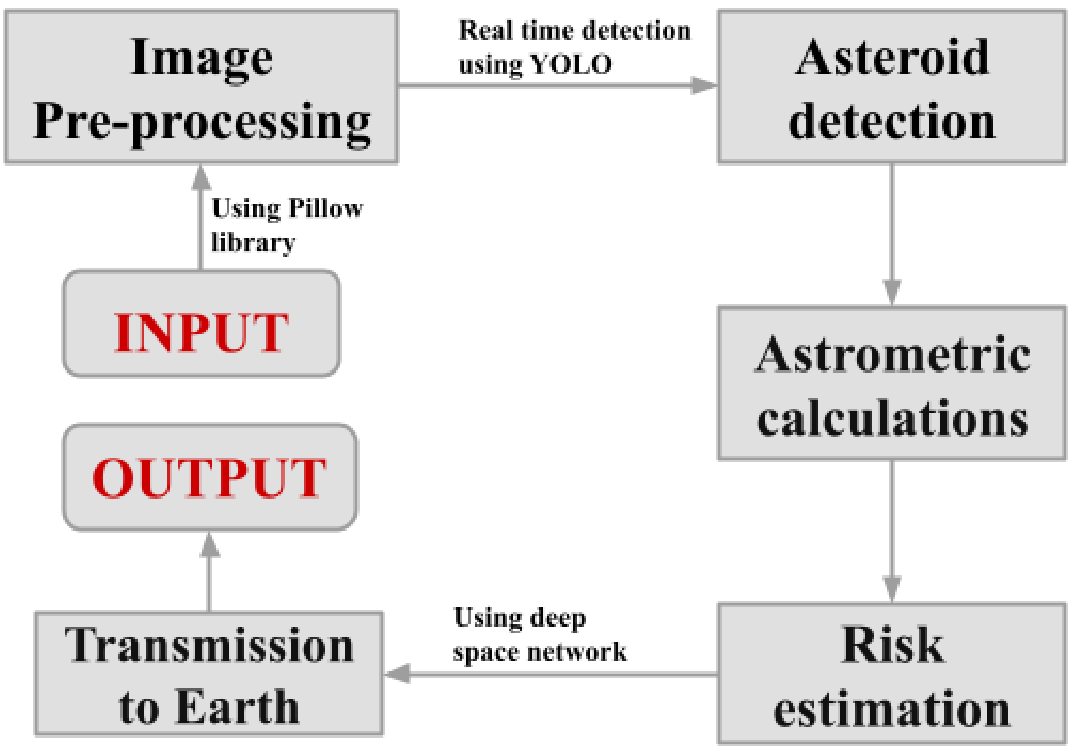

Fig. 1. Block Diagram of Proposed Methodology

4.1 Dataset

The proposed system requires a dataset of space images captured by the satellite after periodic intervals for that particular area. Images should be clear so that algorithm could get trained perfectly else image pre-processing is needed to be done to make them clear. The accuracy of the system depends on the data training for the future detection. More the number of images more will be the accuracy of system. For high accuracy of system nearly 10,000 images are required in the dataset.

The images are obtained from various technical sources and space-based websites like National Oceanic and Atmospheric Administration (NOAA) and Jet Propulsion Laboratory (JPL). Every day, NOAA collects hundreds of gigabytes of data from satellites, radars, ships, weather models, and other sources. The NOAA Big Data Project (BDP) was formed to investigate the benefits of retaining clones of critical observations and objectives identified in the Cloud system in order to perform direct calculations on the data without the need for further dissemination [18]. JPL is in charge of NASA's Center for Near-Earth Object Studies, which keeps track of planetary bodies that pass near to Earth's orbit [19]. Photojournal by JPL is interface to the Planetary Image Archive (PIA) contained within the Planetary Data System Imaging Node. The home page graphic serves as a high-level entry point to the thousands of high-resolution images and their accompanying products which have been made available to the public from data returned by various JPL missions over the course of many years.

