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Master thesis

Interactive cartographic visualization of satellite data and their orbits based on user-centered design

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Statement of Authorship

Herewith I declare that I am the sole author of the submitted Master's thesis entitled:

"Interactive cartographic visualization of real-time satellite data and their orbits"

I have fully referenced the ideas and work of others, whether published or unpublished. Literal or analogous citations are clearly marked as such.

Munich, 18.11.2021 Shlesha Acharya

ABSTRACT

For this study, various operational and junk satellites dataset are studied to design an interactive interface. This complex time-dependent data is suitable for researching novel cartographic visualization approaches because they challenge the existing practices. This research aims to optimize the cartographic visualization of satellites and their orbits. Additionally, the cartographic interactions and user-friendly interface design required for the preparation of an interactive map have been explored. For this purpose, a prototype of an interactive real-time web map has been developed, taking the user-centered design workflow (Needs Assessment – Prototyping – Implementation – Deployment - Maintenance), data management, and interactions (Pan and Zoom, Retrieve, Search and Filter, Overlay). The utility and usability of a map are checked with the help of a user study consisting of pre-test and post-test questionnaires. The pre-test questionnaires will help to understand the user's general background. The post-test questionnaires will help to understand the experience of the user while using the application.

Keywords: user-centered design, satellites orbit, interactive web map, interface evaluation

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ICA	International Cartographic Association
API	Application Programming Interface
2D	Two-dimensional
3D	Three-dimensional
NASA	National Aeronautics and Space Administration
GEO	Geostationary orbit
MEO	Medium earth orbit
LEO	Low earth orbit
TLE	Two-line element
SGP	Simplified General Perturbation
SDP	Simplified Deep Space Perturbations
JSPOC	Joint Space Operations Center
AFSPC	Air Force Space Command
NORAD	Northern American Aerospace Defence Command
WebGL	Web Graphics Library
UCD	User-centered Design
GIS	Geographic Information Sysstem

1
INTRODUCTION

The advent of satellite launching started with Sputnik as launched by the Soviet Union in 1957 (Witze, 2018). The usage of satellites is gradually growing in various fields such as criminology, climate change, aerospace, and cartographic research, thereby increasing the number of satellites. This has also increased the risk of collision of objects in space, potentially damaging numerous satellites in the constellations (Gottlieb et al., n.d.). Additionally, the announcement of multiple aerospace companies, including SpaceX and OneWeb, to launch thousands of satellites in the future has a possibility of making space a more congested and dangerous place (Grush, 2018). This has led to various organizations developing an application that can visualize the satellites for the effective management of space. It is also important to study the debris or other junk satellites' track record to keep a trace of their location. The satellites are continuously changing their position around their orbital path, which necessities the visualization of those satellites and their orbits. The accurate orbital visualization can help the proper launching of more satellites in upcoming years to prevent clashes and clustering of satellites.

The satellites present in space are spatially located, whose representation can be efficiently and effectively done through the means of cartography. The International Cartographic Association (ICA) defines cartography as the discipline that deals with the art, science, and technology of making and using maps (Griffin et al., 2017). The map design was primarily limited to the paper map. Easy access to the internet, technology and Geographic Information Systems (GIS) led to the rapid growth of digital maps and gradually shifted to interactive real-time maps. Real-time data collected from any event is stored in the form of a regular updating remote database and can be portraited as maps; these types of maps are real-time maps. Something happening in the real world in a specific location can be portraited in the form of an interactive digital map. Cartography and visualization intersect at a point where accurate orbital visualization can be done through the tool of interactive real-time maps, serving a role to help end-users be aware of the available satellites, analyze the pattern of satellite increment, and be informed of the existing problem of satellite crowding (Sack, 2017).

In the present context, more than 11,000 satellites have been launched in Space (Andy, 2021). This huge amount of data has challenged the cartographers in terms of finding the proper representation method. The visualization of these orbiting elements in a static map can be challenging and cluttery. An interactive application effectively designed can serve the purpose of representing a large amount of data and effortlessly conveying the information to users (Pietsch, 2015). Additionally, the advancement of technologies and the internet has allowed map designers to experiment with various digital platforms for visualization, shifting the use of static maps to digital maps (Çöltekin et al., 2009). One of the challenges for the map developers is to design the application considering its visual aesthetics, to engage the users in the exploration of the interface. The simplification of satellite visualization is essentially an act of generalization to encompass more general users in the sphere of the complex satellite world.

1.1 Problem statement and motivation

The increase in the number and usage of satellites has made it a requirement for cartographic intervention. A proper representation method in this domain is necessary. The cartographic principles, such as visual contrast, legibility, figure-ground, elements hierarchy, and balance, must be considered to enhance the aspects of visualization, comprehensive menu navigation, and user-friendliness when designing a map (abuckley, 2011). In recent times, some organizations have been focusing on designing satellite maps; however, it seems too technical for general map users. The target audience for such satellite applications is often those having the technical knowledge of satellites. It is important to shift the focus on general users while developing satellite applications to encourage interaction.

The role that satellites visualization systems play in our daily lives is often taken for granted. The satellites contribute to our well-being and uplift the quality of life through technological advancement (Agency, 2016). Hence, it is equally important for general users to be able to use such visualizing interfaces in a frictionless manner since the satellites have been playing a vital role in enabling us to achieve our objectives innovatively. The general map users having minimum or no knowledge about satellites must be reached out to while developing the application. Such applications should be designed in a way that is generally user-friendly, and they can make the most out of it when they are interested in using the interface. The users must be allowed to take the information from such interfaces along with the interaction.

The Application Programming Interface (APIs) allows the map designers to experiment with the interface design. The existing application uses a dark background with a 3D virtual globe for the satellite representation. The 3D virtual globe used for visualizing many satellites is used because of the easy accessibility to the resources. However, the uncertainty lies in the question that if the users prefer the virtual 3D globe or the 2D flat map for the satellite representation. The research can serve as a roadmap for future satellite map designers.

The satellite maps are not being designed by considering a user-centered map design workflow. The preference of users, while they are using these mapping applications, is still a matter of research. It is unanswered scientifically if users are interested in having the interface to be customizable. The customization allows users to engage in the interface and invest their time in exploring the available information and other existing features present in the application.

The suitable satellite comparison method is an effective way to analyze the orbiting elements. They orbit around the path at different altitudes. The comparison of satellites based on the altitude and orbits helps to check the satellites' availability and current and future placement. There is a need for effective cartographic techniques, guidelines, and interactive elements in preparing web-based interactive real-time maps. The cartographic input in the comparison method will explain the comparison with various self-exploratory visual aesthetics. The adaptation of interactive real-time maps in various fields catalyzes finding the proper ways of visualization. Such effective visualization can immensely help in scientific, technological, and aesthetic realms.

1.2 Research objectives and questions

1. **To design a prototype of an interactive web-based application to visualize satellites and their orbits.**

RQ1.1 What are the available sources to extract the satellite data for visualization?

RQ1.2 What platforms are being used for designing satellite visualization interfaces?

RQ1.3 How is the interactive application designed considering the requirements of users?

2. **To explore the various satellite visualization aspects in the designed application.**

RQ2.1 How can the satellites be represented effectively in the interactive web-based map?

RQ2.2 Are 2D or 3D maps more effective for displaying satellites on an interactive web-based map?

RQ2.3 What color or other graphic variable choices must be studied for designing a customizable interface? Does the user prefer a customizable or fixed interface?

RQ2.4 How can two or more user-selected satellites be visualized together for a comparison?

3. **To evaluate the designed application.**

RQ3.1 How can the utility of the interface be evaluated?

RQ3.2 How can the usability of the interface be evaluated?

RQ3.3 How is the effectiveness of the interface evaluated?

1.3 Thesis structure

Chapter 1: It consists of the introduction to the problem statement and motivation of the thesis with the relevance to the topic. It is divided into three sections: problem statement and motivation, research objectives and questions, and thesis structure. This chapter deals with the motivation behind the research, states the research objectives and shows the breakdown of the thesis structure.

Chapter 2: This chapter is divided into four sub-sections. The first section explores the available kinds of literature on data exploration and its visualization. The literature sources of the requirement of preparation of an interactive map and its evaluation are discussed in the second section. The third section compares the existing satellite visualization application. Finally, the last chapter summarizes the entire chapter.

Chapter 3: A brief explanation of the methodology used for the study is explained. The preparation of the prototype, its data design, and expected outcomes are discussed in the first section of the chapter. Similarly, the methods used for the user study are mentioned in the second section. The chapter is concluded with the help of its summary.

Chapter 4: The results of the prototype design and the survey are presented in this chapter. The analysis and discussion of this are also displayed. This chapter is divided into four sections: prototype design, visualization, evaluation, and summary.

Chapter 5: The conclusion and the outlook of the thesis are explored in this chapter with limitations and future recommendations.

2
BACKGROUND INFORMATION

This chapter consists of a brief description of the resources required for the development of the interactive web application to visualize satellites. The importance behind the selection of those resources has been discussed. This chapter is divided into four sections. The first section, "data management and visualization", gives an insight into the satellites, their classification, and data extraction, followed by its method of visualization in a web application. Another section, "the design and development process," talks about the existing cartographic practices for designing an interactive map, the user-centered design workflow, and the evaluation method of interactive maps. The comparison of existing applications for the visualization of satellites has been explored. The last sub-section provides a conclusion of this chapter.

2.1 Data management and visualization

2.1.1 Satellite data and their orbits

Any object in space orbiting or circling around any other bigger object can be defined as a satellite (Writer, 2020). National Aeronautics and Space Administration (NASA) mentions a satellite as a moon, planet, or machine that orbits a planet or star (May, 2015). Two types of satellites: natural satellites and artificial satellites, are present in space. The Moon and the Earth are natural satellites as they orbit the Earth and the Sun, respectively. Artificial satellites are launched in space by humans for various purposes such as navigation, communication, weather forecasting, and earth observation. The number of satellites in space, increasing exponentially, owes to the importance of the ability to see large areas of earth at one time resulting in the collection of data quickly and accurately, compared to those instruments on the ground (Ackerman, 2017).

The satellites revolve around other larger orbits in a path called the orbit. This exists because of the virtue of gravitational force in that object. The path that the planet takes around the sun is not a perfect circle. This theory is explained by Kepler's laws of planetary motion, which states that all the solar planet rotates in an elliptical orbit with the Sun at one focal point (Jia, 2014). This means that the distance between the sun and the planet is constantly changing as the planet goes around its orbit. Furthermore, this theory supports that a satellite also revolves around another object in a Keplerian orbit. Hence, the knowledge of the geometry of the Keplerian orbit contributes to the prediction and visualization of the position of the satellite and its orbits.

The motion of a Keplerian trajectory takes place in the three-dimensional plane, where position and vector velocity are the two important parameters (Awale & Bidari, 2020). Three individual components are needed to describe each of the two parameters, resulting in a total of six orbital elements to understand a Keplerian orbit. Figure 1 represents the visualization of a Keplerian orbit with its labelled components.

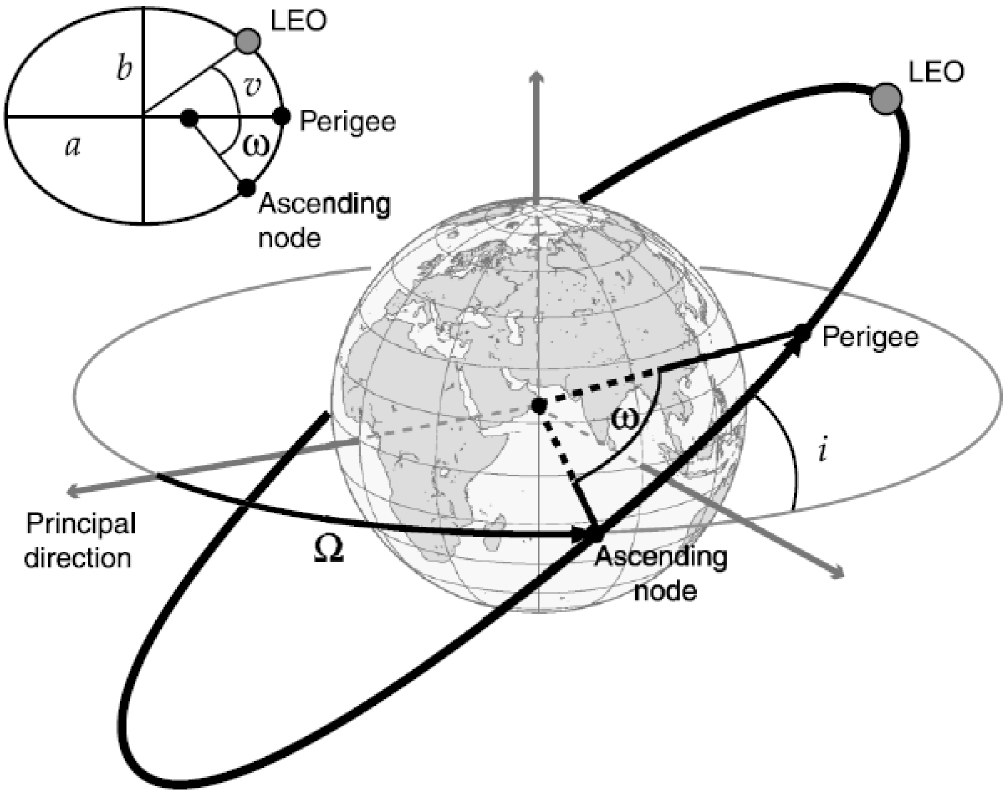


Figure 1 Keplerian elements of satellite orbit adopted from (Mousa et al., 2006).

The above figure explains the Keplerian elements, considering a satellite in low earth orbit (LEO) as an example: (1) semi-major axis (a), (2) eccentricity (e), (3) orbital inclination (i), (4) argument of perigee (ω), (5) longitude of the ascending node (**Ω**), and (6) mean anomaly (v). Each of these elements is briefly explained below in Table 1:

Table 1 Six orbital elements based on Keplerian trajectory.

Semi-major axis (a)	The semi-major axis determines the size of the orbit, helping for the determination of a 2-D shape.
Eccentricity (e)	Eccentricity explains the "shape of the ellipse" as the satellite follows the elliptical path. When e=0, the ellipse is a circle, and when e is very near to 1, it is a very long and skinny ellipse. It also contributes to the determination of the 2-D shape of the orbit.
Orbital inclination (i)	The orbit ellipse lies in the orbital plane, which always passes through the centre of the earth but may be tilted by any angle at the equator. The resulting tilted angle between the orbital plane and the equatorial place is called the orbital inclination. The inclination angle is a number between 0 to 180° by convention. The satellites which stay near the equator have an inclination angle of 0 degrees. Hence, their orbits are known as equatorial orbits. Similarly, orbits with inclination near 90° are called polar orbits as the satellite crosses over the north and south poles.
Argument of perigee (ω)	The point closest to the earth of the satellite is called perigee, also known as periapsis or perifocus (Ahmed, n.d.). The argument of perigee or angle of perigee is a single angle to orient the orbit ellipse in the orbital plane. In addition, the point where the satellite is farthest from the earth is called apogee, also commonly known as apoapsis or apifocus. A line drawn connecting perigee and apogee is called the line-of-

	apsides. The angle between this line-of-apsides and the line of nodes (explained in the above sub-section) is called the argument of perigee.
Longitude of the ascending node (Ω)	It is also known as the right ascension of the ascending node. It helps in defining the longitude at which the orbit passes upward to the earth-reference position.
Mean anomaly (v)	The position of the body in orbit is obtained from the mean anomaly. It is an angle measured between the perigee and the position of the body in orbit. Mean anomaly is defined to be 0° at perigee and 180° at apogee.
Drag (Optional)	Drag orbital element helps to know the rate at which mean motion is changing due to drag or other related effects. Its unit is revs/day, and it is a small number. Drag values for low-orbiting satellites are on the order of 10^4, and that of high-orbiting satellites is 10^-7 or smaller.

