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EXECUTIVE SUMMARY OF THE THESIS

Spatial Computing to Support Space Traffic Management

LAUREA MAGISTRALE IN SPACE ENGINEERING - INGEGNERIA SPAZIALE

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1. Introduction

Over the past decade, as noted in [2], the number of space objects in Earth's orbit has increased significantly. The increasing number of space objects in Earth's orbit raises questions about the safety and sustainability of space. A collision between two space objects can trigger a chain reaction that renders the orbit non-operational. Moreover, in the last 10 years, the number of active satellites has begun to increase exponentially, challenging the safety of Earth's orbit, amplifying the likelihood of collisions, and creating new challenges for managing space traffic and debris.

As a result, in recent years, academia, institutions, and space agencies have increasingly focused on managing space traffic around Earth.

To address the problem, the ONU COPUOS (Committee on the Peaceful Uses of Outer Space) adopted seven guidelines, which have been accepted by all member states. These guidelines are operationalized by the individual space agencies of the countries ([7], [3]).

The strategies consist of design measures to prevent collisions by choosing non-congested orbits, operational strategies to avoid collisions, and disposal strategies, requiring that satellites do not remain in operational orbits for extended periods.

Focusing on the operational strategies, it consists of three different analyses: conjunction assessment, risk conjunction assessment, and conjunction mitigation. The first step involves computing the relative distance between objects, and if this Euclidean distance is below a threshold, the two objects proceed to the second step. This analysis is made only for tracked objects of the Space Situational Awareness (SSA) program, which generally focuses on objects larger than 1 cm.

In the case of a break-up event, however, data may not be immediately available, and conjunction assessment analysis can face accuracy problems. This is because such analyses may not provide a comprehensive understanding of the full impact of the event, particularly in the critical moments right after the break-up. Furthermore, current tools used to analyze break-up events typically focus on long-term propagation, assuming that debris is evenly distributed along the orbit [6]. However, this assumption is not accurate in the moments immediately following the event, when the debris is still very close together and not yet evenly spread out, posing a challenge to the tools' effectiveness.

To assess the problem, a research question to solve in this thesis is:

What is the interaction between Space debris and Spacecrafts in a small time span to manage a break-up event?
To answer this question, a tessellation of Low Earth Orbit (LEO) space is performed using Voronoi cells, and the interaction of these cells with debris generated by a break-up event is studied.
A key aspect to consider is computational time; otherwise, the analysis won't be useful for management purposes. Moreover, due to the increasing number of new actors in the space field, another important aspect is the ability to understand the analysis. Therefore, a Virtual reality (VR) tool for post-processing has been developed.
The executive summary is structured as follows:
Section 2 provides a brief background on the three main technologies adopted:Propagation, Voronoi, and VR.
Section 3 describes the methodologies adopted.
Section 4 presents the first case study.
Section 5 provides the second case study.
Section 6 concludes the work.

2. Background

2.1. Propagation

An astrodynamic model is a mathematical approach used to predict the position of space objects by considering initial conditions and the forces acting on the spacecraft. Traditionally, there are three primary types of models: numerical, analytical, and semi-analytical; each with distinct advantages and limitations. Recently, a fourth model, density-based propagation, has been introduced.
A numerical model uses computational methods to solve differential equations step-by-step, accounting for complex forces such as multi-body gravitational effects, atmospheric drag, and solar radiation pressure. This high-accuracy approach is essential for detailed and long-term trajectory planning, though it requires substantial computational resources.
An analytical model uses explicit equations based on idealized conditions, such as a two-body system, allowing for rapid computations but with lower accuracy.
A semi-analytical model combines explicit equations with numerical techniques, balancing speed and accuracy by modeling primary forces analytically while numerically addressing more complex perturbations. This method is suited for long-term predictions where moderate accuracy suffices.
The density-based propagation model estimates debris behavior by focusing on spatial distribution rather than individual objects, enabling efficient tracking of large debris populations. This approach, which models the density and spread of debris clusters, is valuable for studying fragmentation events and dense orbital regions while minimizing computational demands.
Although the density-based propagation model offers advantages in accuracy and computational efficiency, its use in Cartesian coordinates requires a very small time step, resulting in high computational time. The semi-analytical model presents certain advantages, but the choice ultimately falls on the analytical model due to the large amount of available data and its computational efficiency, which allows for multiprocessing division based on time. Secondly, the numerical approach is chosen for debris, providing high accuracy for the model.