In supervised learning algorithm, we are needed to split the dataset in two parts, testing and training. Training set is a subset of dataset used to train a model. This trained model is tested on another subset of dataset called as testing data. The train-test data splitting is done to estimate the performance of algorithms when used to make predictions on testing data. We have split the data as 28% testing and 72% training as shown in Fig. 2. More the data we train more is the accuracy, hence training set is always taken bigger than that of testing set.

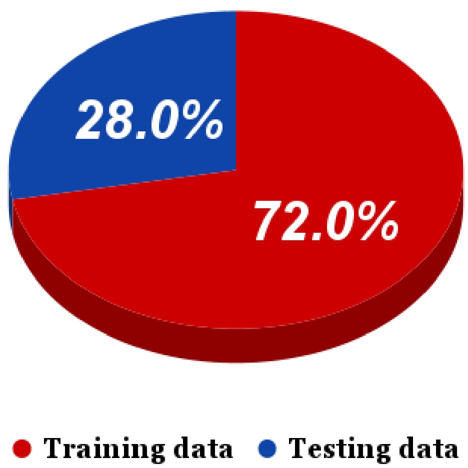

Fig. 2. Data Splitting Ratio

4.2 Pre-processing

The training set of data needs to be pre-processed for removing noise from images. The Python library Pillow is used to remove background noise. Once the images are processed and cleared then we can label the objects in that image. Programmers can add as much as classes while labelling such as planets, comets, satellites as per expected result after detection. According to classes images are labeled using OiDv4 toolkit. Below Fig. 3 shows the labelling of objects using OiDv4 toolkit.

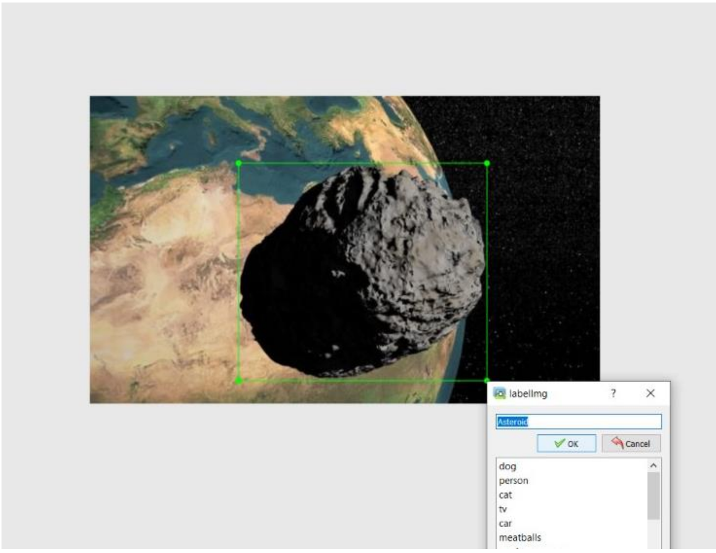

Fig. 3. Labelling using OiDv4 toolkit

We have used Google Collab as a platform for implementation. Imported darknet repository from GitHub for downloading pre-define weights. Following Fig. 4 is the flow chart of system setup form stage of data labelling to testing.