Although satellites down from the ground look similar, they perform differently depending on their orbital path, altitude, orientation, and function. A classification of these satellites helps to learn about the satellites in detail. Artificial satellites launched in space serve a purpose. Hence, one of the ways to classify satellites is based on their application: (i) Navigation satellites, (ii) Communication satellites, (iii) Earth observation satellites, (iv) Weather satellites, (v) Astronomical satellites, (vi) Miniaturized satellites. These satellites which are still functional in space are also called operational satellites. Various objects are left behind the space after a satellite is launched. This happens either because of the unsuccessful satellite launch or the failure of objects returning to the atmosphere once the mission is completed. These dead space objects are called debris or junk satellites.

Furthermore, satellites can also be classified based on their mass into small satellites and large satellites. Small satellites are those having a mass between 10 to 500kg, and large satellites consist of a mass of over 100kg. Technological advances in micro-electronics have challenged large satellites increasing the number of small satellites (Konecny, 2004). These satellites are called CubeSats, which in recent years are contributing to different perspectives, and are in the virtue of replacing the large satellites because of their effective development time, cost, reliability, and mission lifetime (Villela et al., 2019).

Another approach is to classify the satellites based on their height above the Earth's surface which is explained as follows:

- Geostationary orbit (GEO)

The orbital period of GEO satellites is almost the same as that of earth rotational orbit, 23 hours 56 minutes and 4 seconds, resulting in the satellites in GEO being stationary over a fixed position. These satellites orbit Earth at an altitude greater than 36000 km. Communication satellites are common GEO satellites that need to be constantly above one place over the Earth. Weather satellites are also often launched in GEO as they can constantly provide the data of the specific area to check the weather trend.

- Medium earth orbit (MEO)

A wide range of orbits between GEO and LEO are medium earth orbit ranging from an altitude between 2000 km and 36000 km. Similarly to LEO, they also do not follow specific paths around the Earth. Hence, it is used by various satellites for different applications. It is commonly used by the navigation satellites like the European Galileo satellite system.

- Low earth orbit (LEO)

LEO has an altitude ranging from 180 km to 2000 km, relatively close to the earth's surface. This proximity of LEO satellites to the earth's surface makes it ideal for several purposes. For instance, one of the important aspects is that it can take high-resolution satellite imaging resulting in its benefit for earth's observation.

2.1.2 The satellite catalog

The orbit of a geocentric satellite can be outlined with the help of a Two-line element (TLE) set. TLE datasets are one of the great sources for tracking data for satellites in Earth's orbit. Any object greater than 10 cm present in the space can have its respective TLE dataset (Kardol, 2018). The TLE dataset is the output from Simplified General Perturbation 4 (SGP4) orbit propagation, allowing rapid and moderately accurate propagation of space object motion. In the present context, the observations are received multiple times a day at the Joint Space Operations Center (JSPOC), controlled by the US Air Force Space Command (AFSPC) (Vallado & Cefola, 2012). JSPOC is responsible for determining the orbits and providing information on tracked objects (Kardol). The quality of the TLE dataset is believed to be improving due to the advanced technology. However, the result from various research shows that the quality is dependent on the satellite orbit and its type (Vallado & Cefola, 2012). In addition, the exact process of updating the TLE dataset is still a matter of research.

The format of the TLE dataset is shown in Figure 2, and the details are explained in Table 2:

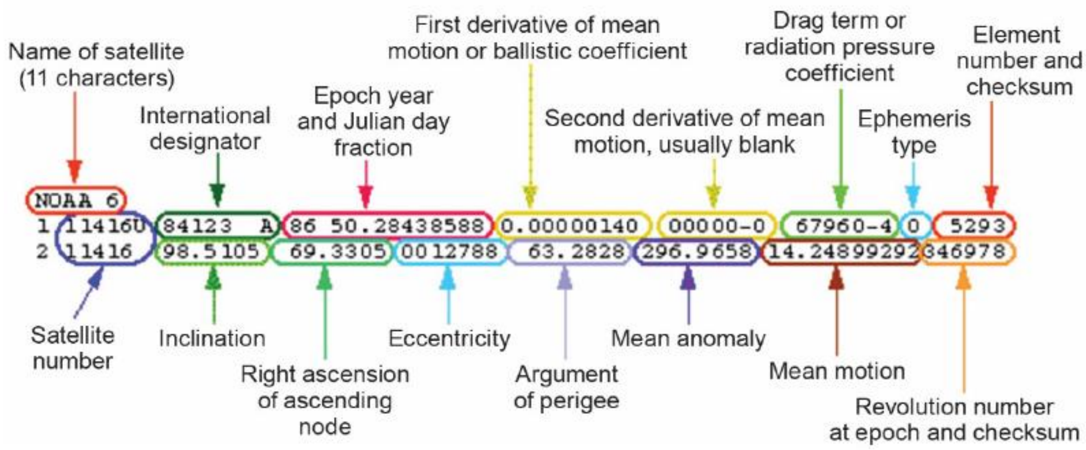


Figure 2 TLE dataset

adopted from (Kuhl et al., 2018).

Table 2 Explanation of TLE dataset.

Elements	Description
Name of satellite	NOAA 6 is a name associated with the satellite.
International designator	98067 A • The first two characters refer to the launch year of the object. • The next three characters indicate the launch number, starting from the beginning of the year. This launch was the 67th launch of the year 1998. • The remaining character indicates the piece of the launch. Piece 'A' is usually the payload.
Epoch year and Julian day fraction	04236.56031392 • The first two digits (04) represent the year. For years >=57, add 1900, and for all others, add 2000. • The remaining character of the field (236.56031392) is the Julian day fraction which means that the day of the year is between 236th and 237th days after January 1st, 2004. • Spaces or numbers are acceptable on the day of the year. (For example: '236' or '006' or '6')
The first derivative of mean motion or ballistic coefficient	0.00020137 • It is the daily rate of change in the number of revolutions that the object completes divided by 2.

	• "+", "-", or "space" can be used in the 34th character position, which indicates the positive or negative value for the 1st derivative of the mean motion. Space means that it is a positive value.
The second derivative of mean motion	00000-0 • It is used to model terminal orbit decay in the SGP4 predictor. • Its unit is revolution /day^3. • It is usually blank.
Drag term	16538-3 • It models the aerodynamic drag on a satellite caused by the sparsely present atmospheric molecules. • Its unit is m^{-1}
Element number and checksum	9993 • It is the count of all the TLEs generated for that object. The counter is increased with time, and once it reaches 999, it reverts to 1.
Satellite number	• The final number is for the checksum of line 1. • It is a satellite Catalog number. • 'U' indicates that it is an unclassified object.
Inclination (degrees)	51.6334

	• It is the angle made by the equator and orbital plane.
The right ascension of the ascending node	344.7760 • It is the angle between the vernal equinox and the point at which the orbit crosses the equatorial plane.
Eccentricity	0007976 • Eccentricity is a constant value that defines the shape of the orbit.

The satellite catalog is a type of document which includes different information about the satellites or any tracked objects in the space that are missing in the TLE dataset. This document contains information particularly related to the tracked objects, like the satellite name, type of the objects, launch date, and decay dates (Kardol, 2018). This information might be useful to the map users resulting in the optimized visualization of the satellites. The satellite catalog can be used as a database to design a search algorithm for the visualization as the users are more likely to search satellites with their name rather than the international designator or catalog id.

In the present context, there are two effective and relevant sources used for retrieving the information on the satellite catalog. For many years, the TLE dataset has been released to the public, which is continuously updated, and the real-time result is easily obtained, first through NASA and most recently through the Space-Track *(https://www.space-track.org/)* website. Furthermore, another available source is CelesTrak *(http://www.celestrak.com/)* which has been regularly working for several decades on providing the TLE catalog (Vallado & Cefola, 2012). Celestrek allows users to download satellite catalogs without using an authorization protocol, whereas the request protocol is difficult to implement in Space-track. The accurate information of the TLE dataset and satellite catalog can be easily obtained from *Celestrek*. However, its application is not updated since May 9th, 2021, whereas *Space-track* is regularly updated as it does not depend only on one person to control the website. The data from *Space-track* is the primary source of the data, which *CelesTrak* regularly copies to keep up to date (Kardol, 2018). The decision needs to be made of choosing the site for obtaining the TLE dataset and satellite catalog while developing a web application for visualizing the satellites.

2.1.3 Satellite position and orbit calculation

The position and velocity of the Earth-orbiting objects can be predicted by using the general perturbations elements sets. Northern American Aerospace Defence Command (NORAD) has generated few models for the propagation of NORAD elements sets which is maintained for all type of space objects. These elements sets are made publicly available to the users, which must be used with one of the models listed below to obtain maximum accuracy on the prediction of the position and velocity of the satellites (Hoots & Roehrich, 1980). The availability of various propagation models has led to the classification of all space orbits based on their orbit period. All objects having a period of fewer than 225 minutes are classified as near-Earth objects and those objects having their period greater than or equal to 225 are deep-space objects. The resulting NORAD element sets are based on these classifications. Hence, the user can calculate the satellite period and decide which prediction model to use.

Specific algorithms are required to analyze and propagate the TLE dataset, which eventually is useful to obtain the parameters of space orbits (Hoots & Roehrich, 1980). There are five mathematical models available for calculating the position and velocity of satellites which are listed below:

- Simplified General Perturbation (SGP)
- Simplified General Perturbation 4 (SGP4)
- Simplified Deep Space Perturbations (SDP)
- Simplified General Perturbation 8 (SGP8)
- Simplified Deep Space Perturbations 8 (SDP8)

Either SGP4 or SDP4 models are used to generate the NORAD element sets, which depends on the near-earth or deep space of the satellites (Hoots & Roehrich, 1980). Furthermore, Satellite.js is a javascript library that combines SGP4 and SDP4 algorithms to make satellite propagation possible. Hence, in this section, SGP4 and SDP4 models are described briefly.

The information present in the TLE dataset is used to produce a list of points (x, y, z, and t) for each satellite using the satellite.js library, which incorporates SGP4 and SDP4 algorithms. In addition, this library contributes the functions needed for SGP4/SDP4 calculations and performs coordinate transformations. It converts the TLE dataset into the individual components called "satellite record" by propagating the paths of objects. Those resulting individual components are finally used to obtain the points along the orbit of the satellite with the help of different functions of the satellite.js library.

As previously mentioned, the TLE dataset is generated periodically, and SGP4 and SDP4 algorithms are used to determine the position and velocity of satellites within a kilometre of magnitude precision (Vallado & Cefola, 2012). The further step for visualizing satellites and their orbital paths in the web interface is to determine their orbit. Furthermore, the importance of orbit determination is to track the space debris and foresee the possibility of collision. The technique behind the calculation of orbit is to estimate the state vector of the satellite containing the orbital elements, the dynamic propagation parameters, and the measurement biases from a first guess and a set of observable measurements (Paulet & Cazabonne, 2021). The accuracy and easy accessibility within the shortest computation time is the challenging factor behind the measured orbits. There are two methods involved in retrieving the orbits: Numerical orbit determination and Analytical orbit determination. The first mentioned method is widely used as its precision level is radical with realistic force models. However, it demands high computation time. On the other hand, analytical orbit determination emphasis on computational speed and sacrifices accuracy.

The next step after the determination of satellite position and propagated orbits is their visualization. A visualization tool is necessary to render 3D models, globe, and maps. Three commonly used tools for visualization are discussed below:

CesiumJS

CesiumJS is an open-source JavaScript library developed by "Cesium: the platform for 3D geospatial", which states that this library can be used for preparing accurate 3D globes and maps (*CesiumJS*, n.d.). The maps are designed with the best possible performance, precision, visual quality, and ease of use. In addition, it is used by developers from all around the world in different fields ranging from aerospace to smart cities to drones to create interactive maps for sharing dynamic geospatial data. The main properties of CesiumJS are:

- Stream in 3D Tiles and other standard formats from Cesium ion or another source
- Visualize and analyze on a high precision WGS84 globe
- Share with users on desktop or mobile

ArcGIS

ArcGIS software and apps are applicable to combine mapping and data analytics to deliver location intelligence. For the same intention, Esri has developed an ArcGIS application programming interface (API) for JavaScript, which allows the user to access the information and build an application without the need for an ArcGIS Online account. All users with the availability of a text editor, a modern browser, and an internet connection can visualize a globe with the help of this API.

Web Graphics Library (WebGL)

WebGL is also a JavaScript API used for providing high-performance interactive 3D and 2D graphics. This is useful within any compatible web browser without the use of plug-ins.

An algorithm is needed to be written in JavaScript after the selection of the globe representation. A visualization tool to represent the satellites and their orbits are designed in coding based platforms.

2.2 The design and development process

2.2.1 Interactive web-map design

Roth, in his cartographic journal, states that all maps are inherently interactive (R. E. Roth, 2012). A conclusion can be drawn from this statement that even static maps can be made interactive. Roth also argues by adding the features of folding the paper map, changing the position of the map from the viewing angle, annotating with pens and colored markers, and by adding pins to identify important locations (Wallace, 2011), an extent of a static map can be adjusted owing to its interactivity (R. E. Roth, 2012). The advancement of personal computing and internet technologies has led to the possibility of active production of new and unique map views, resulting in the production of real-time interactive maps (MacEachren and Monmonier 1992). The objective of interactive maps depends on the variety of the end-users (experts to the general map users), visualization attempting to breakdown the complex data to simple, and the willingness to produce aesthetic maps based on current and existing events (R. E. Roth, 2013b; Tolochko, 2016).

Information visualization deals with both representation and interaction (R. E. Roth, 2013b). The following sub-section deals with the data-representation-interaction design workflow, which needs to be addressed while preparing all types of interactive mapping applications. This helps enlighten the existing best practices specific to interactive web map designs.

Representation

Cartographic representation helps convey the geographic information, which comprises of the perception (how maps are seen), cognition (how maps are understood), and semiotics (how maps are infused with the meaning) of a map (R. E. Roth, 2012). The representation design includes the consideration of the visual variables and layout design. Roth argues that the most significant graphic representation is the identification of the available visual variables and their proper use to convey the information (R. E. Roth, 2012). The layout design focuses on the correct placement of elements on a map.

Visual variables describe the graphic dimensions in which a map or other visualizations can be diversified to provide available information to the users (R. E. Roth, 2017). Bertin listed seven basic visual variables and presented the importance of changing their perceptual properties to obtain meaningful representation (Garlandini & Fabrikant, 2009). He also identified visual variables as selective, associative, ordered, and quantitative. This list was updated by Morrison (1974) by adding two additional variables, namely: color, saturation, and arrangement. Finally, MacEachren (1995) extended the list by adding crispness, resolution, and transparency, which was comparatively easier to manipulate because of the digital production (R. E. Roth, 2017).

