An Efficient Algorithm for Collision Avoidance Between a Solar Array Satellite and Space Debris[1]

Varun Ahlawat
New Delhi, India

DOI:10.37648/ijrst.v12i04.004

Received: 24 August 2022; Accepted: 06 November 2022; Published: 01 December 2022

ABSTRACT

Half of the risk to any satellite is from debris collision. The main body of the satellite, housing the main electronics is encapsulated by bulletproof outer layers but most satellites include solar panels as the only energy source and they cannot be covered with multiple kevlar layers or any safety material. As space junk keeps on increasing, we seek to mitigate the tragedies related to it. Every collision in turn creates many new space junk particles which drives a positive feedback chain reaction, which could ultimately lead to a phenomenon known as "Kessler Syndrome"[1], which can render whole space unusable altogether. Several private companies like "LEO-Space" and government agencies are working to help solve this issue, yet some countries perform anti-satellite operations for military purposes each of which creates more than tens of thousands of pieces greater than 0.5 centimetres (that cannot be stopped by layers of protective material) traveling at relative speeds of up to 12km/sec on an average(which usually stay in their orbits for more than 100 years, depending on their altitudes and orbit). China (in 2007), the USA (in 2009), India (in 2019), and Russia (in 2021) have performed these so-called "tests" in the orbits of the altitude of the international space station creating countless debris of various sizes that would stay as a threat in most used orbit i.e. LEO(roughly 160km to 2000km above the earth's surface).

INTRODUCTION

Today in Low Earth orbit there are a total of more than 5,00,000 identified objects greater than the size of a marble(1/2 inch), and more than 50,000 objects up to 4 inches. The satellites which have to use large solar arrays with an orbit within LEO, i.e. within 2000 km above the earth's surface are highly vulnerable to this debris, and to prevent their collision we can use many different methods, one of which is physical deflection. One of the most common ways that are used by ISS–is to slightly change the orbit. But for that, information about the debris' trajectory has to be known at least a few hours before the nearest approach. For the longevity of say 50 years, especially for future projects such as space-solar farms, a live deflection algorithm is presented in this paper. That could prevent collision without any prior information about the debris' trajectory even a few minutes ago. The following paper discusses the most efficient logic which can be integrated with a lidar or em wave-based parallax detection system using machine learning to track down those hypersonic speed particles and take live action–based on the position and velocity vector.

The probability of a satellite in the LEO, colliding with space debris is more than 30% in the span of a year. So for a satellite to operate in LEO for 30 years would[2]. The probability of such a collision is roughly 99.997746%.

Shortcomings of Debris Assessment Software (DAS) and similar ground-based debris detection techniques:

In a full lifespan of a solar array satellite, there will be numerous interactions with undetectable and untraceable objects, that are hard to be accounted for using ground-based Debris Detection Software, which keeps track of all identifiable objects. There has to be a live debris detection system that can not only detect the debris' position, but also the velocity with respect to the satellite and solar plane of its solar array. Having more and more such solar array satellites can help track the debris, which can then be updated into the DAS or a universal library with all potentially dangerous pieces of debris[3].

[1] *How to cite the article:* Ahlawat V., An Efficient Algorithm for Collision Avoidance Between a Solar Array Satellite and Space Debris, IJRST, Oct-Dec 2022, Vol 12, Issue 4, 14-24, DOI: http://doi.org/10.37648/ijrst.v12i04.004

Both working in tandem can help in almost eradicating any further increase in space debris and related accidents.
Having such a robust database of all debris could mitigate calamities with the satellites even without the detectors or modular structure, required for collision avoidance.