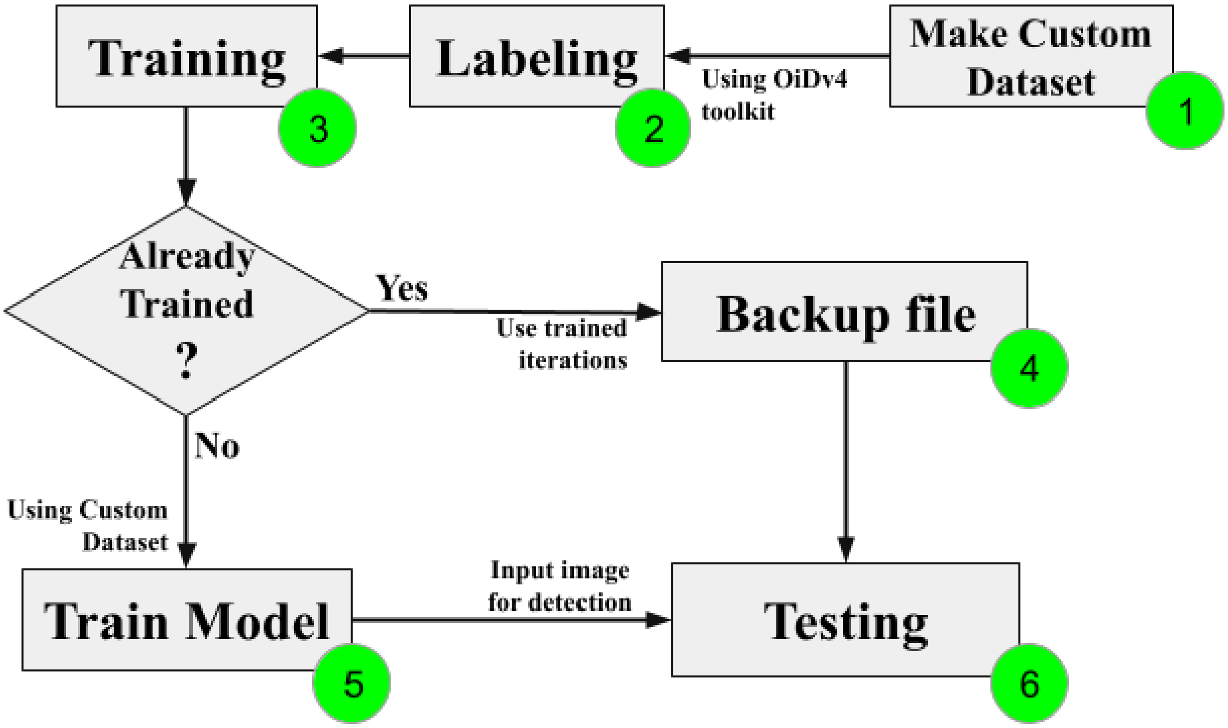

Fig. 4. Flow for Data Training & Testing

a. Custom Dataset: -

Dataset is the most important part of any system, so it is necessary to identify the correct needed images for the training of models. Hence, we have to make a custom dataset by collecting images from various sites and saving them locally in one folder and removing irrelevant images. We need to make sure that each image in the dataset folder is of the same extension.

b. Labeling: -

We have to manually make bounding boxes around each object and label them accordingly for all images using OiDv4 toolkit which uses python library labeling. It will generate a text file with class id and image dimensions.

c. Training: -

The dataset labeled in previous stage will be used to train model. If model is already trained then will send to backup file else will train it using custom dataset.

d. Backup File: -

We have to create a backup folder to store the labels which have been trained. After every 100 iterations a new file is made in the backup folder. The backup weights can be used after the model is trained successfully.

e. Train model using custom dataset: -

The model fetches the configuration file and trains the images according to given values. It unzips the dataset and reads the text file generated in the labelling section. It is recommended to train the model for a high number of iterations though the time required would also increase.

f. Testing: -

We can use images of any format or size for testing. The images need to be stored in the right directory or else it would not show up.

4.3 Detection of Asteroid

The satellite will have the camera fitted in it, which will be used as source of input for real time detection of asteroid. We have used the YOLO algorithm for real time detection where predictions are made from one single network. It can be trained end-to-end to improve accuracy. YOLO is more generalized [20]. It outperforms other methods when generalizing from natural images to other domains like artwork. YOLO algorithm is very versatile and can also be used in real time detection. The biggest advantage of using YOLO is its superb speed – it's incredibly fast and can process 45 frames per second. YOLO accesses the whole image in predicting boundaries. With the additional context, YOLO can demonstrate fewer false positives in background areas. Using this algorithm, we can detect real time objects fast and accurately. Below Fig. 5 shows that the asteroids are detected and bounding are made covering each of them.