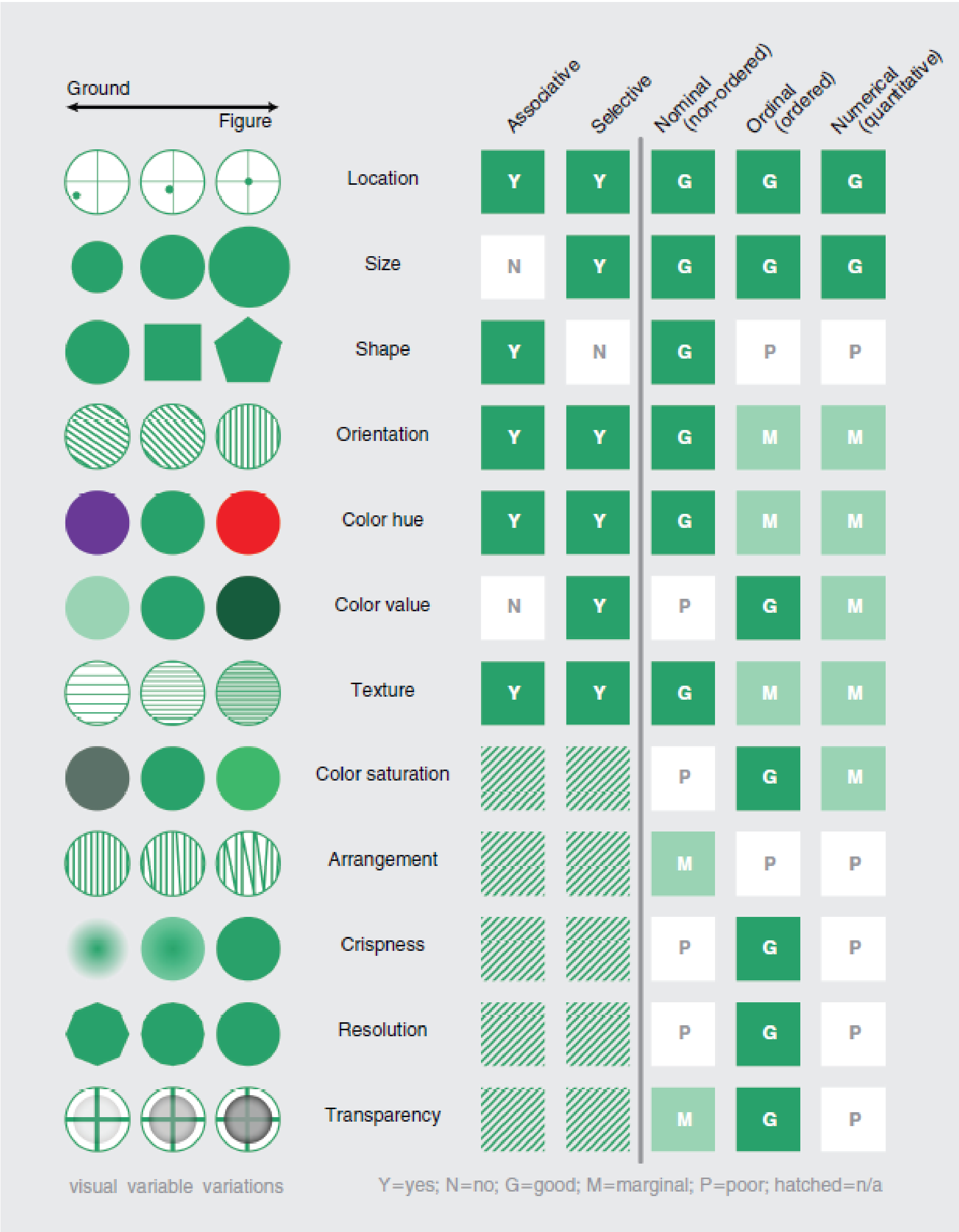


Figure 3 Visual variable

adopted from(R. E. Roth, 2017).

The initial list of the visual variable by Bertin is briefly explained in this section, which is extracted from the work of Roth (2017). *Location* describes the position of the map symbol relative to a projected spatial coordinated system in cartography. The amount of area occupied by a map symbol is explained by *size*. *Shape* describes the outline of the map symbols. The direction of rotation of the map symbol from "normal" is defined by the *orientation* variable. The *color hue* helps to explain the dominant wavelength of the map symbol on the visible portion of blue, green, and red colors. Lastly, the *color value* visual variable describes the relative amount of energy emitted or reflected by the map symbol (R. E. Roth, 2017).

The aesthetic part of a map design is depended on the layout design. The proper placement of map elements in a map determines the layout design. Map elements are the integral parts of a map, starting from map title, legend, map scale to supplemental text box and graphics (Muehlenhaus, 2013). Even though most of the map elements are similar in paper and web maps, some additional elements (e.g., interactive legend) are reconceptualized in the case of web maps, and some elements, such as zoom buttons for adjusting the scale of the map, are new to web mapping (Tolochko, 2016). Some of the map elements are mentioned in the following Table 3, where it has been briefly discussed how they are implemented in web mapping.

Table 3 List of map elements and their implementation in web-mapping.

Map elements	Possible web map adaptation (s)
Map title	A temporary splash screen of a map title can be used, which disappears when the user starts to interact with the interface rather than a static title.
Mapped area	The ability to pan, zoom, click, and drag the mapped area allows the users to control the frame and choose what part of the map they want to look at.
Map scale	The importance of designing a web map is to allow the user to view the map at different zoom levels. Map designers should carefully allow the

	zoom level only when necessary. Zoom levels are visible in all the web maps.
Supplemental information	Supplemental information can include embedded text, links, images, graphics, videos and be displayed interactively. For instance, when the user clicks on a button or a map feature, the extra detail is displayed. This information can be presented as information windows or as a tooltip (on top of the map itself, moves with the pointer).
Labels	The size and number of labelling on the map keep on changing at different zoom labels.
Inset/Locator map	It changes to match the current view as the user interacts with the map. It helps the user to zoom into the main map by drawing a rectangle of the desired area on the inset.
Map metadata	It includes the name of the cartographer, data sources, map projection, and many more, which are not required to be displayed directly on the map but should be easily provided.
North arrow	It rotates interactively as the user rotates the map.
Legend	Allows for interaction with the legend to affect the map, such as being able to turn/off layers, adjust the timeline of temporal map data, etc.
Menu*	The menu provides the map user with additional options and interactivity
Help*	Provide the link to information for map users who need help learning how to use the map.

These map elements with (*) are specific to web maps and not in traditional cartography. The table is adapted from the thesis of Tolochko (2016).

After knowing the available map elements, it is of absolute importance to know their placement order on the map. Dent et al. (2008) has defined visual hierarchy as the placement of map elements and objects into a logical order, based on their relative importance (Dent et al., 2009). Mueblenhaus (2013) has revitalized his concept based on the idea that certain map elements' placement should be emphasized over others depending on the map's purpose (Muehlenhaus, 2013). Dent's visual hierarchy focuses on designing meaningful maps in print medium only. Hence, based on Dent's observation, Muehlenhaus has come up with web-specific visual hierarchies which can and must be manipulated based on the communicative purpose and end-users of the map (Muehlenhaus, 2013). Table 4 suggests visual hierarchy levels for general, thematic, and animated web maps:

Table 4 Visual hierarchy levels for web map design

adopted from (Muehlenhaus, 2013) with reference to (Dent et al., 2009) work in thematic mapping.

VISUAL HIERARCHY LEVELS FOR WEB MAP DESIGN

	General Interest Web Maps	Thematic Web Maps	Animated Web Maps
Level 1	Title/Splash Screen Map Symbology Key Reference Data Info Windows (opened)	Title/Splash Screen Thematic Visualization Legend	Title/Splash Screen Animation Symbology Map Symbology Temporal Legend/Interface
Level 2	Base Map Base Map Labels Navigation/Directions Tools	Base Map (generalized) Info Windows (opened) Chart Graphics	Base Map Legend Info Windows (opened) Locator Map
Level 3	Map Interactivity Pan/Zoom/Rotation Tools Print/Share Map Features	Base Map Labels Map Interactivity Pan/Zoom/Rotation Tools Menus with Additional Tools	Base Map Labels Map Interactivity Pan/Zoom/Rotation Tools Menus with Additional Tools
Level 4	Locator Maps Chart Graphics Multimedia Supplements	Locator Maps Multimedia Supplements	Multimedia Supplements Chart Graphics
Level 5	Supplemental Information Attribution and Copyright Neatlines/Grids/Graticules Tool Tips	Supplemental Information Attribution and Copyright Neatlines/Grids/Graticules Tool Tips	Supplemental Information Attribution and Copyright Neatlines/Grids/Graticules Tool Tips

The visual hierarchy suggests that irrespective of the maps type, the title and the splash screen is in the first level and the base map takes the second level. This hierarchy must be considered while designing the elements of a map, and the priority must be provided accordingly.

Interaction

Cartographic interaction, which is an important aspect in the field of interactive cartography, geovisualization, and visual analytics, is defined as the dialogue between a human and map communicated through a computing device (R. E. Roth, 2013a). The objective of interaction design is to allow easy access and manipulation of the task information by making sure that people *can do the right things at the right time* (Rosson & Carroll, 2002). The components of cartographic interaction are the user, computing device, and map, as shown in Figure 4 below:

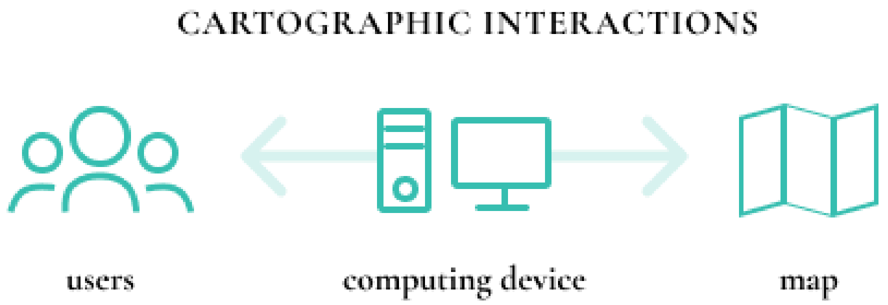


Figure 4 Cartographic interactions
adopted and modified from (R. E. Roth, 2013a).

It can be derived from this interactivity nature of cartographic interactions that the type of interactions that can be provided through an interactive map is depended on the objective of a map user, the existing skills of the map designer or developer, and the specification of the computing device (R. E. Roth, 2013a). However, these components shown in Figure 4 do not explain how a cartographic interaction must be started and implemented on the map. Hence, Roth reproduced the stages of interaction mentioned in Norman's *stages of action model*, explaining how the interactions are exchanged in cartography (Norman, 1988; R. E. Roth, 2013a). The following Figure 5 explains the stages of interactions based on the context shown in the above Figure 4 of the cartographic interaction definition.

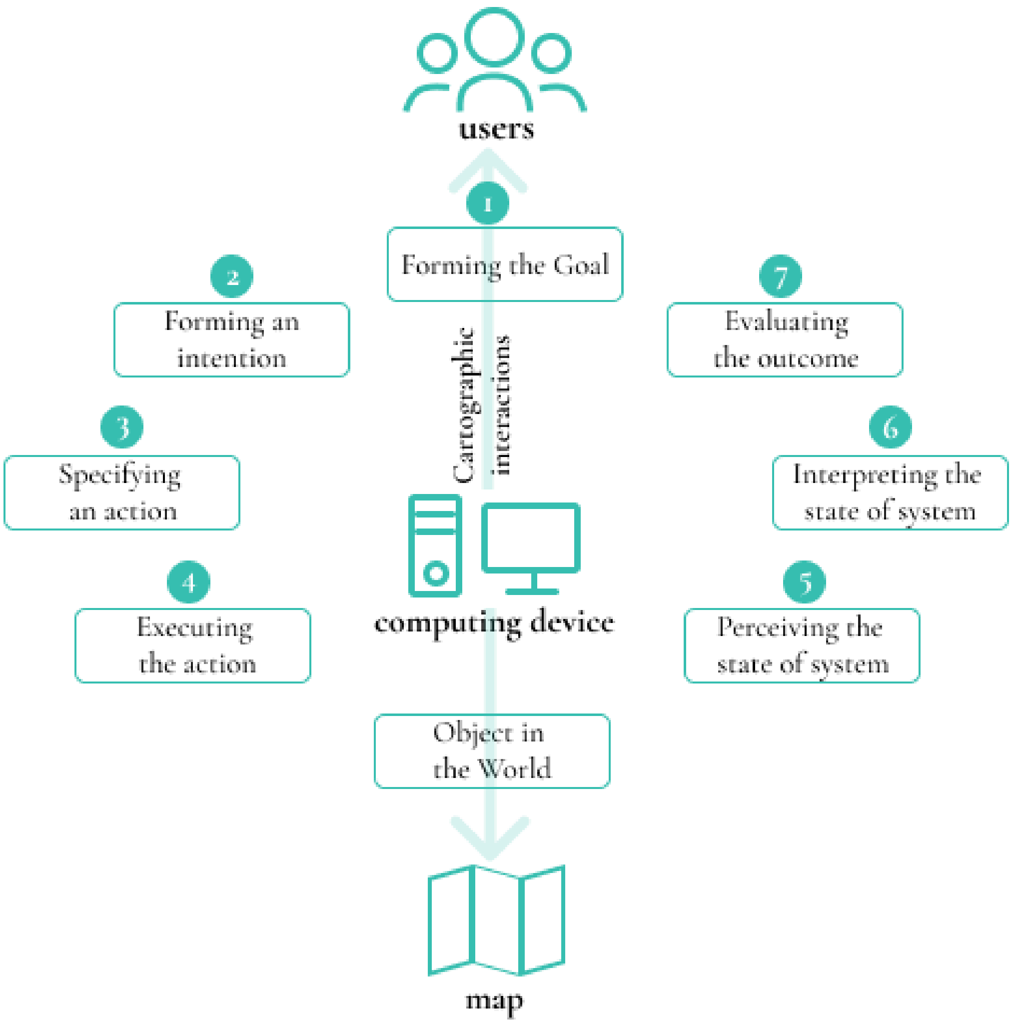


Figure 5 Stages of interaction

simplified from the work of (R. E. Roth, 2012).

Roth (2012), in his research, briefly explains the stages of interaction. The first stage of this action model is (i) *forming a goal* which can be an open-ended task considered as a goal. *(ii) Forming the intention* is the formulation of a closed-ended task described as an objective of the project that works on the path of a goal. The next stage is *(iii) specifying an action*. This stage deals with the identification of a system function described as an operator, which supports the objective. *(iv) Executing the action* employs the operator through an input device. The next step is to see the result through a display device which is *(v) perceiving the state of the system stage*. After seeing the result, the meaning of the change in the display is evaluated in *(vi) interpreting the state of the system stage.* The final stage is *(vi) evaluating the outcome*, which compares the perceived meaning to the original open-ended goal and checks if the goal is achieved (R. E. Roth, 2013a).

Roth (2012) identifies three basic cartographic interaction primitives: (i) the objective-based approach categorizes interactions based on the close-ended goals that the user wants to accomplish while interacting with the map in the second stage of the interaction cycle (R. E. Roth, 2013a). The main objective primitives are “identify” and “compare” (R. E. Roth, 2012). (ii) operator-based approach divides the cartographic interactions based on the interactivity tools used to achieve the objective of the users. The main operator primitives, according to Roth (2012), are “brushing”, “focusing”, “linking”, and “zoom”. (iii) operand-based approach distinguishes the interaction based on the characteristics of the recipient of the interaction operators (R. E. Roth, 2013a). “temporal”, “data”, and “object” are the most used operand primitives (R. E. Roth, 2012).