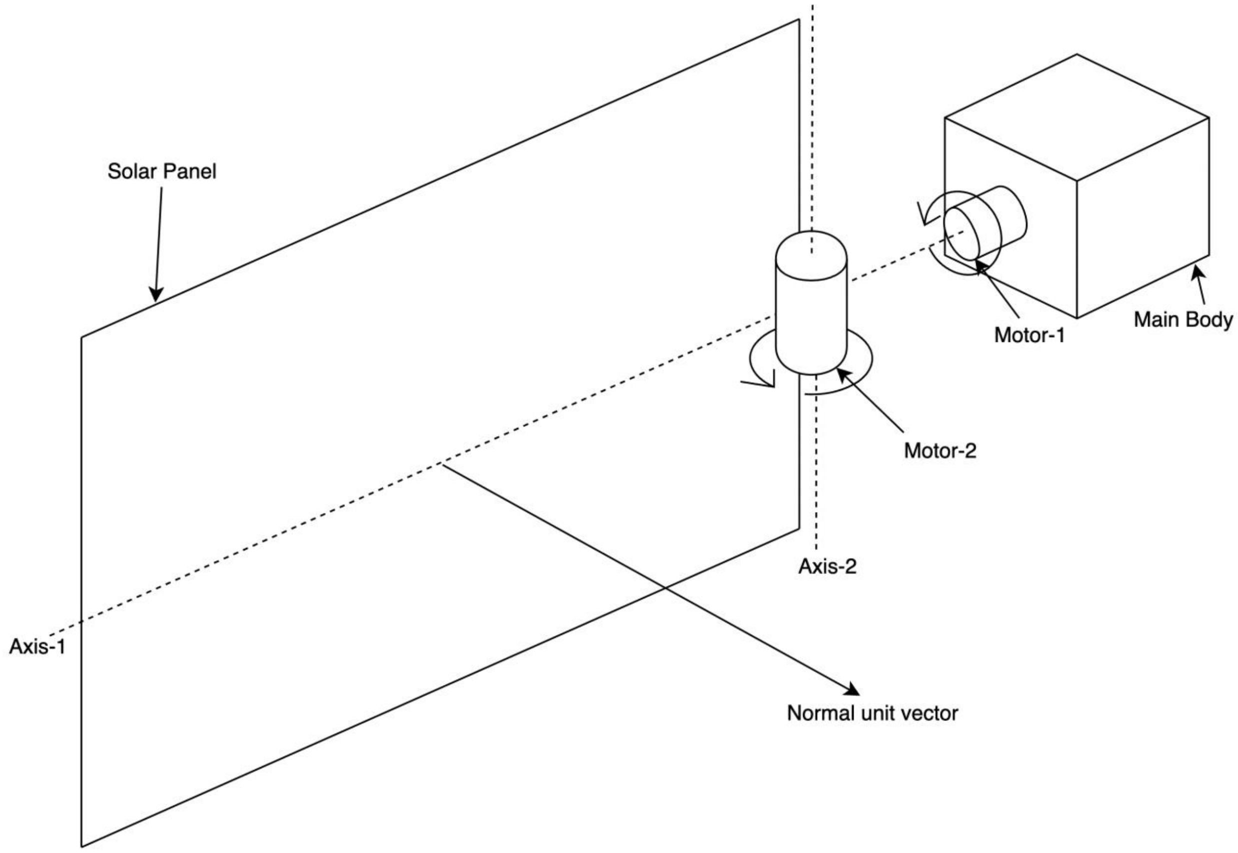

Fig. 1.1 Expanded view of the structure - rigid solar panel's connection to the main body.

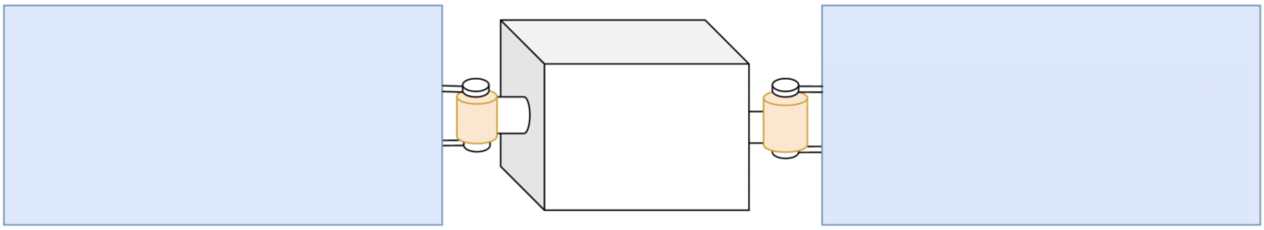

Fig. 1.2 General overview.

Default notations every time debris comes in proximity:
$\hat{a}$ = direction of the Axis1
$\hat{b}$ = direction of the Axis2
$\vec{n}$ = normal vector for the panel/plane for any given moment
Defining the $\hat{\imath}, \hat{\jmath}, \hat{k}$ initial:

$$\vec{a} = \hat{k}$$
$$\vec{b} = \hat{\jmath}$$

Also;

$$\vec{n} = \hat{b} \times \hat{a}$$
$$= \hat{\imath}$$

With these notations as a reference, the algorithm will proceed.

Detecting the debris:

With the help of machine learning algorithms, hypersonic debris could theoretically be detected within the darkness of space. But because of the average relative speeds of about 10 km/s, the accurate detection of such debris could be dauntingly difficult to implement and has to be done from at least a few kilometers away in order to have even the slightest chance for the avoidance algorithm to successfully avoid.

Even with two 360-degree gimbal high-speed cameras, having a zoom lens camera on each and with sufficient parallax will be able to–first spot, and then detect the debris live[4]. But there has to be some mechanism for the gimbals to know where to point each of the cameras–in order for the object's velocity and position vectors could be precisely calculated from the footage.

A high-precision Radar will first have to confirm the presence of the debris, then in the direction of that debris, gimbals will be actuated finally pointing both cameras towards it. Then machine learning detection algorithms could be used over the input data from the two zoom lens cameras, detecting the debris from a few kilometers away, to determine:

a. The position vector.
b. The velocity vector[5-8].