Each bounding box of asteroid is labelled as asteroid along with the accuracy percentage. As while labelling the data, we have only created a class for asteroid and have trained data only for asteroid. Hence, in output image we can see that earth is not detected and is unbounded. This shows that the algorithm is giving accurate results.

Fig. 5. Detected Asteroids

4.4 Astrometric calculation

After the asteroids are detected then we need to find the threat to satellite due to that detected asteroid. To calculate the threat to satellite we need to consider some parameters like size, direction, velocity and time of collision. The values of these parameters are calculated using concepts of astrometric calculations. Fig. 6. shows the flow of our astrometric calculations.

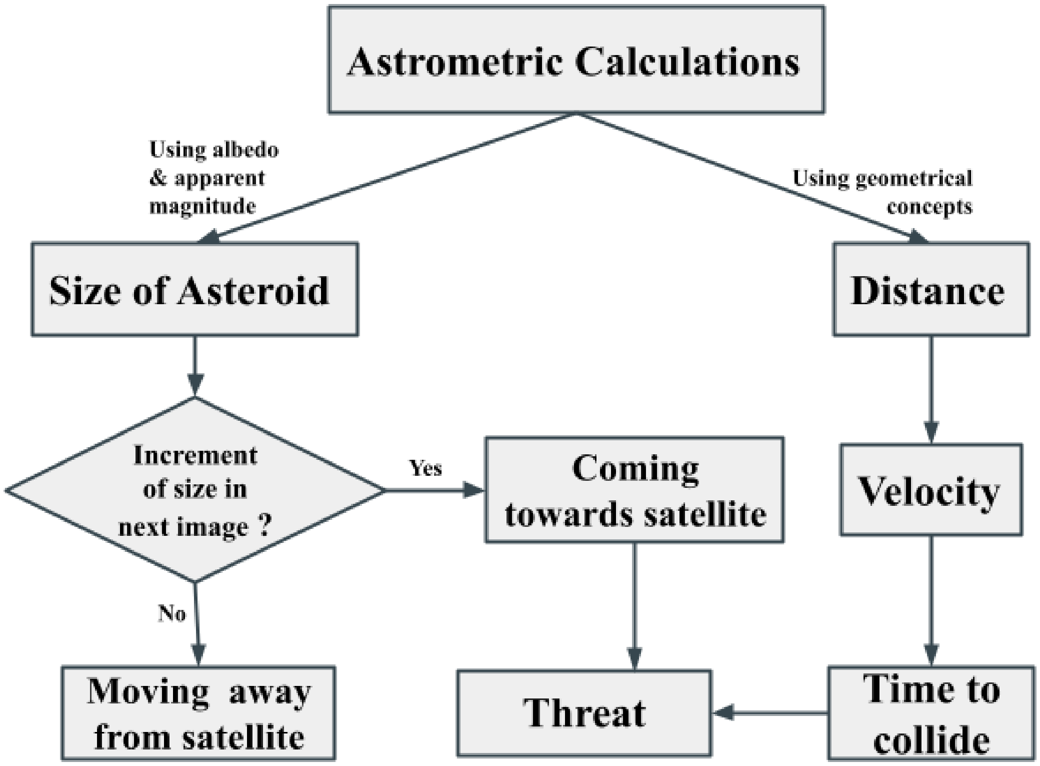

Fig. 6. Astrometric Calculation

Satellite protection is totally depending on the accuracy of astrometric calculations. Hence, it is needed Hence, it is needed take proper formulae and assumptions for predictions of the threat. In the below Fig. 7 showing asteroid movement towards satellite, we have highlighted the parameters and abbreviations used in the calculation. Suppose, distance between satellite and asteroid of diameter 'D' is 'S_1' and asteroid travel from the one position 'P_1' to other position 'P_2' in the time 't' resulting change in distance to 'S_2'.