All three interaction primitives play an important role in the designing phase of interactive maps. However, the operator primitives are explained in detail in this section as they describe the components of the interface design of a map. These primitives are further compartmentalized into work and enabling operator primitives (R. E. Roth, 2013b). Work operators allow the user to accomplish their objective, whereas enabling operators to allow the user to set up and save their work for future reference (R. E. Roth, 2013b; Tolochko, 2016). During the design phase of the interactive map, the map developer must decide which operative primitives to include or exclude, which affects the interaction between the user and the final map product. The list of these primitives is included in Table 5 below:

Table 5 Cartographic Interaction operator primitives

adopted from (R. E. Roth, 2013b).

	Interaction operator primitive	Description
Work Operators	Pan	Changes the geographic center of the map; adjusts the part of the map that is in the current view, since part of the map is off the screen
	Zoom	Changes the scale and/or resolution of the map; "zoom in" commonly refers to changing from a smaller to larger scale, while "zoom out" refers to changing from a larger to a smaller scale. Zoom can also describe a change in map detail without a change in map scale.
	Retrieve	Requests details about a particular map feature or features of interest, usually through direct manipulation (e.g. clicking on the feature).
	Filter	Identifies features or places on the map that meet one or several conditions, defined by the user. Can be confused with Search, see below for clarification.
	Search	Identifies a specific place or feature of interest on the map. Similar to Filter (see above), with the difference that Search identifies a specific feature, while Filter produces multiple results that match specific characteristic(s).
	Overlay	Adds or removes features in the current map view (e.g. toggle layer visibility).
	Reproject	Changes the map projection.
	Resymbolize	Changes the design of a map, but does not change the map type itself (e.g. a change in color scheme for a choropleth map, while still using the choropleth map type).
	Reexpress	Changes the map representation type (e.g. changes from choropleth to proportional symbol).
	Arrange	Changes the layout of different views in a linked visualization.
	Sequence	Creates a set of related maps that are placed in a particular order (e.g. small multiples showing change over time).
	Calculate	Computes new information about map features (e.g. calculates new statistics).
Enabling Operators	Import	Loads a new dataset or map to the current map view.
	Export	Pulls out geographic information or a map created by the map interface to be used in different map setting or interface.
	Save	Conserves the current state of the map, including its associated geographic information and/or the current system status.
	Edit	Alters the underlying geographic or attribute information of the map.
	Annotate	Allows the user to add text or graphics to the map interface.

The basic interactions used for the interface design are pan, zoom, retrieve, filter, search, and overlay. These elements allow easy interaction within the user interface, which should be integrated while designing an interactive web map. The usage of the remaining interacting elements depends on the purpose of the map design. It is suggested to provide various interacting tools to the users; however, it should not be confusing to use.

2.2.2 User-centered map design

As argued by Norman, user-centered design (hereafter "UCD") is a philosophy based on the early and active needs and interests of the user during the design process, with an emphasis on making usable and easily understandable products. The final product designed based on the UCD aspect is a result of an iterative process that is influenced by the end-users (Abras et al., 2004). The positive transformation in the user-interface design, in the field of human-computer interaction, information visualization, and web design, has been possible due to the consideration of human needs during the design process by the researchers and user-interface designers (Shneiderman et al., 2017),(Tolochko, 2016). The use of UCD for designing maps in both web-based and mobile-based applications is exponentially increasing, used and supported by various scholars (examples: (R. Roth et al., 2015), (Wang, 2014),(Robinson et al., 2011)).

While preparing the earliest desktop-based application, the user-centered design was not considered, even though it was already introduced in the field of GIS for a long time (Tsou, 2011). Traditionally GIS projects were taken over by the map designers, developer, and their experience related to GIS and cartography, rather than the consideration of the user's needs (Tsou, 2011). In addition, UCD is desired by interactive map users during the conceptualization, evaluation, and refinement process of their mapping systems, but prior evidence assumes that UCD might not be common in such practice (R. E. Roth, 2015). The reason behind the deviation from the UCD approach might be the lack of access to the target users, time, and money to perform user study, and also a general belief that the designer knows best (R. Roth et al., 2015). However, it is important to consider UCD while designing an interactive map as it owes saving a project's resources, considering that it is more costly to make extreme changes after the interface has been deployed to the end-users, compared to making adjustments in the earlier stages of design and prototyping (Krug, 2006).

UCD is a highly iterative design process (Haklay, 2010), and its objective is to enhance the user experience by obtaining feedback from the users throughout the entire process (Tolochko, 2016). The importance of iterative evaluation and revision of a design while considering UCD is emphasized by Nielsen (1988) in his work on usability with the following ten elements of usability engineering lifecycle (R. Roth et al., 2015), namely: (i) knowing the user, (ii) competitive analysis,

(iii) setting goals, (iv) participatory design, (v) coordinated design, (vi) guidelines and heuristic analysis, (vii) prototyping, (viii) empirical testing, (ix) iterative design, and (x) collecting feedback from field use. Robinson has adapted these ten elements to come up with a simplified version of the user-centered design process, which is shown in the following diagram (Robinson et al., 2005).

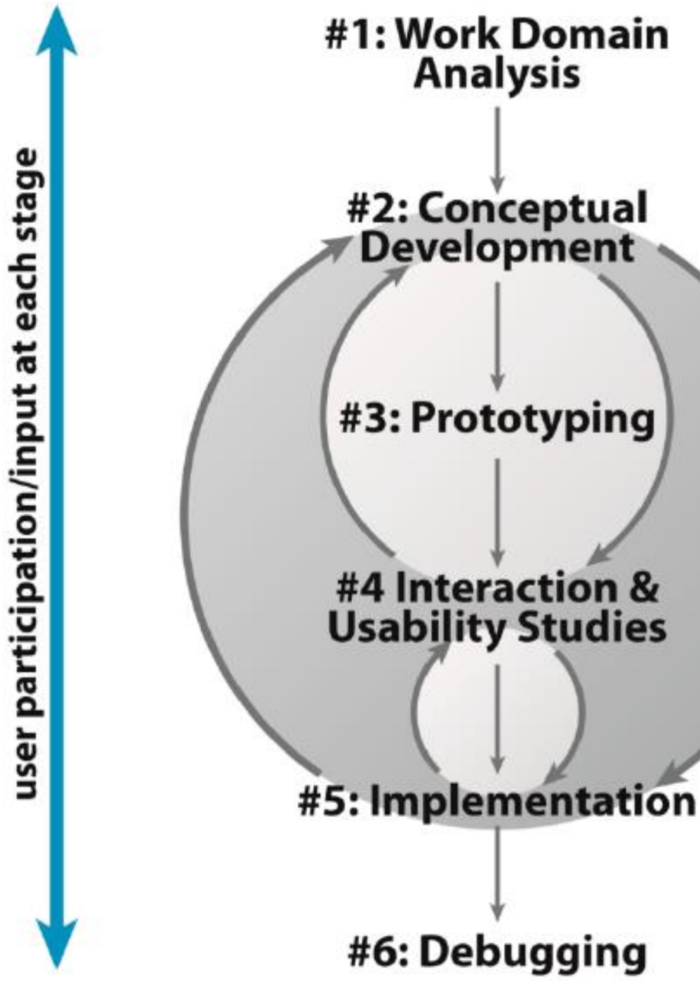


Figure 6 Iterative process of user-centered design adopted from (R. Roth et al., 2015).

Work domain analysis is the first stage of the UCD iterative process, also known as needs assessment or requirement analysis (Tolochko, 2016), where it deals with the primary research and communication of ideas between clients and developers (Robinson et al., 2005). The goal of the *conceptual development* stage is to prepare a written formulation of desired attributes necessary for the application, based on the work domain analysis and requirements of end-users (Tolochko, 2016). Finally, a graphical concept prototype is drawn regarding the layout, tools, and architecture of the application (Robinson et al., 2005). After this stage, the *prototyping* stage begins, resulting in the preparation of highly functional and interactive mock-ups. The *interaction/usability assessment* stage is incorporated in the UCD process to obtain feedback from the users formally and informally. This helps to understand how effectively the prototype works and if it is obligatory to make some changes. The necessary changes are implemented in the *implementation* stage, making sure to avoid the critical issues in the development of the application. The last stage is *debugging* stage, which focuses on the stability and compatibility of the application (Robinson et al., 2005).

2.2.3 Evaluation of interactive map

The act of evaluating an interactive web map is important throughout the map design process to verify that the cartographic interface has met the objective of intended end-users and is not limited only to its aesthetic design (R. E. Roth, 2013a). Demsar argues that even in a "quick and dirty" evaluation, the designers obtain informal feedback from users at all phases of the design process (Demšar, 2007). Feedbacks for the evaluation are collected through various observational mediums made when the target users are interacting with the interface (Tolochko, 2016). The map designer can detect the existing problem in the interface through the users' feedback and plan accordingly to resolve these problems (Rosson & Carroll, 2002).

Evaluation of a map is the main process to determine whether an interface is successful in obtaining its goal (Tolochko, 2016). The success of a map interface can primarily be obtained from the *usefulness* of an interface *(usability and utility)*, which helps to check whether the application can be used to perform certain tasks to obtain the desired objective (Demšar, 2007). *Utility* suggests whether the designed interface can perform its defined task to obtain the goal, whereas *usability* describes how well the users can interact with the interface (Nielsen, 1992). When having a debate on what comes first in the utility-usability trade-off, Roth and his team argue that it is important first to consider "users" before making a decision (R. Roth et al., 2015). Hence, it is important to understand the three Us of UCD: users, utility, and usability, to evaluate the success of an interface.

As the name suggests, in user-centered design, the priority must be given to the end-users by defining the *target user group* or the community of users the interactive map is intended to support (R. Roth et al., 2015). Roth and his team have offered four groups of end-users that map designers must consider at the beginning phase of recognizing their audience, which is: (i) key stakeholders or domain experts having more experience and knowledge than the typical users, (ii) the target users where project team need to translate the abstract of users into a concrete requirement, (iii) the target users who are likely to evolve, and therefore the interface should also evolve with the target users, and (iv) the target users who exhibit substantial diversity in their characteristics and needs (Nielsen, 1992).

As mentioned in the previous paragraph, *usability* can be defined by how easy it was to use the interface (Grinstein et al., 2003; R. Roth et al., 2015). Additionally, in the case of interactive map u*sability* is also the extent to which a computer system allows the users to achieve specified goals and does so effectively, efficiently, and satisfactorily (Ivory & Hearst, 2001). Usability.gov has adopted the guidelines from Nielson, which lists five measures of usability as follows (Affairs, 2013; Nielsen, 1992):

i. **Learnability:** how fast can the user understand the interface without previous use
ii. **Efficiency:** how fast can the user perform the desired task after getting to know the interface
iii. **Memorability:** how well can the user remember the functionality of the interface the next time s/he uses it
iv. **Error frequency and error security:** how frequently are users making mistakes while performing the tasks and how critical are those mistakes
v. **Subjective satisfaction:** how well does the user enjoy the interface.

The productivity of the work can be primarily evaluated from the first four measures, (i) to (iv), whereas (v)th measures the involvement of the user with the interface (R. Roth et al., 2015).

Along with the usability guidelines, it is also important to be aware that if the designed interface is informative enough to achieve the end user's goal. The guidelines for measuring the utility of the interface are not frequently available in the literature, as compared to the usability evaluation

(Tolochko, 2016). Roth et al. (2015) has put forth two approaches as the guidelines for evaluating utility which is briefly described below:

i. **Benchmark tasks:** the capability of the user to complete the desired tasks while interacting with the interface
ii. **Analytical products:** the hypotheses generated, knowledge constructed, or decisions made by the user while interacting with the interface.

The benchmark tasks help to understand how correctly the users provide the answer to the question provided to obtain the desired goal. On the contrary, analytical products help to comprehend the perception of the users about the interface.

After understanding the importance of users, utility, and usability to evaluate the success of the interface, it is also an utmost necessity to be aware of the relationship between them. The interconnective nature of these three components of an interface success is shown in the following Figure 7:

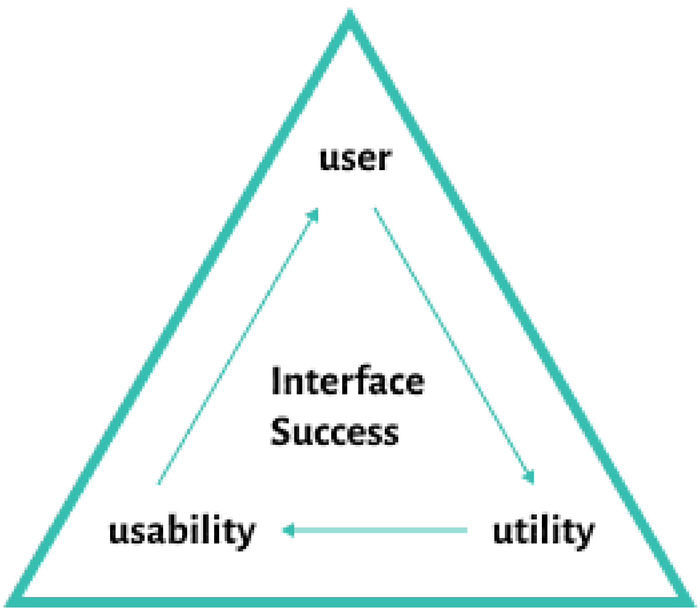


Figure 7 Interface success relationship adopted from (R. Roth et al., 2015).

During the primary stage of the interface evaluation, the user interacts and identifies the potential issues related to the usability of the interface and provides their inputs about the possible revisions to its utility in the next version (R. Roth et al., 2015). The measures required for utility and usability should be collected during this evaluation process. This relationship suggests firstly to collect the user needs and characteristics, and then to set the utility threshold to respond to these user requirements, and thirdly to improve the usability of interface design based on the utility threshold, and lastly to return to the user to evaluate the interface, leading to a new *user-utility-usability* loop (R. Roth et al., 2015).

2.3 Existing applications

In this section, a brief review of three existing applications is done to understand how they are designed. The comparison is focused on the data extraction, the medium of designing the visualization, and the interaction that are used for the preparation of the satellite visualization application. The TLE dataset for these three applications is extracted from space-track.org, and the satellite.js JavaScript library is used for the calculation of satellite position. The comparison of the existing application based on their representation and interaction are shown in Table 6 below:

Table 6 The comparison of existing applications to visualize satellites.

	Representation	Interaction
Satvis.space (Ahmed, n.d.)	**Built** with CesiumJS, Satellite.js, Vue.js, Workbox. **3D** virtual globe representation is found with the possibility to change into 2D. **A single** color dot symbolic representation of satellites is observed.	Pan, zoom, retrieve, filter, overlay
Satellite map - Esri	**It is built** with ArcGIS API for JavaScript, Bootstrap, jQuery.	Pan, zoom, retrieve, filter

(Esri, n.d.)	**3D** virtual globe representation is found. **A single** color dot symbolic representation of satellites is observed.	
Stuffin.space (*Stuff in Space*, n.d.)	**Built** with WebGL. **3D** virtual globe representation is found. **Multiple** color dot symbolic representation, which classifies space objects based on their types (satellites, rocket bodies, and debris), is noticed.	Pan, zoom, retrieve, filter, search

Table 6 compares the existing applications based on which platform was used for the representation of the application and the interactions used. This comparison helps to understand the pattern of developing satellite visualization applications.

2.4 Summary

The satellites are classified in terms of their application, mass, or height above the Earth's surface. These classifications help in the preparation and production of concise methods to obtain information on satellites and their Keplerian orbits. Every satellite(>10cm) has its respective TLE, which is a concatenation of general perturbation elements. The satellite catalog and TLE dataset are used in satellite identification. Mathematical models, namely SGP, SGP4, SDP, SGP8, and SDP8, utilize the TLE dataset to obtain the position and orbit of satellites. The obtained information then can be developed into interactive visual maps using software development tools/libraries like CESIUM, WebGL, and Esri API.