After the detection of the position vector of the debris:

The position vector of the center of visible area will be assumed as the center of mass of the particle itself, and an error corresponding to the farthest point will be considered(to take into account the size/dimensions of the debris), which could be sampled across multiple frames for better accuracy:

$$\vec{N_o} = \begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix}$$

The velocity vector of the debris(which will be constant with time), in the initial frame of the satellite's motion:

$$\vec{V} = \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix}$$

In the small duration of the interaction, the following would be a fairly precise position of the particle at any time t could :

$$\vec{N} = \begin{bmatrix} X_o + t.V_x \\ Y_o + t.V_y \\ Z_o + t.V_z \end{bmatrix}$$

Determining the impact location:

We can resolve the complicated two-dimensional rotation, about two perpendicular axes, of the panel into the following, two, simpler transformations:

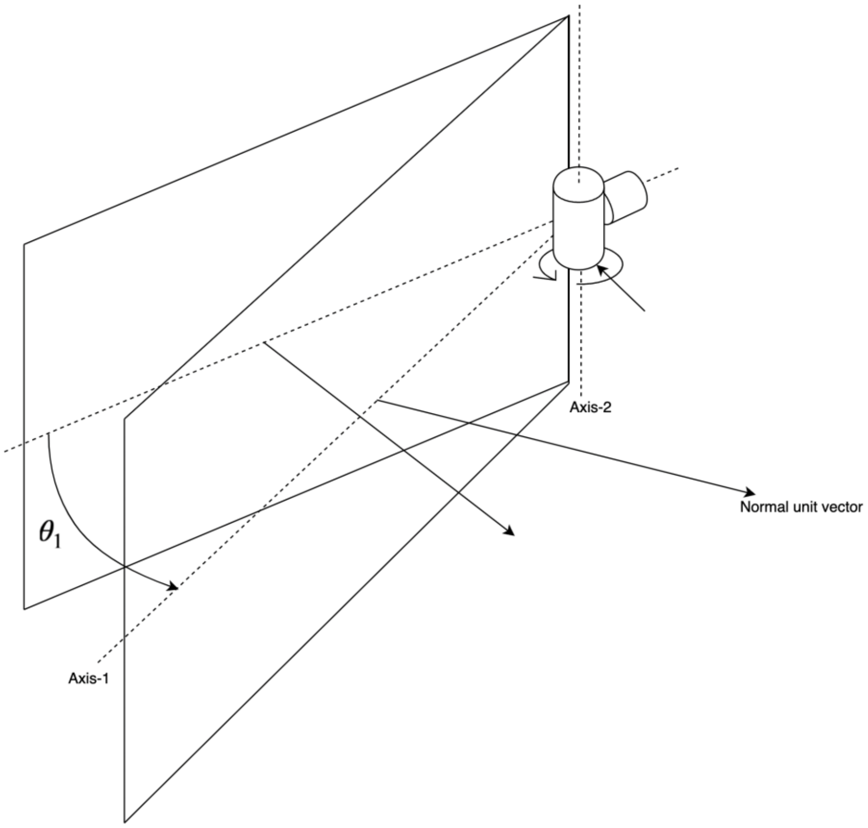

Fig. 2.1. $Axis1 \rightarrow \theta_1$

Angle traversed by Axis-1 = θ_1. And after the transformation, of angle θ_1, about Axis2, as shown above in the *Fig. 2.1;*

$$\hat{a} = < \sin\theta_1, 0, \cos\theta_1 >$$
$$\hat{b} = < 0,1,0 >$$

The vectors $\hat{n}, \hat{a}, \hat{b}$ will always be mutually perpendicular, therefore the normal vector after the transformation will be:

$$\vec{n} = \hat{b} \times \hat{a}$$
$$\vec{n} = < \cos\theta_1, 0, -\sin\theta_1 >$$