2.2. Voronoi

Voronoi diagrams are mathematical structures that divide a space into distinct regions based on proximity to a set of predefined points, known as sites or generators.
In a Voronoi diagram, each region contains all the points that are closer to its associated site than to any other site in the space. The boundaries between these regions, called Voronoi edges, are equidistant from neighboring sites.
Delaunay triangulation is a method for connecting a set of points to form triangles, ensuring that no point lies inside the circumcircle of any triangle. This structure is complementary to the Voronoi diagram, as both represent different facets of the same point set. There are some properties of Voronoi cells and Delaunay triangulations that should be highlighted. Firstly, each Voronoi cell is a convex shape, meaning that, given any two points inside the cell, the line connecting these two points will always stay within the cell.

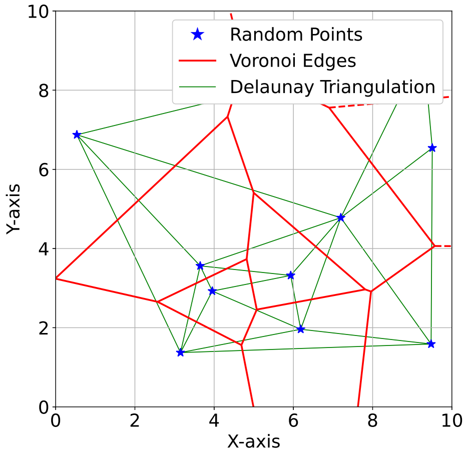

Figure 1: Voronoi example.

Another key property is that the edges (or faces, in 3D) of a Voronoi cell are perpendicular to the line connecting the two generating points of the cells. In other words, the Delaunay connection between the two points is perpendicular to the boundary faces of their corresponding Voronoi cells.
An example is provided in Figure 1.
A novel approach [1] in space traffic management is to use Voronoi cells to track changes in cell topology, which helps detect when objects are reducing their distance and approaching a potential minimum distance. This method significantly reduces computation time compared to NASA's standard tools.

2.3. Virtual Reality

Virtual Reality (VR) immerses users in simulated environments, allowing interaction with digital surroundings using headsets, gloves, or controllers. Initially used by NASA in the 1990s for astronaut training, VR has gained popularity due to advancements in accessibility and simulation accuracy, with companies like Meta and Apple leading the way in immersive technologies. In the context of space traffic management, VR is increasingly being used to visualize and understand complex spatial data [4], such as 3D Voronoi structures, which help in understanding the division of space for managing satellite and debris interactions.
For this thesis, VR is utilized primarily as a post-processing tool to improve understanding of 3D spatial division, especially when using 3D Voronoi structures. Unreal Engine, known for its high performance and data exchange capabilities, is used to support these simulations.

3. Methodology

This chapter describes the methodology adopted to address the thesis question. The algorithm is outlined in Algorithm 1. It begins by propagating debris using a numerical statistical approach or propagating data for already observed particles. Following this, a loop is initiated where, for each timestep, the positions of active satellites are updated and used as the centers of Voronoi cells. For each cell, its volume is calculated, and the debris density is determined by dividing the number of particles by the cell's volume. Finally, the data is packaged and sent to the Unreal Engine, where it is projected in a VR environment.

Algorithm 1 Voronoi Density computation

```
Propagate the debris generated by brek-up event
for each time step do
    Propagate the active satellites
    Create Voronoi discretization
    Compute the volume of the Voronoi cells
    Compute the number of debris in each Voronoi cell
    Compute density of each cell
end for
Save packed data
```

The algorithm can therefore be divided into three parts: propagation, Voronoi generation and volume computation, and final visualization in Virtual Reality

3.1. Propagation

For active satellites, an analytical model is used to balance accuracy and speed, utilizing dSGP4 for efficient batch computation of satellite positions. The algorithm uses TLEs retrieved from Space-Track.org and employs multiprocessing by dividing tasks by time steps. Since satellite positions are computed in the TEME frame, a transformation to J2000 is performed. Due to the rotational nature of TEME, it is necessary to know the epoch date, and the release epoch of each TLE is used for this transformation, as suggested in [8]. For debris, if TLEs are unavailable, NASA's Breakup Event Model [5] provides initial conditions, and debris is propagated using a numerical model that accounts for J2 and drag perturbations.

