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# Introduction

## 1.1 Background and Motivation

Since the late 1990s, technological advancements have facilitated the design of smaller and lighter satellites with improved capabilities. Concurrent improvements in launch technology have broadened access to the space industry, allowing a diverse array of operators to deploy an increasing number of satellites into orbit (Peterson, Sorge & Ailor, 2018). Especially in recent years, commercial investment in space has increased, with multiple commercial companies proposing or funding the deployment of very large constellations of small to medium-sized satellites, leading to a surge in the space population (Muelhaupt et al., 2019).

An analysis of the global number of space objects—including satellites, probes, landers, crewed spacecraft, and space station flight elements launched into Earth's orbit or beyond—reveals a surge from 1810 to 2163 between 2021 and 2022. This increase is noteworthy, considering the average annual number of objects launched into space remained relatively constant at approximately 110 until 2012 (Figure 1).

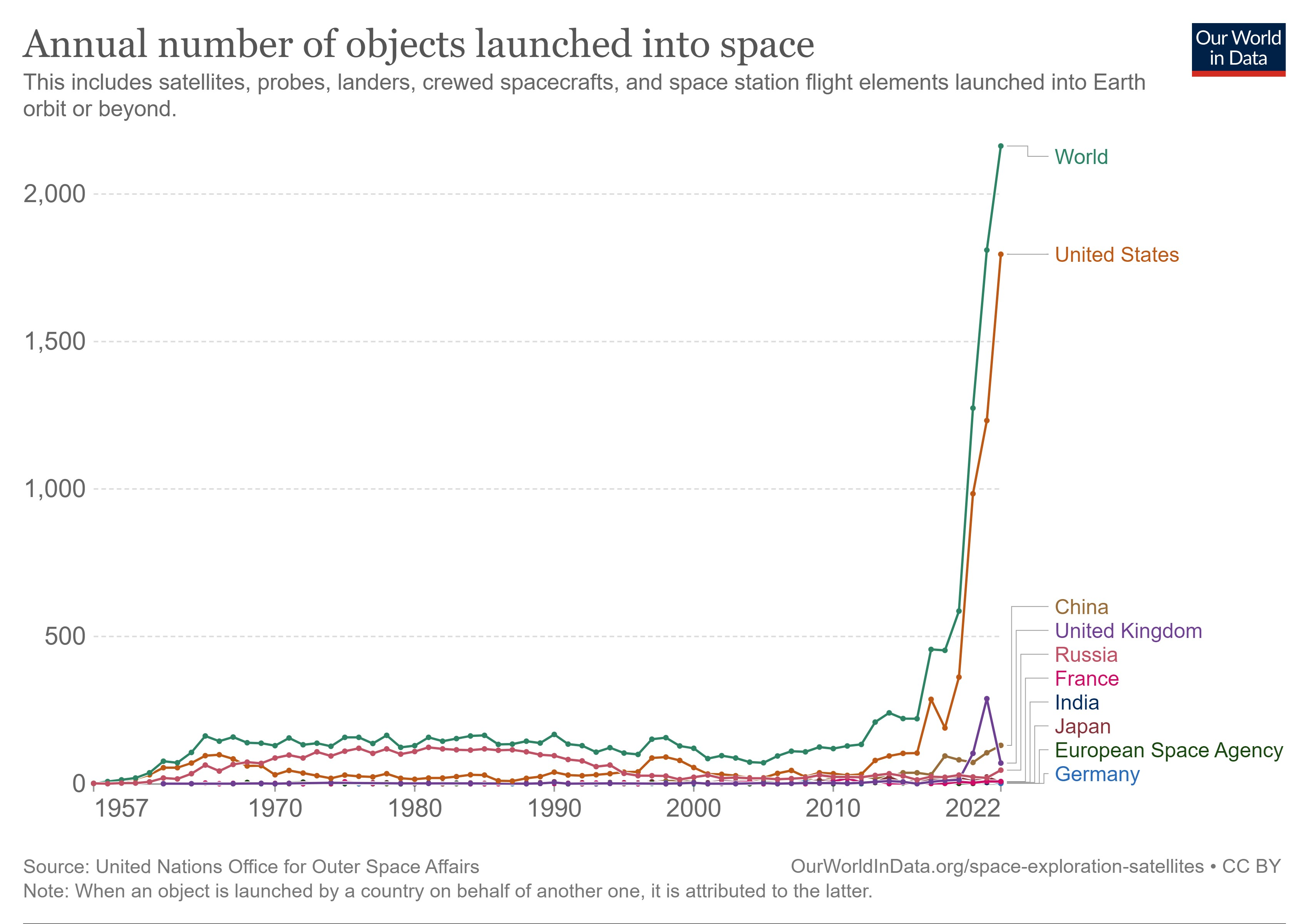


Figure 1. The annual number of objects launched into space (Our World In Data, 2023)

The exponential increase in the space population has introduced complexities in space operations and amplified the risk of collisions, instigating concerns regarding possible space crowding. Despite International treaties affirming that space should be used for the benefit of all, with nations cooperating to leverage space technology in achieving global development goals, there seems to be a lapse in stringent regulations and management (Kopal, 1966). Countries such as the United States, China, Russia, and Japan have expressed increasing concerns about potential conflict in space, simultaneously escalating their investment in both military and commercial activities in outer space (ZURICH, 2022). The attitude towards the rapidly growing space population is reflected by Elon Musk's remark, "A couple of thousand satellites is nothing. It's like, hey, here's a couple of thousands of cars on Earth, it's nothing" (BBC News, 2021).

The evident absence of comprehensive global regulation underscores the urgent need for increased public awareness and international governance, directing the race for space towards collaboration rather than conflict. The visualization of spatial populations can play a crucial role in this effort by translating abstract concepts into tangible, easy-to-understand forms that are accessible to a wider audience, thereby inspiring greater public participation and support for responsible space management (Interaction Design Foundation, 2023).