The development process of an interactive map revolves around information visualization, a user-centered approach, and evaluation of the map. Representation and interaction are the backbones of a map design process. Here, the available visual variables are identified and meaningfully represented. The layout design is determined by the proper placement of map elements. The placement of map elements should essentially follow a logical hierarchy or order based on their relative importance. The interaction design should allow users to access the map conveniently to achieve their goals. The whole design process should be based on the needs of users, which is described by the concept of UCD. UCD itself is an iterative process where the feedback of users is obtained in the entirety of the process. This contributes to the evaluation of interactive maps as well. The success of a map interface can primarily be obtained from its usability and utility evaluation Usability is the measurement of how easy the interface is for users. The ability of the user to perform a certain task and the decisions made during the usage are analytically quantified by a utility. This contributes to the success of interactive map development.

3 METHODOLOGY

In this chapter, a brief description of the methods used for the thesis is explained. A workflow used is represented with the help of a flowchart. It consists of three sub-sections, which explain the design of the prototype, the survey done for the evaluation of the prototype, and the summary of the chapter.

A mixed research method was used to achieve the research objectives and answer the research questions. A background study of the existing satellite visualization applications was performed to select the data, type of representation, and the interaction of the interface. These representing elements selected were to be implemented in the application design. An online-based survey was performed to check the preference of the end-users for the visualization of the interface. The evaluation of the designed application was done based on the discrete rating scale system. Finally, a quantitative and qualitative analysis approach was chosen for the evaluation of the survey result.

A detailed analysis of the existing application was conducted to understand the basic requirements of cartographic elements needed for the preparation of an interactive map. This analysis was performed on finding the prerequisite of data, representation, and interaction. The Application was designed based on the UCD approach considering these requirements. The detailed study of the UCD approach for the preparation of an interactive map was examined with the help of the available resources, which is explained in chapter 2. After the collection of necessary elements and the basic information for preparing an application, FIGMA software was used to prepare the mock-up prototype. This is a high-fidelity interactive prototype of a web map that was built with the browser-based user interface design application, *Figma* (*Figma*, n.d.). It allows the implementation of various interactive tools, which are useful for the user study and beneficial for designing a user-centered application.

A user study was done in the form of an online survey, particularly to achieve two objectives: (i) to answer the research question about the visualization of the satellites and (ii) to evaluate the interface based on its utility and usability. The workflow of the methodology used for the thesis is shown in the following Figure 8:

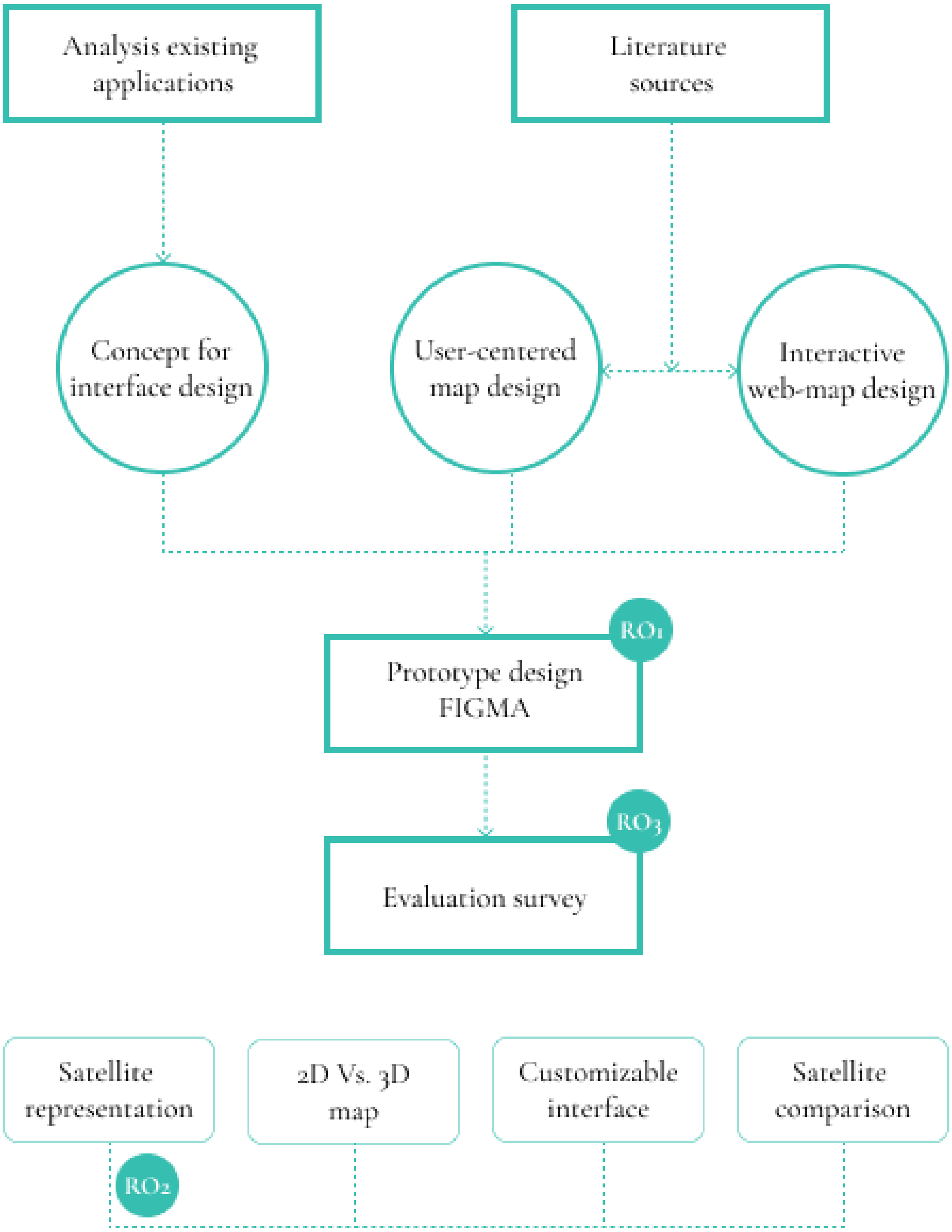


Figure 8 Workflow of the methodology.

In the online survey, the visualization questions consisted of a screenshot of the specific window of the application. Multiple-choice questions were asked to users with the ability to choose a single answer. An open-ended question was also asked to know the reason behind their preference. The qualitative results were analyzed with the help of Microsoft Excel. The feedback of the users as an answer to the open-ended question was first analyzed qualitatively and then quantitatively. Keywords were extracted from the script, and a treemap was created to visualize the results.

3.1 Prototype design

A brief explanation of the methods used in the prototype design is discussed, such as data design, the expected outcome of the prototype, various components of the interface design, and the outlook of the final designed product. This section also focuses on the limitations and use cases of the finished prototype product.

3.1.1 Data design

As explained in chapter 2, sub-section 2.1.2 *satellite catalog*, there are dual sources available for satellite data which are Space-Track and CelesTrak. Although the dataset available in Space-Track is more updated as compared to CelesTrak, for this research, the CelesTrak data is chosen because it does not require authorization. Secondly, this study is concerned with the prototype design for the visualization of the satellites and not the fully functional application design, which finds the data extraction from CelesTrak as effective and compatible. Additionally, CelesTrak offers data downloading based on the classification of the satellites such as special interest satellites, weather resources satellites, communication satellites, navigation satellites, scientific satellites, and miscellaneous satellites. This feature has helped in the classification of the satellites while designing the interface of the application.

Upon request of GPS operational satellite data, the format that appears in the CelesTrak is shown in Figure 9 below:

```
GPS BIIR-2  (PRN 13)
1 24876U 97035A   21293.54530054  .00000048  00000-0  00000-0 0  9996
2 24876  55.4804 165.0335 0054050  54.3622 306.2406  2.00562666177845
GPS BIIR-4  (PRN 20)
1 26360U 00025A   21293.76075498 -.00000014  00000-0  00000-0 0  9993
2 26360  53.8697  88.7855 0054983 174.6823  68.5389  2.00563372157165
GPS BIIR-5  (PRN 28)
1 26407U 00040A   21293.25045834 -.00000040  00000-0  00000-0 0  9996
2 26407  55.6338 282.7934 0176400 283.9750 152.0856  2.00558797155830
GPS BIIR-8  (PRN 16)
1 27663U 03005A   21293.69459021 -.00000039  00000-0  00000-0 0  9998
2 27663  55.6838 282.5753 0121753  38.1098 134.4826  2.00551879137209
GPS BIIR-9  (PRN 21)
1 27704U 03010A   21293.68389284 -.00000103  00000-0  00000-0 0  9994
2 27704  54.9223  33.0307 0243669 298.3691  84.4973  2.00569131136003
```

Figure 9 A format of a TLE dataset.

After the request is made, the data so received is the TLE dataset, whose description can be found in section 2.1.2 of the background information chapter. In general, this dataset is used for the calculation of the position and orbit of the satellites. However, it is only taken as a reference for this prototype design. Hence, the placement of the satellites visible in the interface is randomly arranged only for visualization.

3.1.2 Expected outcome

In designing the interface, the following features mentioned were deliberately chosen to meet the expected outcomes. These criteria were derived from the literature sources and analysis from similar available applications.

1. A **simple navigation menu design** is used with minimum icons which are self-exploratory so that the users are guided from one window to another frictionlessly. The name of the icons is placed close to them or is visible on the hover to avoid the confusion of users while interacting with the interface.
2. The **search function and filter option** are kept, allowing the users to select the individual and group satellites based on their function and characteristics, respectively. This feature is inserted so that the users can find their desired satellites quickly and view their information.

3. The **2D and 3D globe** representations are displayed in the interface. The idea behind it is that the use of a 3D and 2D globe can effectively visualize numerous satellites and the individual satellite to see its path, respectively.
4. The **comparison window** is designed to compare two or more user-selected satellites. This allows the users to compare the satellites based on their altitude and orbits in different timeframes.

3.1.3 User-centered interface design

The prototype interface is designed considering the UCD workflow, which is in its initial phase. Robinson and others have come up with the six design stages for UCD workflow, which are explained in the 2.2.2 subsection of the background information chapter. The following Figure 10 compares the proposed workflow and how it interlinks with the user, usability, and utility evaluation method of the UCD design process.

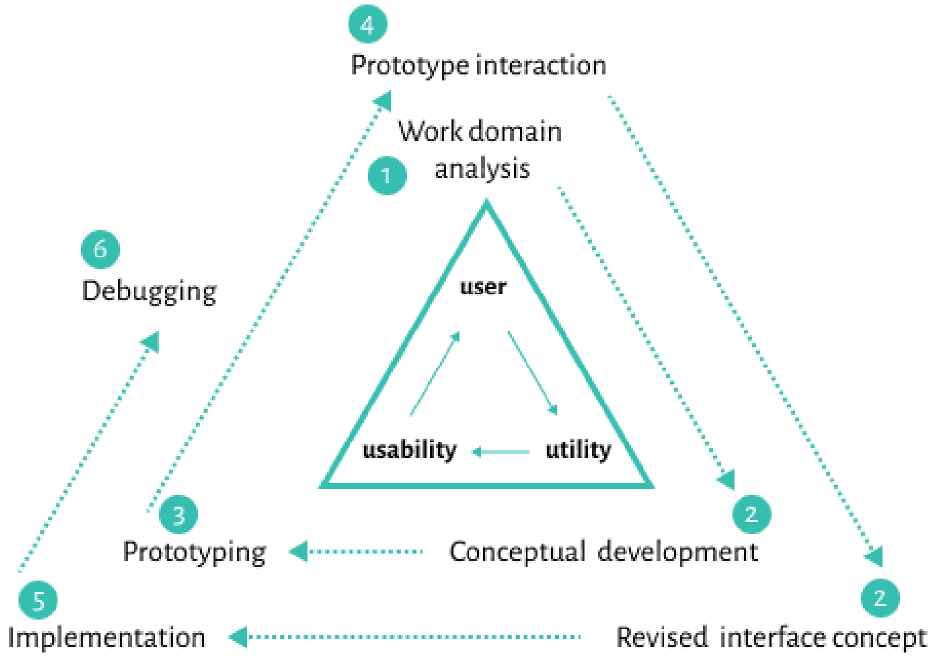


Figure 10 User-centered design as an iterative process adopted and revised from (R. Roth et al., 2015).

Figure 10 consists of a triangle in the centre and dash arrows run from number one to six, representing the workflow of the application. The workflow is designed to iterate through three evaluation components. For instance, *work domain analysis (1) and prototype interaction (4)* check the interface with the perspective of users; *conceptual development and revised interface concept (2)* examine the application based on the utility; *prototyping (3) and implementation (5)* evaluate the usability of the interface. The workflow numbered in this figure () is per the workflow of the UCD laid down by Robinson (Robinson et al., 2005).

The triangle represents the interconnectivity of user, utility, and usability. This interrelationship between these components should be maintained while designing an application, as schematically shown by the dashed arrow in figure (). While designing the application *SatelliteViz*, firstly, the users of the interface were analyzed, and all general map users willing to be aware of the satellites were selected. After the users were determined, the concept of the application was designed by considering the available maps, such as the *Esri satellite map* and *Stuff in space*. One of the shortcomings of these web maps was their technicalities, which made it difficult to navigate for the general users. *SatelliteViz* was designed to overcome this difficulty and make it easier for the users to understand the navigation process. Based on the abovementioned concept formed, a prototype was designed and was informally tested by a few users. Upon their feedback, an initial concept was revised and adopted in the prototype. Generally, these stages are repeated as long as the map developer is not satisfied with the users' feedback, and after a final debugging, the application is deployed to the users, and the application is considered as successful. Here, for the final evaluation of the application, one formal user test through an online questionnaire was done, where the users' feedback was analyzed for this research project.

3.2 Survey

This section focuses on the workflow of the online questionnaire-based survey carried out to evaluate the mock-up prototype of the application, which is explained in the previous section of prototype design. The description of the survey, participants, and the evaluation method is presented.

3.2.1 Description

The user study was an online-based survey consisting of various objective and subjective questions. The survey method for this study was chosen because feedback from many diverse groups of users from different educational backgrounds was required. In the present context, it was not feasible to arrange a face-to-face survey or an interview.

The survey took place on the platform called *Qualtrics*. The survey was divided into five sections: (i) the general information of the participants, (ii) interface interaction, (iii) evaluation of the performance, (iv) utility and usability test of the application, and (v) subjective questions. The first section is the pre-test questionnaire to get a perspective on the participants. As the application was designed for all kinds of map users, it was important to know the basic information of the users. The survey was designed to be finished in approximately 25 minutes. It was distributed to the users through various social media platforms.

After the general information of the users was taken, they were put to interact with the interface to be familiarized with the application. The users were now requested to answer the post-test questions which were related to the application. Here, the participants had to perform the designated tasks and answer the questions related to the visualization of the satellites. Then, the users had to evaluate their performance based on the difficulty or easiness of using the interface. Further, the utility and usability of the interface were checked with ten questions each. In the section of subjective questions, two open questions were asked to get feedback and suggestions from the participants regarding the interface.

3.2.2 Participants

The user test was surveyed on participants from various educational backgrounds. They were not restricted on the grounds of age, gender, or familiarity with the subject matter. The participants were asked to state their major educational background to get an idea of how the interface was perceived by participants from different backgrounds. A total number of 40 participants partook in the survey, out of which 28 were males, and 12 were females with the age range of 18-54. The following Figure 11 illustrates the educational background of these participants.