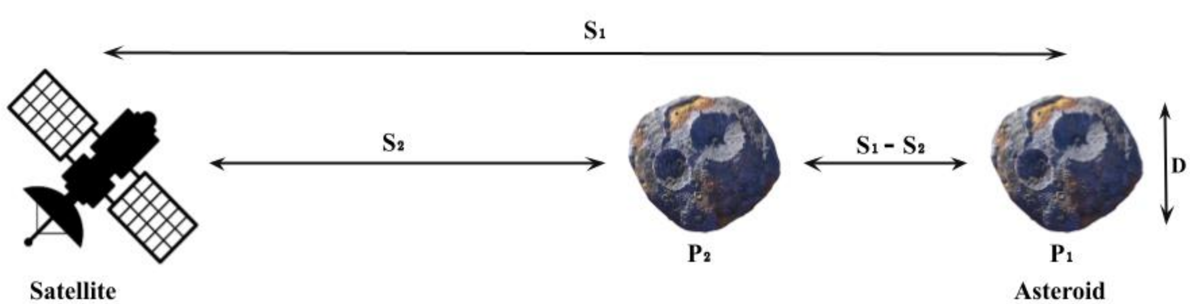

Fig. 7. Asteroid Movement

4.4.1 Size

Using all these above stated parameters will first calculate the size using diameter of asteroid. Asteroids don't have any particular shape but are majorly circular or oval, so we will find diameter of asteroid and then using area of circle formula will find its size. An asteroid's diameter can be estimated using its absolute magnitude 'M' and an assumed geometric albedo 'a' [21] as in equation (1).

$$\boldsymbol{D = \frac{10^{-0.2M}}{\sqrt{a}} \times 1329\ km} \quad \textbf{(1)}$$

The absolute magnitude of the asteroid is calculated using equation (2) having parameters as distance of asteroid from satellite and sun along with the observed magnitude of asteroid while detection.

$$\mathbf{M}\ (\theta) = \boldsymbol{m - 5\ log(d_e \times d_s)} \quad \textbf{(2)}$$

Here,

D - Diameter

M - the absolute magnitude of the asteroid

a- albedo[1]

m - observed magnitude[2]

d_e- Distance of asteroid from satellite

d_s- Distance of asteroid from the sun (assumed as 1AU)

θ - phase angle (assumed earth-sun-asteroid angle to be zero)

4.4.2 Direction

Now, to find the direction of movement of the asteroid we will have to calculate size of the asteroid twice for two different positions of asteroids. Like once the model detects a bounding box labelled as "asteroid", the model will calculate the size of asteroid using above mentioned formula. After a significant time, model will again try to find that object and if it gets detected again, then the model again calculates size of the asteroid. If the size of asteroid is increased in the second detection, then that means asteroid in moving close to the satellite and may hit the satellite. But if the size of asteroid is decreased then that justifies that asteroid is moving away from the satellite and it's not a threat.

4.4.3 Distance

Triangle similarity will be used to determine the distance between our camera and the detected asteroid.

$$\boldsymbol{S_1 = \frac{D \times F}{P}} \quad \textbf{(3)}$$

Here,

S_1= Distance of a satellite from the asteroid

D= Diameter of an asteroid

F= Focal length of the camera fixed in satellite

P= Apparent width in pixels

For applying this formula, we need to have the width of the object i.e. (D) the diameter of our detected asteroid, the focal length of the camera that we are using in the satellite to take pictures (F) and finally the apparent width in pixels (P). Using the above equation (3), we can determine the distance between asteroid and the satellite [22].

---

[1] Albedo of an earth crossing asteroid is assumed as 0.1 and its common range is from 0.05 to 0.25.

[2] The size of an asteroid as measured with a CCD camera using a suitable method to extract.

4.4.4 Velocity

Velocity is defined as displacements upon time. As the above Fig. 7 shows asteroid displacement is 'S_1-S_2' within the time interval of 't'.

$$V = \frac{S_1 - S_2}{t} \qquad \textbf{(4)}$$

Here,

V= Velocity of an asteroid

S_1= Distance between satellite and asteroid at P_1

S_2= Distance between satellite and asteroid at P_2

t= Time taken by the asteroid to travel from position P_1 to P_2.