3.2. Voronoi

The computation of Voronoi cells in satellite regions faces challenges when boundaries, such as the Earth's surface and the outer limits of low Earth orbit (LEO), are introduced. These boundaries, necessary for a correct subdivision of the space, create non-convex volumes, as Voronoi cells typically assume convexity. To address this, Voronoi cells are first computed without boundaries, and then filters are applied to refine cells that intersect the defined boundaries. For cells that extend beyond these boundaries, vertices are adjusted to represent the intersection with the spherical surfaces. The boundaries computation starts by identifying intersections between the Voronoi cell's network of edges and the boundary spheres. Each segment of the Voronoi cell's network is tested for intersection with the boundaries, and when an intersection is found, a new vertex is created at that point. These new vertices are then added to the Voronoi cell, effectively truncating the segments that intersect the boundaries.

Volume computation is then performed by dividing the refined Voronoi cells into tetrahedra and summing all the small volumes computed using the following formula:

$$V_{tetrahedra} = \frac{|(\vec{v_1} \times \vec{v_2}) \cdot \vec{v_3}|}{6} \tag{1}$$

Where $\vec{v_1}$,$\vec{v_2}$ and $\vec{v_3}$ are the vectors originating from one of the four vertices and extending to the other three vertices. For non-convex volumes, a subtraction between the original cell and the discarded part of the cell is performed to obtain the correct volume.

Finally, the density of debris within each Voronoi cell is computed by dividing the number of debris fragments insight the cell by the volume of the corresponding one.

3.3. Virtual Reality

To visualize the Voronoi cells, a virtual environment is created using Unreal Engine 5, incorporating space objects like Earth, Moon, and stars. The environment is built with spherical meshes for Earth and Moon, while dynamic atmospheric and surface textures are applied for realism. A reference frame transformation ensures consistency between Unreal's left-handed system and the right-handed coordinate system used in calculations. The Voronoi cells are generated by using data from the previous algorithm, where each satellite's position, Voronoi vertices, and density are utilized to create custom meshes in the scene. These meshes are then colored based on density, with a material representing the density values, where green indicates low density and red indicates high density.

4. Case 1: Break-up event of Long March 6A

The first case study analyzes an explosion event involving the Long March 6A rocket, which was launched on August 6, 2024, with the first alert received on August 8, 2024.

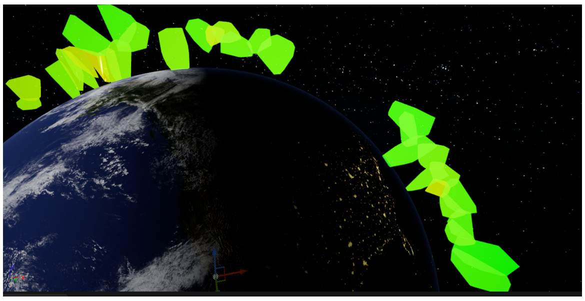

Figure 2: VR image of Voronoi cells at 7:39:24 of 2024-08-07 Case 1.

The analysis uses initial TLEs from Space-Track for 70 trackable debris objects, simulating the breakup event. The simulation is performed over a 24-hour period divided into hourly time steps, with no prior propagation required, improving computational performance. The simulation takes 28 minutes and 32 seconds for 24 time steps without multiprocessing, with potential for significant time reduction using a server and multiprocessing. In VR, only Voronoi cells containing fragments are shown as visibile in Figure 2.