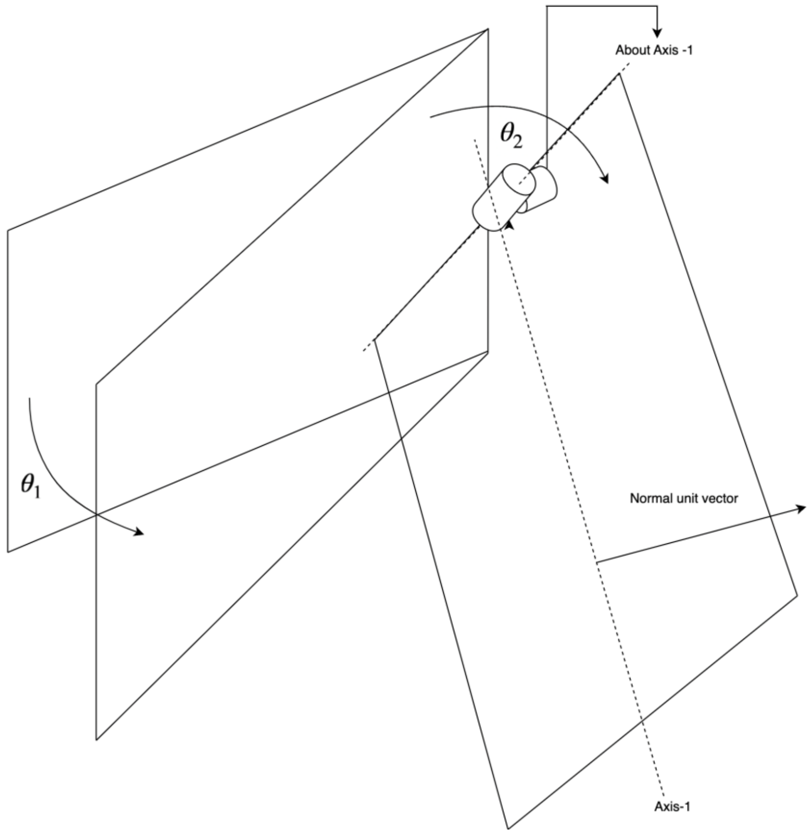

Fig. 2.2. $Axis2 \rightarrow \theta_2$

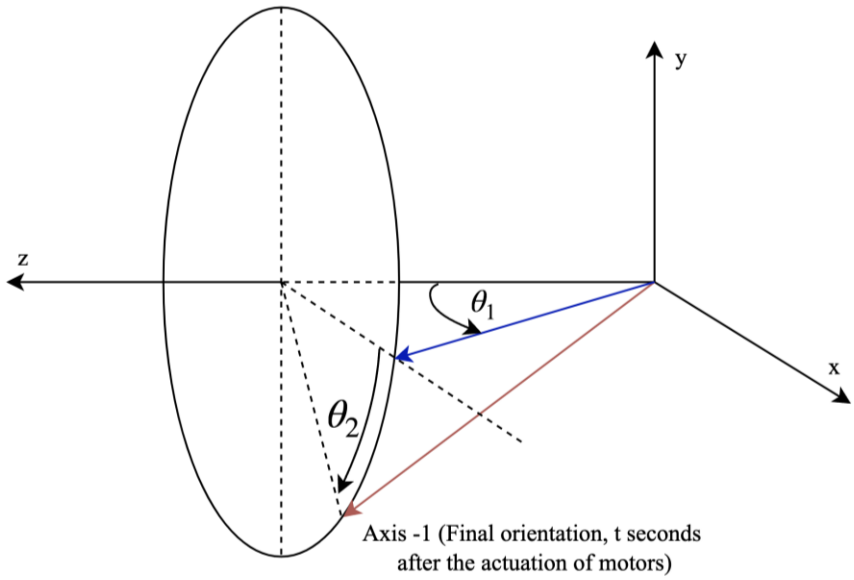

Fig. 2.2.1 Transformation of the Axis1 due to the rotation: $\theta_2 \rightarrow Axis2$

After the final transformation;

$$\hat{b} = < \sin\theta_2, \cos\theta_2, 0 >$$
$$\hat{a} = < \sin\theta_1 \cos\theta_2, -\sin\theta_2, \cos\theta_1 >$$
$$\vec{n} = \hat{b} \times \hat{a}$$

$$= < \sin\theta_2, \cos\theta_2, 0 > \times < \sin\theta_1 \cos\theta_2, -\sin\theta_2, \cos\theta_1 >$$

After the cross-product:

$$\vec{n} = \begin{bmatrix} \cos\theta_1 \cos\theta_2 + \sin\theta_2 \\ -\sin\theta_2 \cos\theta_1 \\ -\sin^2\theta_1 - \sin\theta_1 \cos^2\theta_2 \end{bmatrix}$$

With the help of the above normal vector transformation at t seconds after the actuation we can now find out the equation of the plane, assuming that the equation for planes of both the panels would be the same, the equation of plane 1 & plane 2 of the panels at t seconds after the detection and taking the origin as the intersection of the two axes, the equation of the plane of the array will be the following:

$$\begin{bmatrix} \cos\theta_1 \cos\theta_2 + \sin\theta_2 \\ -\sin\theta_2 \cos\theta_1 \\ -\sin^2\theta_1 - \sin\theta_1 \cos^2\theta_2 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} = 0$$

$$x(\cos\theta_1 \cos\theta_2 + \sin\theta_2) + y(-\sin\theta_2 \cos\theta_1) + z(-\sin^2\theta_1 - \sin\theta_1 \cos^2\theta_2) = 0$$

For now assuming that the equation for planes of both the panels would be the same, the equation of plane 1 & plane 2 of the panels at t seconds after the detection:

$$x(\cos\theta_1 \cos\theta_2 + \sin\theta_2) + y(-\sin\theta_2 \cos\theta_1) + z(-\sin^2\theta_1 - \sin\theta_1 \cos^2\theta_2) = 0$$

The perpendicular distance of the debris from the panels' plane (both panels would be parallel at any given instant, oriented normally so that the maximum solar radiation can incident on it):

$$p = \frac{(X_o + t.V_x)(\cos\theta_1\cos\theta_2 + \sin\theta_2) + (Y_o + t.V_y)(-\sin\theta_2\cos\theta_1) + (Z_o + t.V_z)(-\sin^2\theta_1 - \sin\theta_1\cos^2\theta_2)}{\sqrt{(\cos\theta_1\cos\theta_2 + \sin\theta_2)^2 + (-\sin\theta_2\cos\theta_1)^2 + (-\sin^2\theta_1 - \sin\theta_1\cos^2\theta_2)^2}} \quad (I)$$

Finding the θ_1 & θ_2 as functions of time:

The angular displacements about axis 1 and 2 from the ground frame on maximum power outputs on both motors simultaneously, after the debris detection, from the motors are θ_1 and θ_2 respectively. In space, if one of the panels will be rotated in any direction, the rest of the satellite would rotate in the opposite direction as angular momentum can be generated out of nothing.

$$L_2|_i + L_1|_i = L_2|_f + L_1|_f$$
$$0 = \omega_1 I_1 + \omega_2 I_2$$
$$\omega_1 = -\omega_2 \frac{I_2}{I_1} \quad (a)$$

To prevent the antenna's alignment from being affected, whether the satellites having symmetrical solar panel arrays can either rotate the solar panel, opposite to the one required to be rotated, or the satellite can adjust the angular momentum using the gimbal(if available). As of now, counter-rotation is not considered. The equations could be changed specifically for each individual satellite.

Now for any given set of motors, satellites, and panels, the actuation of any of the moments of inertia could be easily found out, and so is the case with θ_1 & θ_2

Assuming that the motors provide constant torque, the motors will be actuated to full that maximum constant torque and the ***normal*** at any time t can be written as the following:

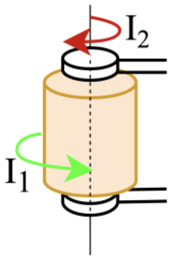

Fig. 3.1. The two moments of inertia about Axis-2.

About the axis along hinge-2(I_1 *is the moment of inertia of solar array &* I_2 *is the moment of inertia of rest of the satellite*);

$$\tau = I_2\alpha_2$$

$$\tau = I_2\left(\frac{d\omega_{2,1}}{dt}\right) \quad \text{Where } A_{b,c} \text{ represents } A \text{ of } b \text{ w.r.t } c$$

$$\omega_2 - \omega_1 = \frac{\tau}{I_2}t$$

$$\omega_2\left(1 + \frac{I_2}{I_1}\right) = \frac{\tau}{I_2}t \quad \textit{From equation (a)}$$

$$\omega_2 = \tau\frac{I_1}{I_2(I_1 + I_2)}t$$

With respect to the ground frame:

$$\int_0^{\theta_2} d\theta_2 = \int_0^t \omega_2 dt$$

$$\theta_2 = \tau\frac{I_{1,a}}{I_{2,a}(I_{1,a} + I_{2,a})}\frac{t^2}{2} \qquad (i)$$

Similarly, about the axis of hinge-1(*here* I_1 *is the moment of inertia of the solar array &* I_2 *is the moment of inertia of the rest of the satellite*);

$$\theta_1 = \tau\frac{I_{1,b}}{I_{1,b}(I_{1,b} + I_{2,b})}\frac{t^2}{2} \qquad (ii)$$

Estimating the impact location:

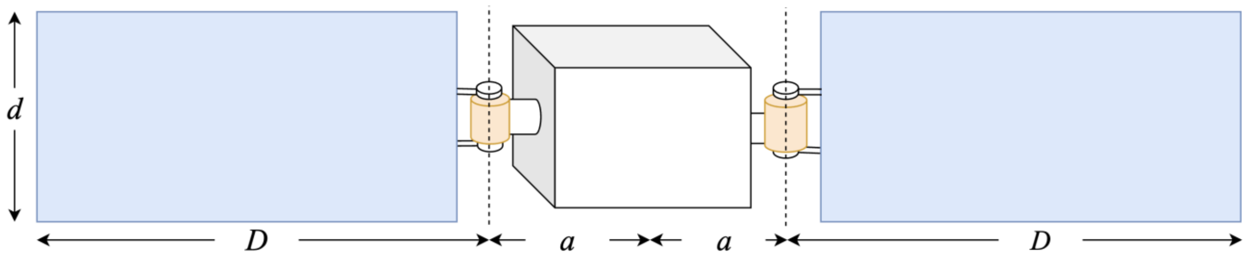

Fig. 4. Dimensions of different parts along the satellite's plane.

Both the solar arrays will always be parallel to each other, normal to the sunlight. We can assume that the plane of the satellite is the same as the plane of the solar arrays, taking the origin as the hinge(intersection of two axes of rotation) on one of the sides, which can be uniquely determined by its normal vector. The initial equation(just after the proximity detection) of that plane:

$$x = 0$$
$$\vec{n} = \hat{i}$$

Coordinates of its point of intersection with the trajectory of debris particle could be found out as:

$$\vec{N} = \begin{bmatrix} X_o + t.V_x \\ Y_o + t.V_y \\ Z_o + t.V_z \end{bmatrix}$$

$$\vec{N}_{(x=0)} \implies X_o + t.V_x = 0$$

$$t = -\frac{X_o}{V_x}$$

Hence the impact location will be:

$$\vec{p} = \begin{bmatrix} 0 \\ \left(Y_o - \frac{X_o}{V_x}V_y\right) \\ \left(Z_o - \frac{X_o}{V_x}V_z\right) \end{bmatrix}$$

Actionable if $(-D \leq Z \leq a)$ and $\left(-\frac{d}{2} \leq Y \leq \frac{d}{2}\right)$.