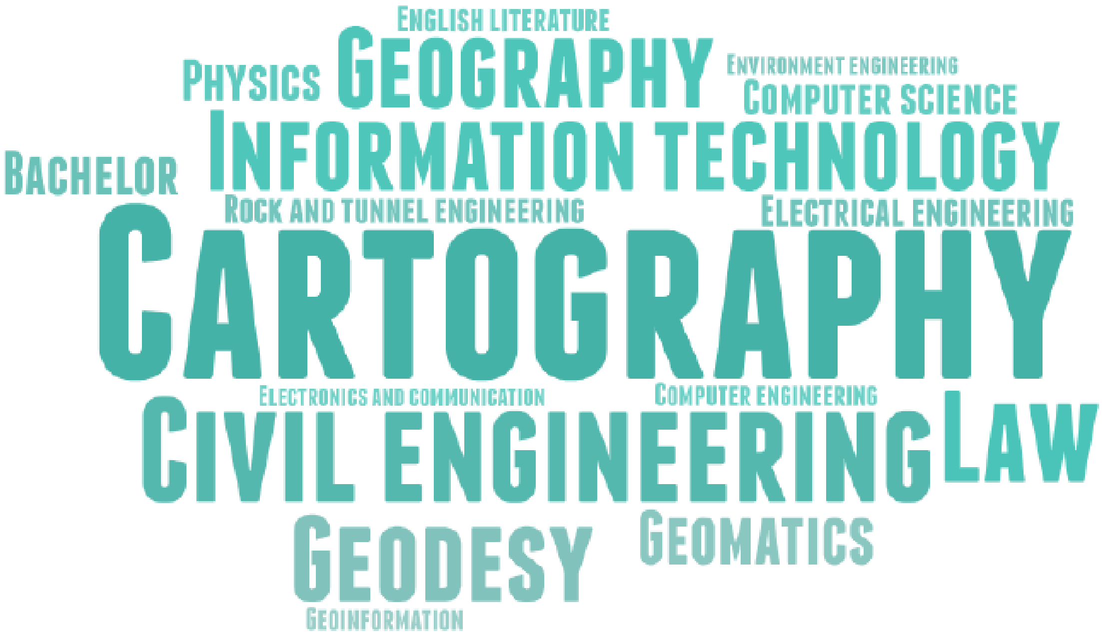


Figure 11 Educational background of the participants.

The users were asked multiple-choice questions related to their familiarity with the interactive maps. Figure 12 shows the pie chart representing the results of the participants. The number indicates that most of the participants are slightly familiar with using the interactive maps, but few users are fully unaware of interacting with the web mapping.

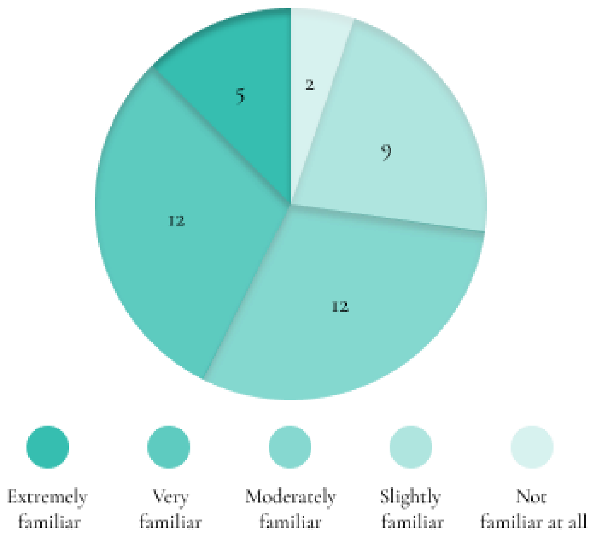


Figure 12 Familiarity of users with the interactive maps.

The familiarity of the participants with the term "satellite" and its types and function plays an important role in this study. Few of the users have little knowledge of the function of the satellites. However, it was found that there exists a participant who is completely unaware of what a satellite is and its purpose. Figure 13 illustrates the user's profile on the knowledge of the satellite and its purpose.

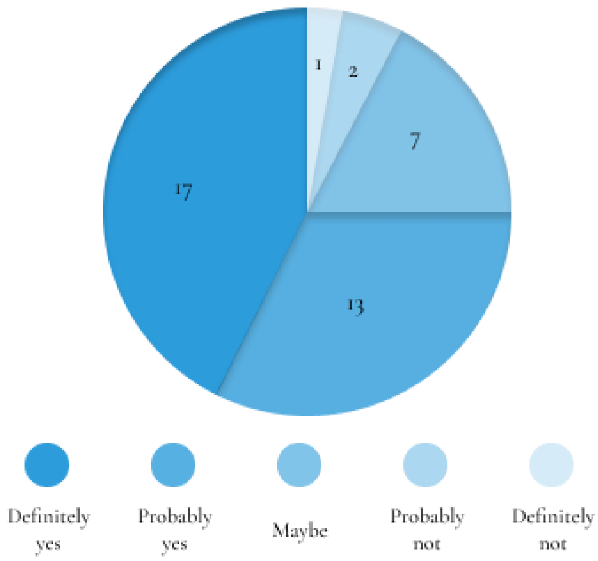


Figure 13 Familiarity of users with satellites and their orbits.

3.2.3 Evaluation method

The participants were asked to interact with the interface where two benchmark tasks were assigned, and they were asked to find the answer. These questions were designed to understand the difficulty experienced by the users while interacting. The correct answers would mean that the interface was effective enough for them to use, and they could easily interact with the application without any prior instructions. The result of these tasks would help to evaluate the effectiveness of the designed application.

Additionally, the utility and usability of the interface were also evaluated through the online survey method. The survey consisted of a total of 20 questions, each for utility and usability. A total of 14 positive questions and six negative questions were asked in the survey. The users were able to answer the questions based on a discrete scale rating. The results were analyzed quantitatively, considering the average value of each question. The positively and negatively framed questions were treated differently. A stacked chart was designed to visualize the overall result.

3.3 Summary

To summarize, out of the two available sources, Celestrek is chosen because it does not require authorization and partly because the objective of the work is to design a prototype. While designing, features such as fewer icons to simplify the user interface, search and filter option, the choice between 2D and 3D visualization and, comparison window to contrast two or more selected satellites were added to meet the expected outcome. Iterative user-centered design protocol was used employing beta versions to users to determine the most efficient prototype possible. Figma has been used to create a browser-based user-centered design prototype allowing the implementation of various interactive tools.

A five-sectioned questionnaire survey, deployed to participants through social media irrespective of their age group and academic background, was used to fine-tune the prototype. Benchmark tests were set up, quizzing the number of satellite and junk satellites in LEO displayed by the prototype they had interacted with while following the instructions in the questionnaire, in which 40 participants took part it. The evaluation of the interface and finding to the visualization questions were done based on the same questionnaire.

4
RESULT & DISCUSSION

In this chapter, the result of the user study is discussed in detail, and its analysis and discussion are presented. This chapter is divided into four sections: prototype design, visualization, and evaluation. In the first section, the outlook of the designed prototype, with its limitations and use cases, are explored. The participant's preference for the visualization of the satellites is analyzed in the second section. In the third section, evaluation, the interface based on utility and usability is evaluated with its analysis. The questionnaire was evaluated based on the survey, and its result is discussed here. The chapter consists of the last section, which summarizes all the results and discussions.

4.1 Prototype design

The prototype was designed considering the expected outcomes and user-centered map design as stated above. In this section, an outlook of the final product, its limitations, and various use cases are discussed.

4.1.1 Outlook

The main view of the prototype is shown in Figure 14. The layout of the interface is designed on the following basis:

- in the centre: the 3D base map is placed consisting of small dots representing satellites,
- in the upper right corner: three interactive icons such as a layer, map, and compare are provided.
- in the middle section of the navigation bar: the search function is positioned,
- in the upper left corner: the filter option and visualize option is placed, and
- in the lower right corner: zoom-in and zoom-out interactive tools are presented along with *help* and *about* icons.

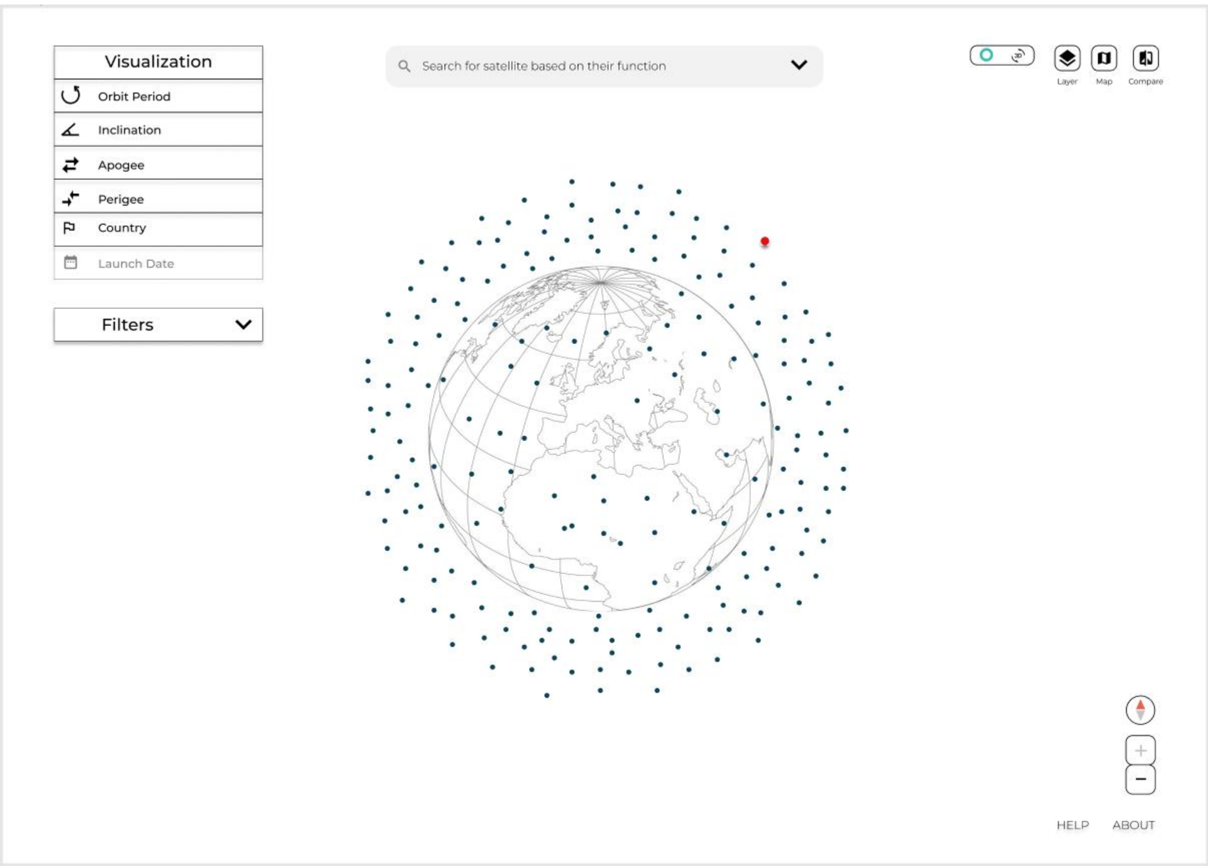


Figure 14 The outlook of the home page of the interface.

Once an individual satellite is clicked, a new window opens up with the satellite description, as shown in Figure 15 below. This window gives an overview of each satellite, starting with their name, TLE dataset format, position, altitude, velocity, and other various details. It also allows the user to switch the base map from 3D to 2D and vice-versa.

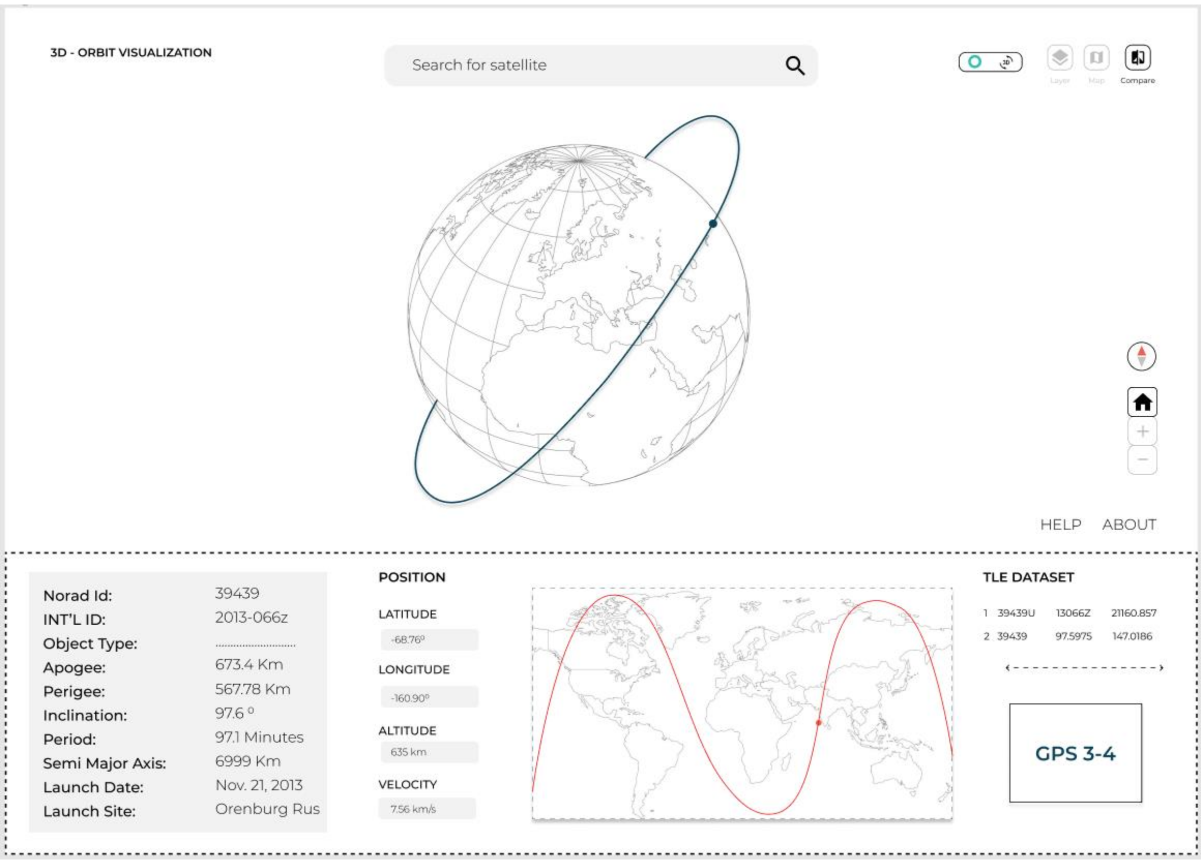


Figure 15 The outlook of the window when an individual satellite is selected.

The *compare* icon allows the users to select two or more satellites and compare them based on their altitude and orbits. The visualization of the comparison of the satellites is shown in Figure 16 and Figure 17. The upper two viewports in altitude comparison allow the users to select an individual satellite or several kinds of satellites. Based on the selection, the y-axis visualizes the altitude of the satellites, and the x-axis visualizes the launched year to compare the satellites. The orbit comparison has four viewports where the upper two ports allow the users to select the satellites for comparison and the lower ports allow the users to visualize the satellite orbits in real-time and the user-selected time.