4.4.5 Time

Time is often calculated using the concepts of motion. Time is defined as displacement upon velocity. Here, total displacement of asteroid is 'S_1' and the velocity 'V' which was calculated using equation (4). Therefore, Time to collide the asteroid with satellite can be calculated using equation (5).

$$Time = \frac{S_1}{V} \qquad \textbf{(5)}$$

Now, depending upon the values of these above astrometric calculations will try to predict the threat probability to the satellite. The astrometric calculations and threat probability will be transmitted to the earth stations as many satellites like NEOSSat are not efficient to perform the estimations of space bodies while orbiting [23]. At earth space stations, depending on this information it will be easy to decide which defence technique is to be used for the satellite protection.

5. Result

As the outcome of our proposed pipeline, we will the detected asteroid for which we will do astrometric calculations. Below Fig.8 and Fig. 9 shows the detected asteroid at two different positions at a time interval of an hour. Based upon these two output figures will calculate the threat to satellite.

Fig. 8. Asteroid at P_1

Fig. 9. Asteroid at P_2

Table 1. Size of Asteroid

Parameter	At P_1	At P_2	Change in size (P_1-P_2)
Diameter	4.2 km	1.1 km	6.8 km

As mentioned in Table 1, the diameter of asteroid at position P_1 is 4.2 km while at position P_2 it is 11km. The change in size is positive that means there is increments in size and asteroid is approaching the satellite. As asteroid is coming towards the satellite, it's a threat. Hence, now we need to find time for collisions so that proper satellite protection techniques can be used. For calculating time, we need distance between satellite and asteroid and velocity of asteroid. Table 2 shows the results for distance between satellite and asteroid at different positions

.

Table 2. Distance of Asteroid

Parameter	S_1	S_2	Change in size (S_1-S_2)
Distance	15.3 km	7.4 km	7.9 km

Now, we have change in distance in given time interval 't' equal to 1 hour, hence velocity of the asteroid will be 7.9 km per hour. Hence time to collide will be 1.94 hours. Table 3 shows the calculations for time of collision.

Table 3. Time to collide

Parameter	Formula	Calculation	Output
Time	$Time = \frac{S_1}{V}$	$Time = \frac{15.3}{7.9}\ hr$	**1.94 hours**

6. Conclusion

The number of satellites in near-Earth orbit is growing rapidly to meet the demands of our technological society. Protecting our properties becomes more important as space gets more congested and contested. The satellite is prone to various debris in space which can pose a great threat. Resulting interest in the detection and tracking of Asteroids has grown dramatically over the previous few decades. With the appropriate dataset and system setup we have obtained real time detection using YOLO algorithm though camera fitted in satellite. The satellite will identify any risk in its immediate vicinity. Because the area for detection from Earth via telescope or sequential photos is so less, then the satellite protection process or the discovery of hazards near any satellite may be delayed. We have used the latest technology YOLOv4 for more precise detection of asteroids from images. Since YOLOv4 is extremely fast and accurate, it looks at the whole image at test time so its predictions are informed by the global context in the image. It also makes predictions with a single network evaluation and hence it makes the process of detection more reliable and less time consuming. The main outcome of this system is to detect any threat that is posed to a satellite from an asteroid. Once this threat is successfully determined we can send a signal to earth so necessary actions can be taken to protect the satellite from the detected asteroid.

The research work done can be utilized for other space assets and planetary defence as well. The work can be done to get more accurate trajectory of the asteroid moving towards the satellite. In future, more powerful algorithms can be used to get accurate results in less amount of processing time.

7. References

[1] NASA's Jet Propulsion, "Solar Syatem Exploration," NASA, 7 July 2021. [Online]. Available: https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/overview/?page=0&per_page=40&order=name+asc&search=&condition_1=101%3Aparent_id&condition_2=asteroid%3Abody_type%3Ailike.

[2] E. Howell, "What is a Satellite?," Space.com, 30 September 2020. [Online]. Available: https://www.space.com/24839-satellites.html.