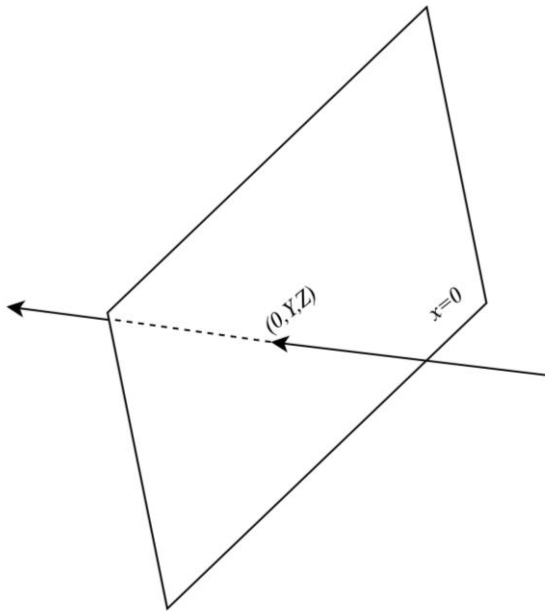

Fig. 5. The intersection point of the initial trajectory of particle & satellite's plane. .

Determining the threshold angles– $\theta_{1_o}, \theta_{2_o}$:

If the solar panel arrays were to be rotated only about one single axis/degree of freedom, then the will exist an angle by which if it is rotated, the plane of panels will become parallel to the linear trajectory of the space debris, such an angle is defined as the threshold angle about that axis.

The direction of debris particles is given as:

$$\hat{V} = \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} / |V|$$

$$\hat{n}' = < \cos\theta_{1_o},\ 0,\ \sin\theta_{1_o} >$$

Calculating θ_{1_o}:

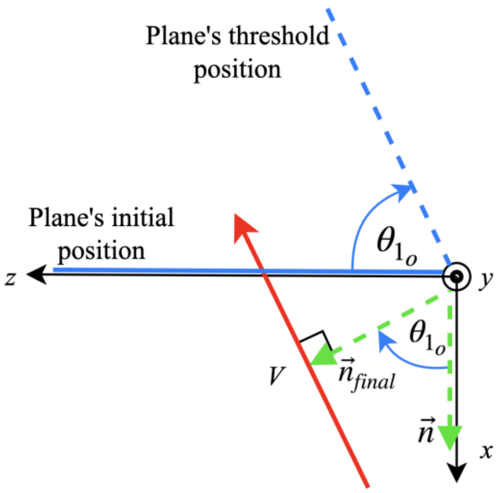

Fig. 6. Top view showing the plane of the satellite, normal vector, and debris particle's trajectory.

The dot product of the two will be zero at the threshold angle:

$$\hat{n}' \cdot < \hat{V}_x, \hat{V}_y, \hat{V}_z > \ = 0$$

$$V_x \cos\theta_{1_o} + V_z \sin\theta_{1_o} = 0$$

$$\theta_{1_o} = \tanh\frac{V_x}{V_z}$$

Similarly θ_{2_o}:

$$\theta_{2_o} = \tanh\frac{V_x}{V_y}$$

Threshold Momentum Estimation:

Any action will be called only if the debris size will be cross a particular threshold size and velocity, which could constitute any significant damage.

The deciding parameters to determine the threshold momentum, for a satellite's body, will be its ballistic jacket's thickness, number of layers, and strength. For the quantitative estimation, different material simulations for hypersonic impact in pristine and hybrid single and multi-layer C3N and BC3 nano-sheets[9], Ceramic/Metal Targets[10] can be used.

If at a certain velocity, the momentum of the projectile will be below the threshold value then it may simply vaporize along with a little vaporization of material of protection layers at the impact sight, causing no harm to the internals of the satellite.

Perpendicular distance as a function of time:

Substituting the angles as a function of time in equation (*I*):