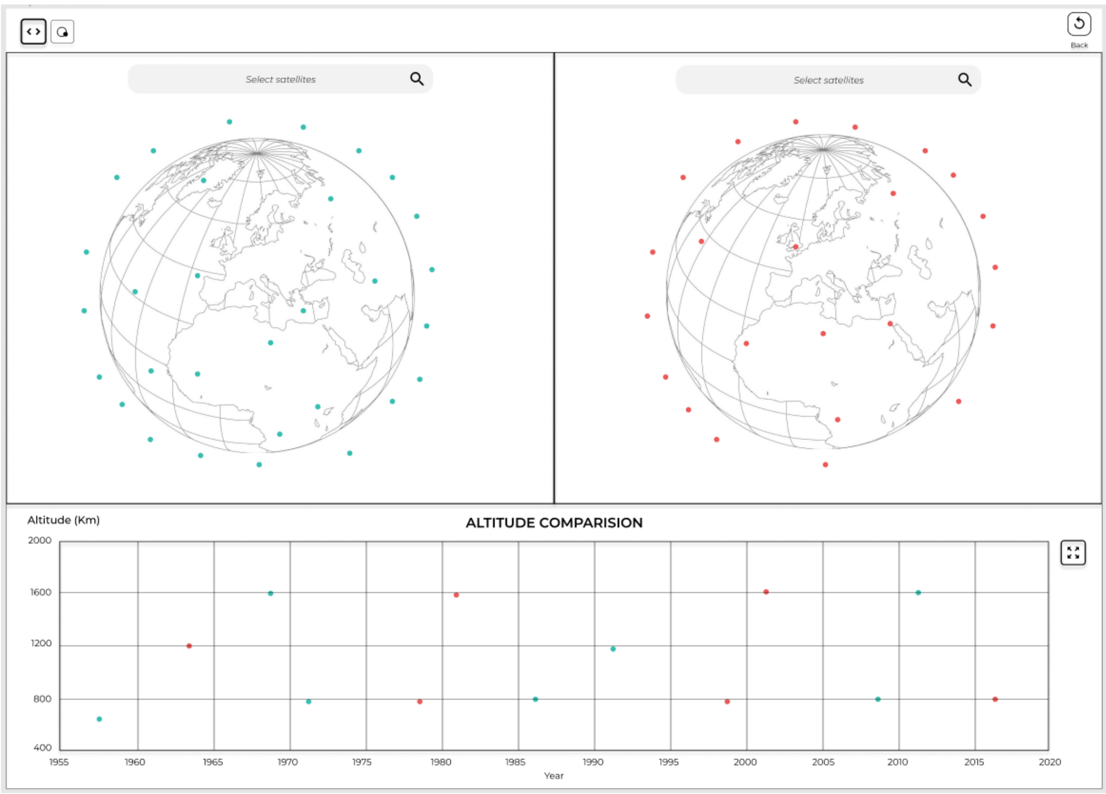


Figure 16 Visualization of altitude comparison.

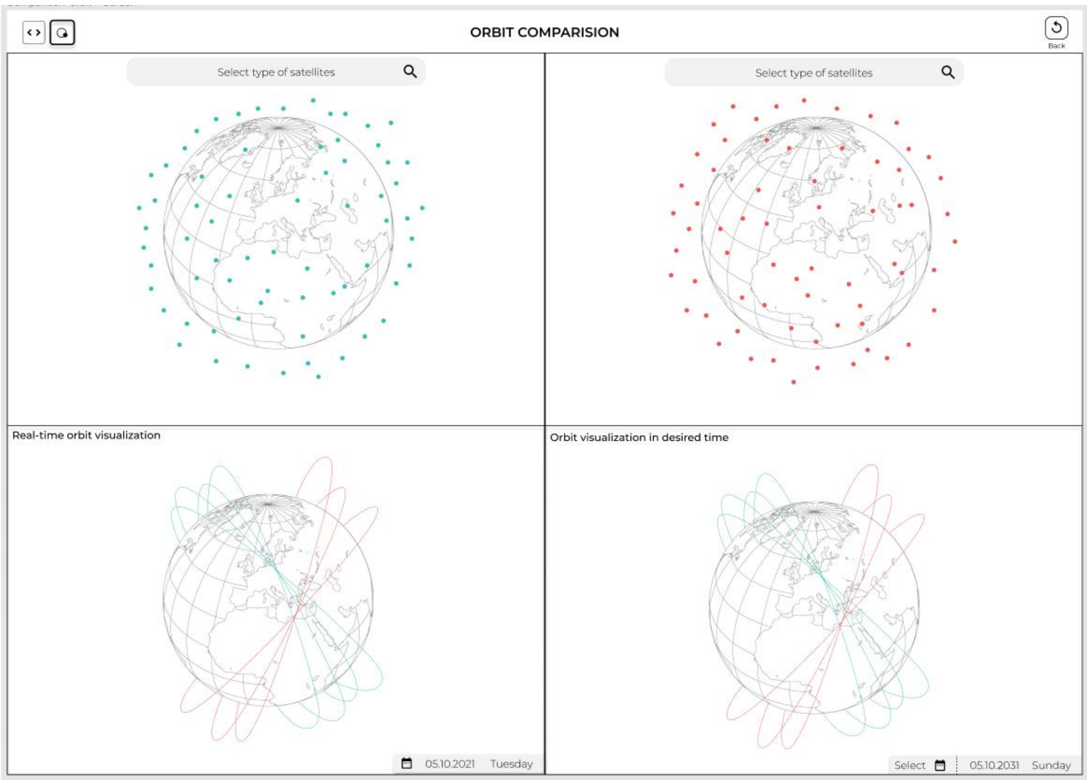
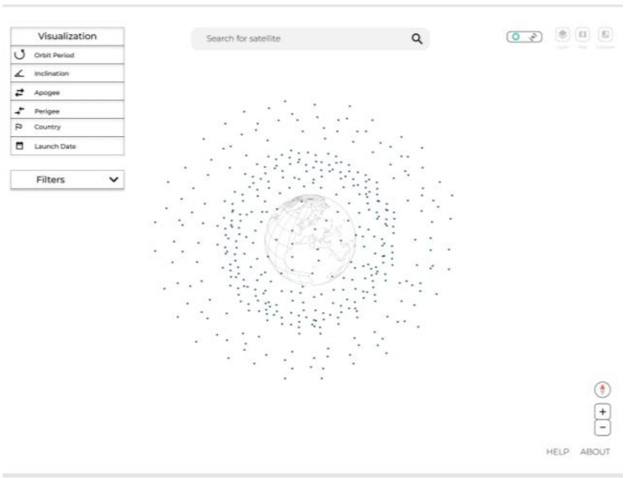
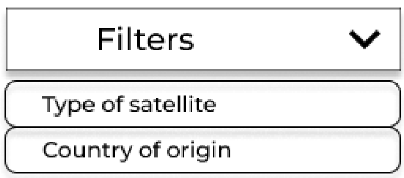
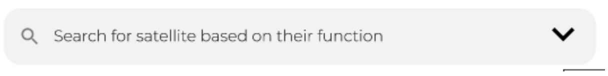
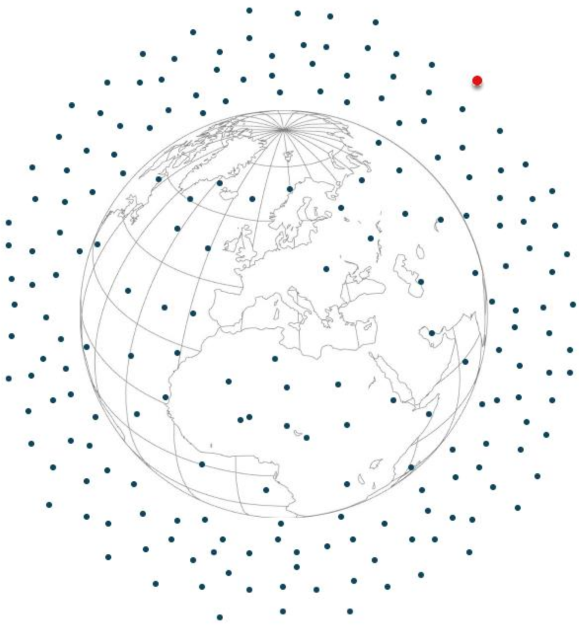
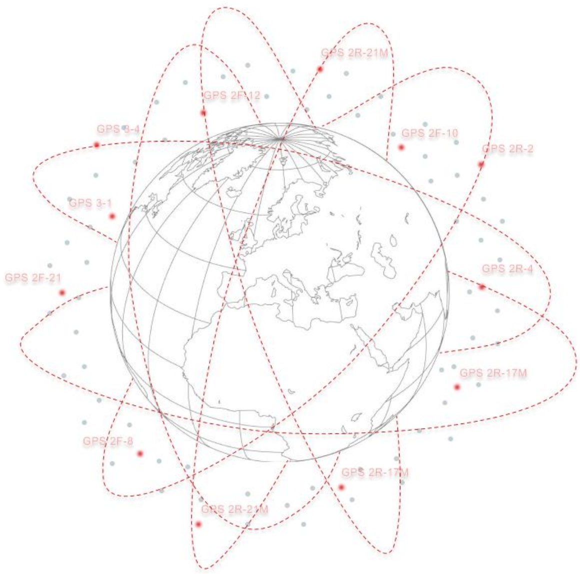


Figure 17 Visualization of orbit comparison.

There are various functionalities available in the interface allowing the users some interactivity which is listed in the following Table 7

Table 7 The interactivity present in the designed application.

Interactivity	**Implementation**	**What does it do?**
Zoom-in and Zoom-out		The zoom-in option allows to visualize satellites in detail, and zoom-out gives an overlook of all the satellites.
Filter		This option allows the user to filter the satellites based on their type and the origin of the country.
Search		The application allows the users to search a group of satellites. These are classified based on their purpose.

Retrieve		A new window providing the information appears when the user clicks an individual satellite. The satellite with the information is in a different color.
Overlay	 	An option was provided to overlay the label and orbit of satellites when chosen by the users.

This prototype can be found in the link SatelliteViz.

4.1.2 Limitations

The prototype is the mock-up of a web application and has its limitations which are listed as follows:

- The application does not allow users to zoom in and out of the interface with the help of a mouse. The rotation of the globe is also not possible.
- The easy shift from one window to another is not possible Due to the lack of an effective back button.
- The information of the individual satellites is absent.
- The position of satellites is randomly placed, and the orbital path of the satellites is not accurate.
- The buttons are functional as per the requirement only.

4.1.3 Use cases

This application is designed to take into account the diverse group of end-users for different purposes.

- **Educational purposes**

The primary intention of this application is to convey basic information about the satellites. This information plays a vital role in keeping the users interested in the satellites and how they function. It can also be useful to those students learning about the satellites in their curriculum.

- **Collision of satellites**

On February 10th, 2009, a US commercial Iridium 33 satellite accidentally collided with an inactive Russian communications satellite called Cosmos-2251, leaving a large amount of debris in low Earth orbit (Kardol, 2018; Witze, 2018). It is possible to obtain the TLE data for a specific date and time. The designed application allows the user to select the specific type of satellite in desired time and compare their orbits. This gives an idea to the user if the satellites can collide in the near future.

- **Space debris visualization**

Since the 1960s, space junk has been the biggest problem for space scientists (Witze, 2018). According to NASA, almost 90 per cent of the space objects at present are inactive satellites and are called space junk (Garcia, 2015). The reason behind this large quantity of debris in recent days is the frequent launch of satellites for various commercial, military, and civil purposes (Witze, 2018). This quantity is believed to be amplified in the next years if the deployment of numerous mega-constellations by big companies such as Boeing, OneWeb, and SpaceX is successful (Witze, 2018). In addition to this, there is an increase in the launch of small satellites like CubeSats through new technologies due to their low cost and the possibility to launch many satellites at once. This has increased the risk of space debris because when they die or when their work is done, they will contribute to the space junk (Miljkovic et al., 2017). The application can help users to visualize space debris feasibly and take the information of the busy sky, which is important for them to be aware of due to its potential threat to life on Earth (Miljkovic et al., 2017).

Space debris or junk satellites can be classified into two groups, namely, payload and rocket-related. In the application, under the "type of satellite" option from the filter dropdown menu, the users can find the junk satellites option. Once the junk satellite option is selected, the total number of junk satellites can be visualized through the dot representation. On the left, infographics are given where the classification of such satellites is made. Figure 18 below shows the window visualizing the junk satellites.

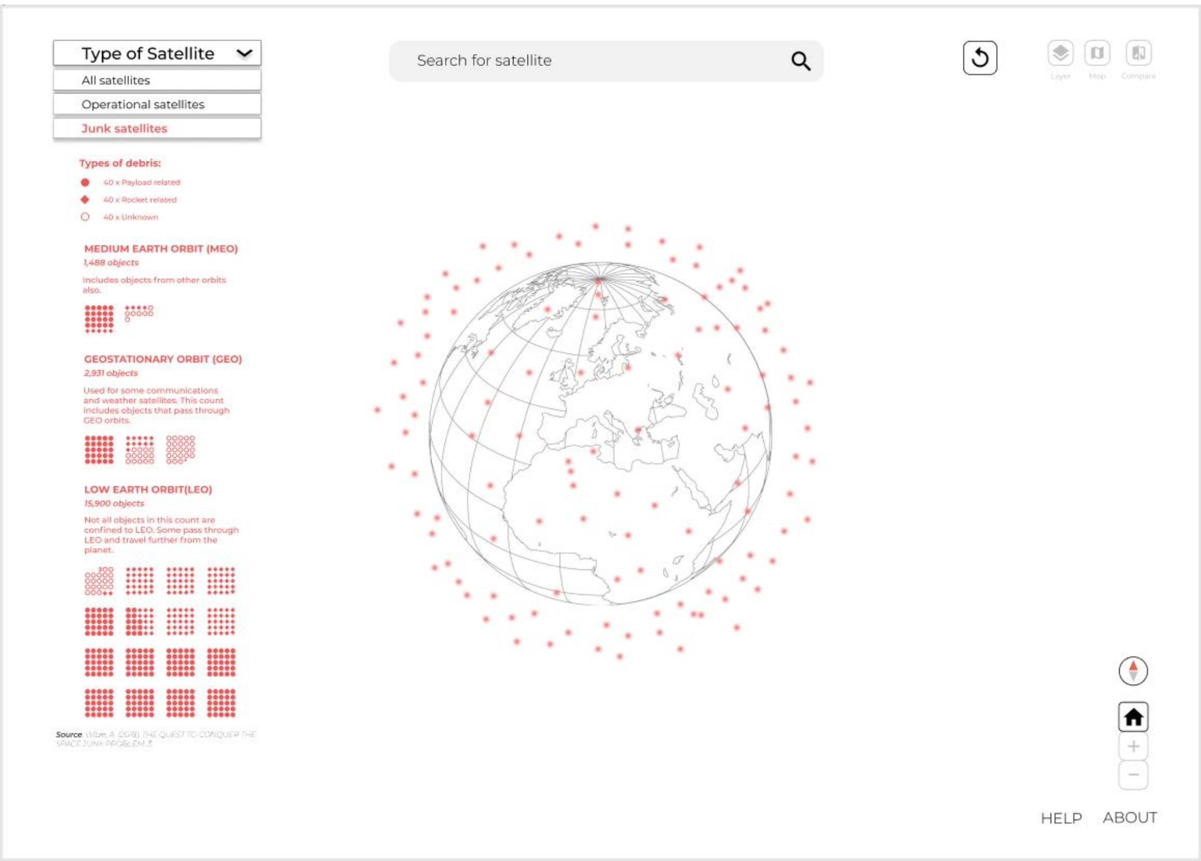


Figure 18 A window to visualize junk satellites.