Numerous space object visualizers already exist, such as Leolab's Low Earth Orbit Visualizer and SpaceAware.io, providing insight into past and current space objects, but there is still a gap in the visualization of future space populations.

However, the UCL Future Space Population Study has begun to address this gap. Utilizing the UCL Orbit Dynamics Library (UCL-ODL) (Bhattarai et al., 2019)—a codebase with associated programs and datasets originally designed to study force modelling strategies—the researchers have been able to accurately calculate the positions of space objects for the next +5, +10, +25 years, incorporating both historical satellite data and future launch plans (Bhattarai & Ziebart, 2021).

This research aims to build upon the results of UCL's existing model for future space population, addressing a gap in space object visualization with a specific focus on future projections. There is already a base visualization tool for future space population (FSP) results, but there is still potential for improvement in the visualization methodology. Therefore, this study will build on the existing base visualization tool to refine and enhance it to provide a more accurate and intuitive representation of future spatial population (FSP) projection data.

## 1.2 Research Objectives

As stated in the chapter of background and motivation, this research project focuses on the visualization development of FSP results. Therefore, the research objectives are:

1. To design a further enhanced FSP Visualizer based on the current UCL FSP Visualizer:

**Objective 1a**: Identify and rectify the primary limitations and deficiencies in the existing Future Space Population (FSP) visualizer.

:

*RQ 1a.1: What are the main limitations or deficiencies in the existing FSP visualizer?*

*RQ 1a.2: How can these limitations or deficiencies be effectively corrected?*

**Objective 1b**: Develop an enhanced FSP visualizer tailored for users with no or little knowledge of space objects, aiming to effectively transmit the main results of the UCL FSP simulations.

*RQ 1b.1: What are the essential data and information that need to be visualized for users with no or little knowledge of space objects?*

*RQ 1b.2: How to implement the principle of visualization to the visualizer to enhance the usability of the FSP visualizer.*

1. To evaluate the usability of the Designed Visualizer.

**Objective 2a:** Implement and conduct usability surveying of the newly designed FSP visualizer.

RQ 2a.1: What are the key components and criteria that should be evaluated to assess the usability of the newly designed FSP visualizer?

## 1.3 Report structure

Chapter 1: This chapter provides an overview of the research project, outlining the primary problem statement and the motivation behind the research.

Chapter 2: This chapter delves into the foundational literature that shapes the project, structured into six critical sections, which are future space population, satellites, visualization, web technology, usability, and the public awareness.

Chapter 3: This chapter offers a concise overview of the methodology employed for the study. The initial section delves into the design and preparation of the prototype, detailing its data structure and anticipated results. Subsequently, the second section outlines the approaches adopted for the user study.

Chapter 4: This chapter reveals the results of the prototype design and user research.

Chapter 5: This chapter will provide a comprehensive analysis and discussion of the findings of the study, incorporating the research objectives and insights from the literature review. In addition, the limitations of the study are discussed in this chapter and directions for future work are suggested.

Chapter 6: The final chapter summarizes the findings in a comprehensive manner by distilling the previous discussion.

# Literature Review

This literature review section provides an overview of the core areas covered. First, it will focus on the future space population (Chapter 2.1) and its related simulation and visualization research. Following this, within the satellite field (Chapter 2.2), this review will explore in depth the orbit types, orbit elements, and coordinate reference systems. Within the visualization section (Chapter 2.3), user-centered design, visualization principles, and current space object visualization tools will be covered. The web technologies section (Chapter 2.4) covers Cesium.js technologies and modern web development techniques. It then explores website usability (Chapter 2.5) and highlights the importance of public awareness (Chapter 2.6) of space object visualization.

**2.1 Future space population**

**2.1.1 Future Space Population Simulation**

University College London (UCL) has made significant progress in the field of space research with the development of the 'UCL FSP Model (v2019)' for Future Space Population (FSP) research. This advanced computational model utilizes current orbital and metadata sources to predict the trajectories, locations and metadata of future artificial resident space objects (RSOs). The model provides a visual snapshot of the potential space landscape under different scenarios in the next +5, +10 and +25 year timeframes, using 2019 as the starting time. The future Space Population Catalog (FSPCAT) file was developed using methods from the UCL Orbital Dynamics Library in this project. The detailed file generation process is shown in Figure 2.

Graphical user interface

Description automatically generated

Figure 2. Diagram of the UCL Future Spatial Population Model (v2019) highlighting the essential elements of the spatial object catalogue propagation algorithm

* + 1. **Future Space Population Visualization**

Based on UCL's base FPS baseline visualizer in 2021, two postgraduate students at UCL undertook a project to enhance its visualization capabilities. Luyang's modifications included several features: an advanced user input module tailored for radar views; a radar window to display radar cross sections of space objects; improved clock and timeline controllers; and a comprehensive statistical analysis module that allows for deeper exploration of the space object data by ownership and orbital type using pie charts and bar charts. For future endeavours, Luyang envisions the integration of custom classifications centered on operational status, interactive click events paired with relevant information pop-ups, and a real-time formula to compute and represent the RCS values of space objects (Luyang, 2021).

On the other hand, Indigo's improvements focus on the diversification of visualization styles. Through user research, Indigo has introduced a 'One Year View', a 'Two Year View' (for comparative analysis) and a 'Hot Spot Aspect Chart'. Notably, user research showed that the One Year View was more effective in enhancing user understanding compared to the other two. As a prospective proposal, Indigo emphasizes the value of click events that triggered by user interaction, including displaying more details of spatial objects and displaying relative orbits (Indigo, 2021).

2.2 Satellites

2.2.1 Orbits

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