$$p = \frac{\begin{aligned}&(X_o + t\,.\,V_x)\left[\cos\left(\tau\frac{I_{1,b}}{I_{1,b}(I_{1,b}+I_{2,b})}\frac{t^2}{2}\right)\cos\left(\tau\frac{I_{1,a}}{I_{2,a}(I_{1,a}+I_{2,a})}\frac{t^2}{2}\right)+\sin\left(\tau\frac{I_{1,a}}{I_{2,a}(I_{1,a}+I_{2,a})}\frac{t^2}{2}\right)\right]\\ &+(Y_o + t\,.\,V_y)\left[-\sin\left(\tau\frac{I_{1,a}}{I_{2,a}(I_{1,a}+I_{2,a})}\frac{t^2}{2}\right)\cos\left(\tau\frac{I_{1,b}}{I_{1,b}(I_{1,b}+I_{2,b})}\frac{t^2}{2}\right)\right]\\ &+(Z_o + t\,.\,V_z)\left[-\sin^2\left(\tau\frac{I_{1,b}}{I_{1,b}(I_{1,b}+I_{2,b})}\frac{t^2}{2}\right)-\sin\left(\tau\frac{I_{1,b}}{I_{1,b}(I_{1,b}+I_{2,b})}\frac{t^2}{2}\right)\cos^2\left(\tau\frac{I_{1,a}}{I_{2,a}(I_{1,a}-I_{2,a})}\frac{t^2}{2}\right)\right]\end{aligned}}{\sqrt{\begin{aligned}&\left[\cos\left(\tau\frac{I_{1,b}}{I_{1,b}(I_{1,b}+I_{2,b})}\frac{t^2}{2}\right)\cos\left(\tau\frac{I_{1,a}}{I_{2,a}(I_{1,a}+I_{2,a})}\frac{t^2}{2}\right)+\sin\left(\tau\frac{I_{1,a}}{I_{2,a}(I_{1,a}+I_{2,a})}\frac{t^2}{2}\right)\right]^2\\ &+\left[-\sin\left(\tau\frac{I_{1,a}}{I_{2,a}(I_{1,a}+I_{2,a})}\frac{t^2}{2}\right)\cos\left(\tau\frac{I_{1,b}}{I_{1,b}(I_{1,b}+I_{2,b})}\frac{t^2}{2}\right)\right]^2\\ &+\left[-\sin^2\left(\tau\frac{I_{1,b}}{I_{1,b}(I_{1,b}+I_{2,b})}\frac{t^2}{2}\right)-\sin\left(\tau\frac{I_{1,b}}{I_{1,b}(I_{1,b}+I_{2,b})}\frac{t^2}{2}\right)\cos^2\left(\tau\frac{I_{1,a}}{I_{2,a}(I_{1,a}+I_{2,a})}\frac{t^2}{2}\right)\right]^2\end{aligned}}}$$

If any real zeros with respect to ***t*** will exist, corresponding to which θ from the $\theta(t)$ relation from equations (*i*) and (*ii*) will lie within 0 to threshold value of θ, then actions will be taken according to the flow diagram as presented in *Fig 7*.

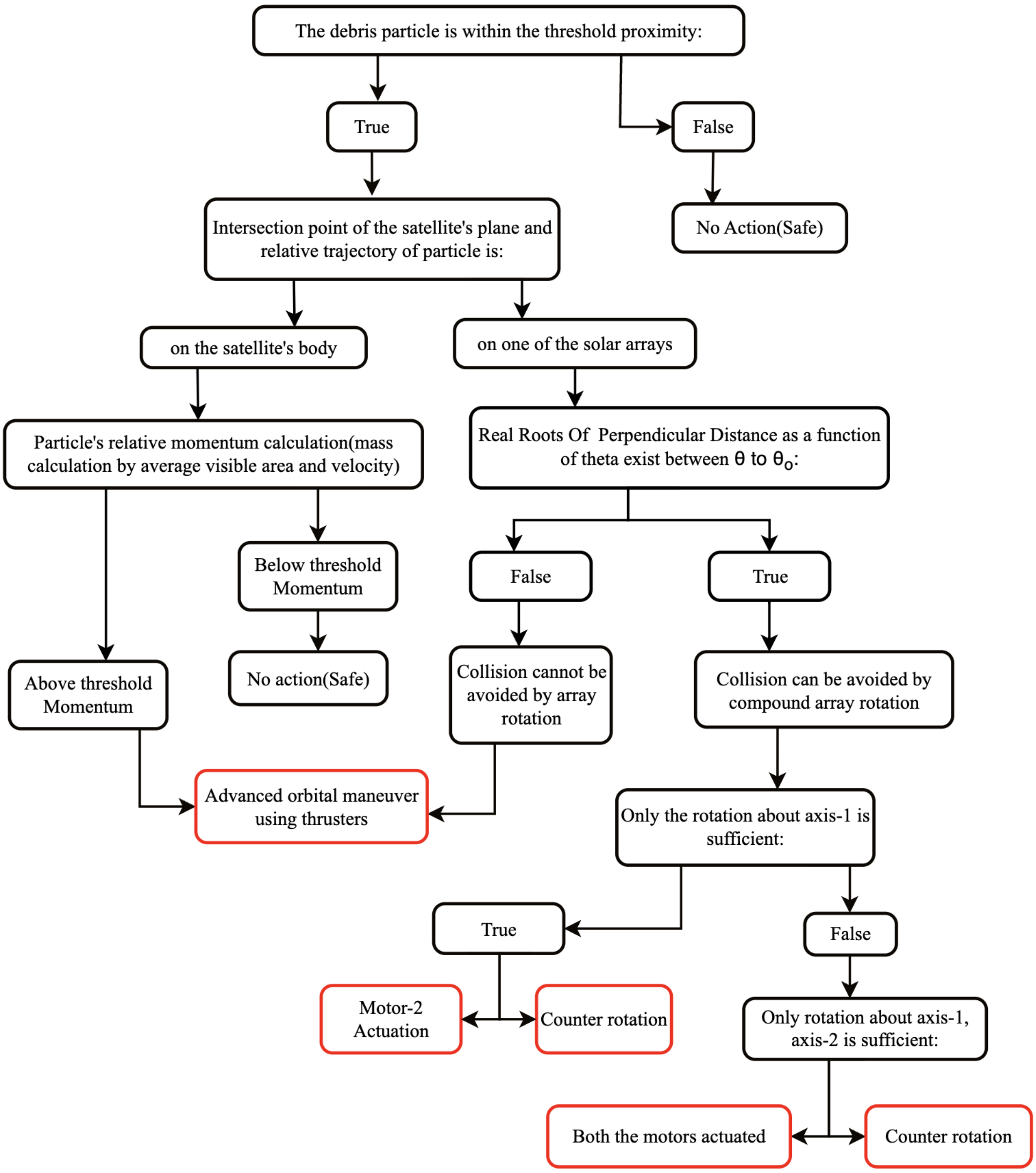

Fig. 7. Flow diagram of the algorithm followed for each individual debris particle.