[3] H. Hakima, *et al* "Space-Object Identification Satellite (SOISat) Mission," in *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2020.

[4] "Anti-satellite weapon," Wikipedia, 10 August 2021. [Online]. Available: https://en.wikipedia.org/wiki/Anti-satellite_weapon.

[5] "Vought ASM-135A Anti-Satellite Missile," National Museum of The United States Air Force, 14 March 2016. [Online]. Available: https://www.nationalmuseum.af.mil/Visit/Museum-Exhibits/Fact-Sheets/Display/Article/198034/vought-asm-135a-anti-satellite-missile/.

[6] "Frequently Asked Questions on Mission Shakti, India's Anti-Satellite Missile test conducted on 27 March, 2019," Ministry of External Affairs, Government of India, 27 March 2019. [Online]. Available: https://www.mea.gov.in/press-releases.htm?dtl/31179/Frequently_Asked_Questions_on_Mission_Shakti_Indias_AntiSatellite_Missile_test_conducted_on_27_March_2019.

[7] D. D. R. Williams, "Cerise," NASA, 29 August 2021. [Online]. Available: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1995-033B.

[8] B. Weeden, "2009 Iridium-Cosmos Collision," 10 November 2010. [Online]. Available: https://swfound.org/media/6575/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf.

[9] L. David, "Russian Satellite Hit by Debris from Chinese Anti-Satellite Test," space.com, 9 March 2013. [Online]. Available: https://www.space.com/20138-russian-satellite-chinese-space-junk.html.

[10] M. Wall, "Space collision: Chinese satellite got whacked by hunk of Russian rocket in March," space.com, 17 August 2021. [Online]. Available: https://www.space.com/space-junk-collision-chinese-satellite-yunhai-1-02.

[11] Z. Chen, R. Khemmar, B. Decoux, A. Atahouet and J.-Y. Ertaud, "Real Time Object Detection, Tracking, and Distance and Motion Estimation based on Deep Learning: Application to Smart Mobility," in *Eighth International Conference on Emerging Security Technologies (EST)*, 2019.

[12] B. Strbac, *et al* "YOLO Multi-Camera Object Detection and Distance Estimation," in *2020 Zooming Innovation in Consumer Technologies Conference (ZINC)*, 2020.

[13] J. C. Green, *et al* "Developing a Comprehensive Application for Satellite Anomaly Analysis and Attribution," in *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2020.

[14] A. Pastor, *et al* "Satellite maneuver detection with optical survey observations," in *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2020.

[15] L. Mugnier, *et al* "LEO satellite imaging with adaptive optics and marginalized blind deconvolution," in *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2020.

[16] G. D. Reeves, *et al* "Earth's Radiation Belts: The Hazards to Satellites and What Can Be Done to Mitigate the Risks?," in *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2020.

[17] A. Archuleta, *et al* "Space Debris Mapping Services for use by LEO Satellite Operators," in *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2018.

[18] "NOAA Data and Software for Commercial Use," NOAA, [Online]. Available: https://techpartnerships.noaa.gov/Partnerships-Licensing/Data-and-Software.

[19] "Asteroid Watch," Jet Propulsion Laboratory, [Online]. Available: https://www.jpl.nasa.gov/asteroid-watch.

[20] J. Fletcher, *et al* "Feature-Based Satellite Detection using Convolutional," in *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2019.

[21] "Asteroid Size Estimator," Jet Propulsion Laboratory, [Online]. Available: https://cneos.jpl.nasa.gov/tools/ast_size_est.html.

[22] A. Rosebrock, "Find distance from camera to object/marker using Python and OpenCV," pyimagesearch, 19 January 2015. [Online]. Available: https://www.pyimagesearch.com/2015/01/19/find-distance-camera-objectmarker-using-python-opencv/.

[23] R. ‘. Scott, *et al* "On-Orbit Observations of Conjuncting Space Objects Prior to the Time of Closest Approach," in *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2019.