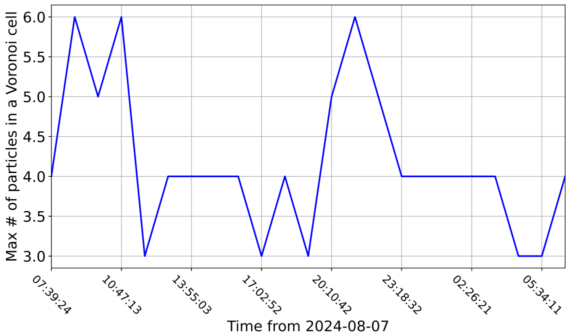

Figure 3: Max number of fragments inside a voronoi cell Case 1.

The results shows in Figures 3 indicate that the number of debris in each Voronoi cell remains constant, the number of active satellites affected, meaning those with at least one debris inside, increases due to the breakup as shown in Figure 4, impacting the density of particles in near space. The mean density of the affected Voronoi cells, as observable in Figure 5, shows a slight decreasing trend.

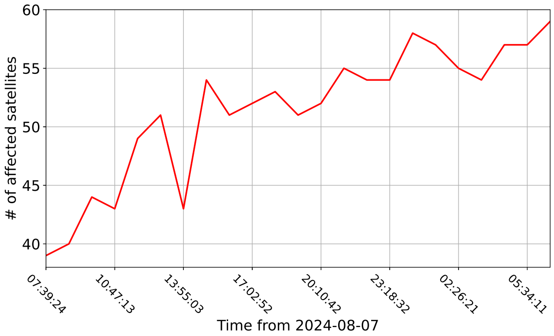

Figure 4: Number of affected satellites Case 1.

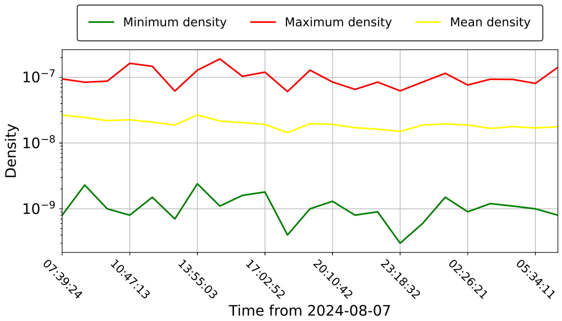

Figure 5: Density Case 1.

5. Case 2: Break-Up Event

The second case study analyzes an explosion using a break-up model to assess its impact in the initial time span. While TLEs may be available hours later, the break-up time can be directly communicated, allowing for the retrieval of the initial state. For this simulation, the initial parameters consist of a mass of 500 kg, an circular orbit with inclination of 60°, and an altitude of 400 km.

The NASA break-up model generates debris fragments up to 0.05 m in size, producing a total of 724 fragments, and provides the initial state and A/M data, which are crucial for propagation using a numerical model that takes drag into account. The analysis spans two hours with a delta time of 6 minutes, and the computation takes 13 minutes and 40 seconds. Figures 6, 7 and 8 show, as before, the progression of active satellites affected, the maximum number of debris in the Voronoi cells, and the density. As debris spreads, the number of particles in each cell decreases, but the density may not, meaning the risk of encountering debris remains high. The VR tool offers a clear and compact visualization of debris distribution, as shown in Figure 9, which is more concentrated compared to the previous case.

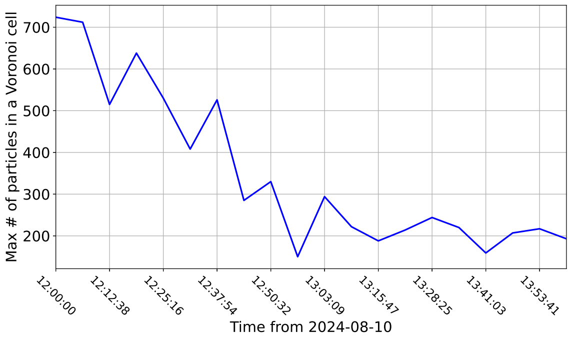

Figure 6: Max number of fragments inside a voronoi cell Case 2.