Decision in case of more than one particle:

If there will be an encounter with more than one debris particle then in most such cases, the whole fleet will be coming from one direction, so that the camera system will be able to take into account all of them in one frame. Also, the zoom could be decreased autonomously, after capturing a few frames with default zoom and feeding those later frames for further detection of any other particle(s) that the camera was not able to capture in previous frames.

There could be countless possibilities of the number of cases that could be made with different values of parameters like the number of debris particles, and their different classifications as hazardous or safe. But there are broadly two decisions that could be taken:

I. Structure modulation to avoid a collision from a single particle, or sometimes even a group of particles.

II. Minute orbital maneuver using thrusters to avoid the collision.

The first action will be taken when the parameters for all detected particles will be within avoidable by a single structure modulation. The second action however will be taken only when there will be one or more hazardous particles that cannot be avoided by the first action.

For action II, an orbital maneuver, an orbital path predicting system could be used to govern thrusters[11-12]

FURTHER POSSIBLE IMPROVEMENTS:

- Gyroscopic motion assistance for modular rotations
- Utilizing the retraction of solar arrays along with the rotation.
- Leveraging further geometrical details by further customizing the algorithm for a specific satellite, for example, antennas or other fragile, exposed components.

CONCLUSION:

This algorithm utilizes the modular movements along the available degrees of motion within the satellites having solar arrays. As large solar arrays sweep more volume while orbiting, they're more prone to debris collisions. The probability of debris to hit on large solar arrays is much more than that for the main body, and hence the main focus of this algorithm was to mitigate the risk of solar panels from colliding with debris particles, and when that is not possible taking the use of other techniques to prevent hazardous collisions to prevent more debris production and ultimately avoiding the Kessler syndrome.

REFERENCES:

1. Kessler, D. J., Johnson, N. L., Liou, J. C., & Matney, M. (2010). The kessler syndrome: implications to future space operations. Advances in the Astronautical Sciences, 137(8), 2010.
2. Ren, S., Yang, X., Wang, R., Liu, S., & Sun, X. (2021). The Interaction between the LEO Satellite Constellation and the Space Debris Environment. Applied Sciences, 11(20), 9490.
3. Johnson, N. L. (2001). Space debris modelling at NASA. EUROPEAN SPACE AGENCY-PUBLICATIONS-ESA SP, 473, 259-264.
4. Bankman, I. N., Rogala, E. W., & Pavek, R. E. (2001). Laser radar in ballistic missile defense. Johns Hopkins APL Technical Digest, 22(3), 379-393.
5. Wang, P., Ando, S., & Kurihara, T. (2009, November). Motion clustering and object detection via modulated integral imaging. In 2009 International Conference on Optical Instruments and Technology: Optoelectronic Imaging and Process Technology (Vol. 7513, pp. 217-222). SPIE.
6. Schauland, S., Velten, J., & Kummert, A. (2007, September). 3D velocity filters for the detection of moving objects in image sequences. In 2007 15th European Signal Processing Conference (pp. 326-329). IEEE.
7. Zhang, G., Yin, J., Deng, P., Sun, Y., Zhou, L., & Zhang, K. (2022). Achieving Adaptive Visual Multi-Object Tracking with Unscented Kalman Filter. Sensors, 22(23), 9106.
8. Rozumnyi, D., Kotera, J. Sroubek, F., Novotny, L., & Matas, J. (2017). The world of fast-moving objects. In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition(pp. 5203-5211).
9. Molaei, F., Eshkalak, K. E., Sadeghzadeh, S., & Siavoshi, H. (2021). Hypersonic impact properties of pristine and hybrid single and multi-layer C3N and BC3 nanosheets. Scientific Reports, 11(1), 1-10.
10. Subramani, K., & Vinoth Kanna, I. (2019). Numerical Simulation of High Velocity Impact on Composite Targets Using Advanced Computational Techniques. In Innovative Design, Analysis and Development Practices in Aerospace and Automotive Engineering (I-DAD 2018) Volume 1 (pp. 399-413). Springer Singapore.
11. Gonzalo, J. L., Colombo, C., & Di Lizia, P. (2021). Analytical framework for space debris collision avoidance maneuver design. Journal of Guidance, Control, and Dynamics, 44(3), 469-487.
12. Seong, J. D., & Kim, H. D. (2013). Optimization of Space Debris Collision Avoidance Maneuver for Formation Flying Satellites. Journal of Astronomy and Space Sciences, 30(4), 291-298.