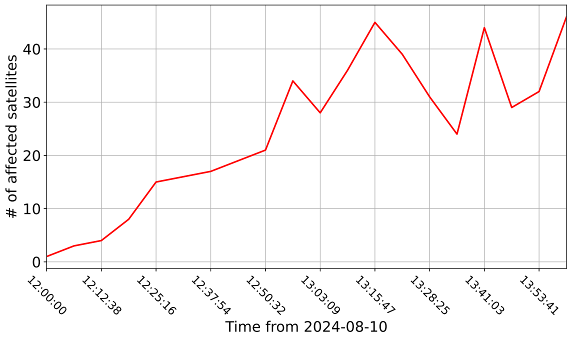

Figure 7: Number of affected satellites Case 2.

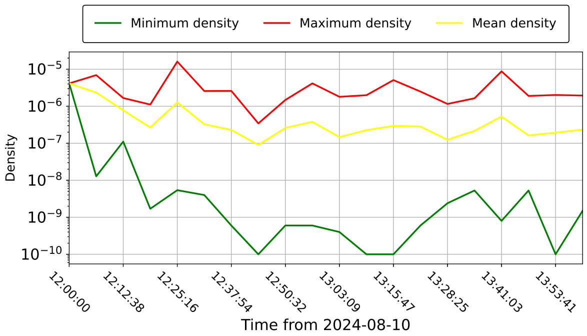

Figure 8: Density Case 2.

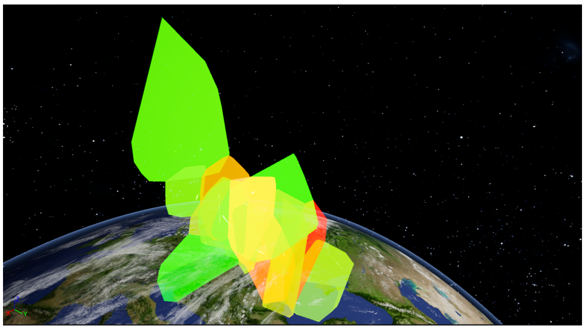

Figure 9: VR image of Voronoi cells at 12:31:35 of 2024-08-10 Case 2.

6. Conclusions

The thesis investigates innovative spatial discretization methods to manage non-cooperative space traffic in orbit, focusing on Voronoi discretization to model interactions between active satellites and space debris. The approach is divided into three phases: propagating satellite and debris trajectories using numerical and analytical models, discretizing space into Voronoi cells to map the evolving scenario, and developing a VR visualization tool to interpret results immersively. Emphasizing computational efficiency, the system enables real-time analysis crucial for decision-making in dynamic situations. Two case studies, one with tracked debris and another with a break-up model, demonstrate the utility of Voronoi discretization for collision probability analysis, indicating that collision risks concentrate in specific orbital regions and intervals. This approach presents a novel, rapid-response tool for space debris analysis, accessible even to non-specialists through VR. Future work may focus on speed optimizations, expanding the model to GEO/MEO or ASAT/Collision events, and refining predictive capabilities by integrating density and collision risk metrics.

References

[1] Jehyun Cha, Joonghyun Ryu, Mokwon Lee, Chanyoung Song, Youngsong Cho, Paul Schumacher, Misoon Mah, and D Kim. Dvd-coop: Innovative conjunction prediction using voronoi-filter based on the dynamic voronoi diagram of 3d spheres. In *Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference*, page 98, 2017.

[2] Heather Cowardin. Orbital debris quarterly news, july 2024. *Orbital Debris Quarterly News*, 28(3), 2024.

[3] ESA Space Debris Mitigation Working Group. Esa space debris mitigation requirements. Technical report, ESA, 2023.

[4] Davide Guzzetti, Dhathri H Somavarapu, and Grant Turner. An assessment of virtual reality technology for astrodynamics applications. In *AAS/AIAA Astrodynamics Specialist Conference, Tahoe, CA*, 2020.

[5] Nicholas L Johnson, Paula H Krisko, J-C Liou, and Phillip D Anz-Meador. Nasa's new breakup model of evolve 4.0. *Advances in Space Research*, 28(9):1377–1384, 2001.

[6] Heiner Klinkrad. *Space debris: models and risk analysis.* Springer Science & Business Media, 2006.

[7] Frederic J Krage. Nasa spacecraft conjunction assessment and collision avoidance best practices handbook. Technical report, 2023.

[8] David A Vallado. *Fundamentals of astrodynamics and applications*, volume 12. Springer Science & Business Media, 2001.