With the knowledge of the increase in space debris, it is also of utmost necessity to understand the urgency of solving this problem. It is argued that no nation, organization, or individual has made a proper effort to be a space trash collector (Pearson et al., 2010). To minimize the problem of space debris, the Agency Space Debris Coordination Committee (ASDCC) has come up with 25-year guidelines for space sustainability, but it has only been implemented by half of the total missions (Witze, 2018). The guidelines laid down by ASDCC are briefly explained herein:

- The satellites are to be lowered into the atmosphere deeply so that they will burn up or disintegrate within 25 years.
- The satellites are to be inactivated at the end of their useful lifetime to avoid their explosion by leftover fuel or other pressurized materials.

Further, various research has been carried out and has proposed the solution to mitigate such problems. Those solutions are briefly given as follows:

- Deploy upcoming satellites with solar sails or light sails so that they can destruct themselves by attaching themselves to existing debris rather than turning them into the trash.

A satellite with a slingshot is to be used so that they will capture a piece of debris and sling-shot the trash to its doom.

4.2 Visualization

The goal of the visualization part of this thesis is to find an effective way of representing satellites, and this task was supported by the prototype design and the user study. The following sub-sections examine the survey results in detail and analyze them.

4.2.1 Satellite representation

Various geometric shapes such as circle, triangle, star, and square are used to represent the satellites. Each geometric shape denotes an individual satellite. These general shapes were chosen over the real shape of the satellites because of the presence of many satellites (more than 19,000), which is impractical to represent. The application tries to visualize the satellite in four different ways;

- With a single color,
- With single color and effect,
- With different colors, and
- With different shapes;

which are shown in Figure 19, Figure 20, Figure 21, and Figure 22.

Figure 19 Satellite representation with a single color.

Figure 20 Satellite representation with a single color and effect.

Figure 21 Satellite representation with multiple colors.

Figure 22 Satellite representation with multiple shapes.

The satellites were visualized in four different ways, and the users were asked to choose their favorite representation and briefly explain the reason behind choosing it. 27 out of 40 users preferred the visualization with different colors compared to other options. The bar graph (Figure 23) hereby shows the participants choosing various representations of their preference.

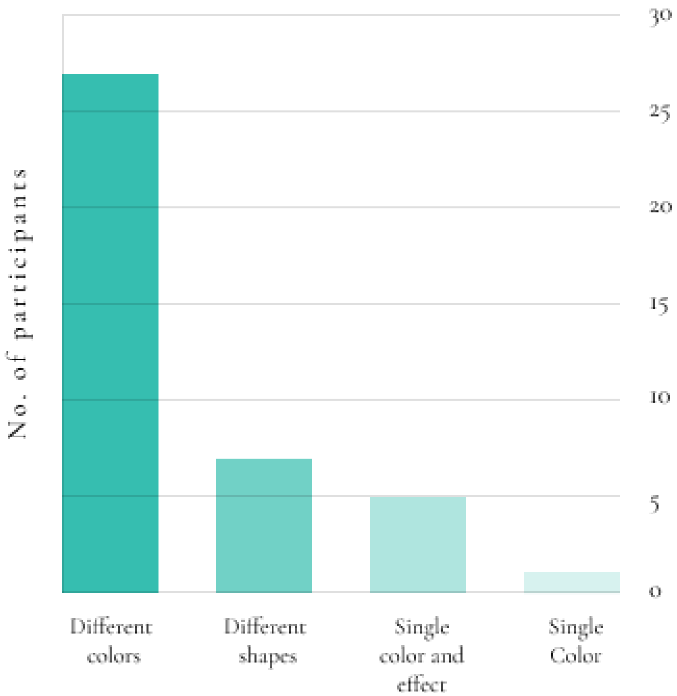


Figure 23 A bar graph showing the users and their preference for satellite visualization.

This color-coding of the satellite representation was used based on the classification of the satellites: navigation, communication, weather, earth's surface, and miscellaneous satellites. A multiple-choice question with the possibility of selecting only one answer was asked to get the opinion of the users. Furthermore, participants were asked to describe their representation preference in detail with an open question. Most of the users were in support of visualization with various colors because of its visual aesthetics and the possibility to classify the satellites. The verbatim answers of the users supporting this statement are as follows, and the underlined words are the keywords:

> *"With different colors, it is <u>easier to distinguish points.</u> I think different shapes also could work, but points should be bigger."*

> *"<u>Easier to discriminate</u> the different types of satellites."*

"Colors used to <u>differentiate state or purpose of each satellite</u>."

"I have chosen different colors since it is <u>easier to distinguish</u> the types of satellites. However, I would prefer removing the shadows of the points."

"<u>Easy to classify.</u>"

"Easier to classify and <u>subtle to the eye.</u>"

"The <u>visual aesthetics</u> and <u>satellite classification</u> together give the best visual outcome. A user can locate the specific type of satellites (which orbits are they generally on) easily."

"I prefer figure 3 because it better <u>illustrates the classification</u> of different satellites."

"Clearly <u>distinguishes the satellite</u> along with <u>visual aesthetics.</u>"

"Different colors or different shapes work for me. the color option makes it easier to <u>differentiate the satellite classifications.</u>"

"<u>Different colors are helpful</u> when there are many satellites near each other. It also helps if there are <u>different properties</u>."

"Different colors make symbols easier to be distinguished."

"Color-coded symbols could categorize by type of show satellite age."

"I like the <u>visual aesthetics</u>, but also I can differentiate the types of satellite. I prefer it over different shapes because they are simpler. Figure 4 seems overwhelming."

"Easier to differentiate."

"Although the single color and effect look soothing, I like the representation with different colors as the satellites look <u>more distinguishable</u> because of <u>higher contrast</u>. Also, different colors/type of satellite would be <u>easier to recognize</u>."

"Easy to classify and <u>clearer to the eyes.</u>"

> *"It gives a general idea of the types of satellite in space."*
>
> *"I think the 'color' gives a clear idea about the content, e.g. classification and having different colors make a quick identification of information easier. I think in this case, I would not choose neither effect nor shapes, which are a bit overwhelming and visually complicated."*
>
> *"It would be easier to identify the types of satellites by looking at the color. The color index should be present."*
>
> *"Clear and distinctive classification"*
>
> *"It looks Vivid."*
>
> *"Descriptive"*

A few respondents preferred the single color, single color with effect, and different shapes representation. This preference was mainly due to less eye strain, visual aesthetics, understanding, and clarity. The underlined keywords describe some of the reasons behind this predilection.

> *"Pleasing to eyes."*
>
> *"Easy to see and identify."*
>
> *"Looks visually good and is easy to read the information."*
>
> *"It's clarity in the present."*
>
> *"Because it's easy to visualize."*
>
> *"For me, shapes are easier to remember than colors."*
>
> *"It becomes visually understandable."*
>
> *"Other options are confusing."*
>
> *"Visual aesthetics"*

Some of the users also suggested combining the color and shape for better visualization. A few users think that the representation depends on the purpose of the interface design. Some of the suggestions from the participants are verbatim presented as follows:

> *"I think it depends on what you like to visualise. For me, the 2nd option seems better in terms of overview. What about combining shape and color? With the other three options, it is difficult to have an overview or see a spatial clustering or a pattern."*
>
> *"I like the more realistic visualization; however, the color classified viz. is also great when prompted."*
>
> *"Aesthetically single color and effect look very good, somehow giving a visual metaphor that the object is not static, but maybe classifying with colors when prompted."*
>
> *"Single color indicates single band, and they are more detailed and can be transferred to others if we have red, blue, green and violet."*
>
> *"I like each visualization for a different purpose. Between the single color options, I like the single color with effect better. I like the multiple colors in displaying which countries have launched each satellite. And I like the different shapes for distinguishing between satellite types. I think it might also be nice to combine both color and shapes so you could visualize both country and type of satellite."*
>
> *"If it only satellites one variable is fine if the visualization should include as well launch date etc. it would be good to have an additional variable in the viz. but this information is missing in the text."*
>
> *"I think it might be the easiest to differentiate, the different colors or somewhat hard to distinguish for me at the circle's size."*
>
> *"At a glance of the distribution of different types of satellites. The one with different is also preferred. However, if more satellites are to be visualised the overlap of the shapes defeats the purpose of relaying information."*

Keywords found in the user's description for selecting a particular representation were extracted and filtered. These words were counted and taken into consideration to design a tree-map for visualizing the preference of the users to the satellite representation. The designed treemap of the keywords is shown in Figure 24 below:

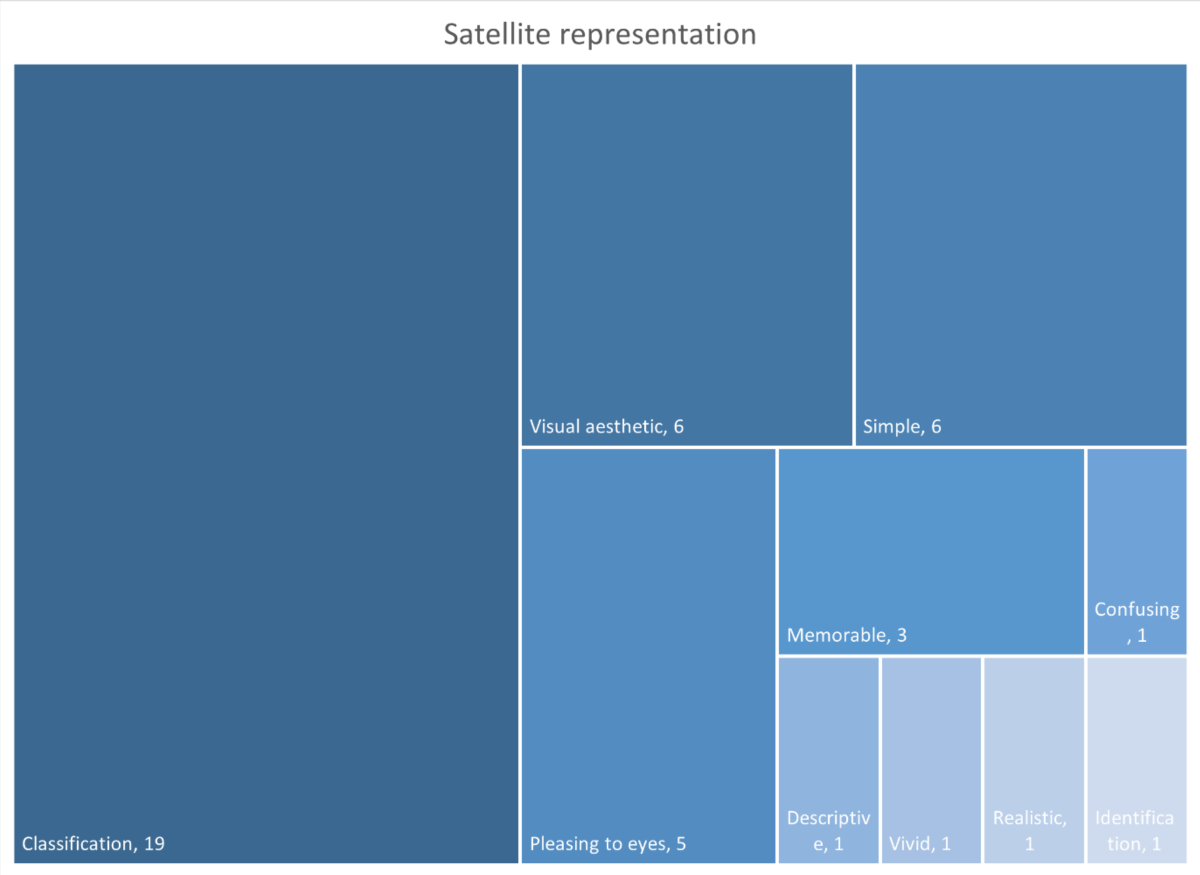


Figure 24 A treemap shows the keywords of satellite representation.

Figure 24 indicates that the users mostly preferred satellite classification because of visual aesthetics and simple interface design.

The visualization of the satellites depends on their objective. For instance, if the purpose is just to show the total number of satellites, then a single color or single color with effect can be used. It is distinct, aesthetic, and does not overshadow the information provided. The "*satellite map*" from ESRI uses a single color to present the space objects, which is simple and distinct. However, if the goal is to make the users understand the type of satellite, their properties, or their classification, then it is important to visualize satellites based on the colors or shapes. "*Stuff in*

Space" classifies the satellites and visualizes them with different colors, based on the type of the space object: satellite, a rocket body, and debris. However, the legend is not visible on the visualization window but is placed in the help section. As mentioned by one of the respondents, if different colors or shapes are used, then the legend should be placed in the visible area of the map. Hence, it is important to provide the information of the legend in a feasible area of the interface.

The preference for multiple colors for the visualization of satellites implies that most of the users find it easy to visualize the satellites based on their classification if multiple colors are used. It appears that they prefer to see the basic information of the satellites in a single window in an effective way, rather than having to click multiple interactions for retrieving the information. This predilection also indicates that when a simple background is used, the users are inclined towards having a vibrant color satellite representation. This might not be the case if the dark theme background is used for the interface design. This preference can be taken as a reference in the future for designing the satellite visualization web application, not only for the classification but for any kind of representation as required by the application.

It can be inferred that the shape representation is not preferred by the users for the classification of the satellites, as the shapes overlap with each other, and it is difficult to perceive them. A different approach of combining shape and color can also be used, which was suggested by some of the participants. This combination is not visible in any of the existing applications to visualize the satellites, except for *Low Earth Orbit Visualization* (*Low Earth Orbit Visualization | LeoLabs*, n.d.). In this application, the color-coding is defined based on the time when the satellites were tracked: last day, last week, and untracked satellites are given green, yellow, and grey colors, respectively. However, the shapes used are the rough schematic outline of the satellites, which makes the visualization cluttered. A combination of different geometric shapes with different colors can be used for the visualization of satellites to give the information of satellites as soon as the users open the interface. This approach can also be considered as an innovative way of representation.

4.2.2 3D vs 2D map representation

This application allows the users to visualize the satellites in 3D and 2D maps, as you can see in the figures () and () in chapter 4, on the section of benchmark tasks. The question was asked if participants preferred a 2D map or 3D map/globe representation to visualize satellites. A slight inclination of the users towards the 3D visualization over the 2D representation was found. The answers given in an open question briefly explaining their preference are cited below.

> *"the sinus-wave-like shape on the 2d globe looks a bit confusing to me. The 3d depiction, in contrast, feels more "natural", is easier to grasp."*

> *"Easy to visualize."*

> *"3d is more intuitive when it comes to understanding the rotation."*

> *"Although the 2-D representation gives a more clearer perspective of the exact satellite position in the globe, 3-D visualization looks more fun to interact and aesthetic so I prefer 3-D representation."*

> *"Because 3d viz gives more realistic explanation."*

> *"generally I do like 2D representations, but in case of satellites, I would go for 3D. The main reasons are the context, aesthetics and having a clear general overview."*

> *"It's easy to perceive the 3D representation. I personally feel difficult to understand the ground track of the satellite in 2D. It does not give realistic movement of the satellites."*

> *"It is more fun."*

The participants believed that this option of 3D globe representation was easier to visualize and understand in addition to its better context, aesthetics, and a general overview. Some of the participants favored the simple visualization rather than the movement of the satellites. It can be reasoned that for the users with little knowledge about the satellites and their functionalities, various details displayed on the screen at once may be confusing. The feedback from the users supporting the 2D view over the 3D view is mentioned below:

"Easy to understand the <u>movement of satellites.</u>"

"2D explains better how the satellite is moving around the globe."

"<u>2D looks more informative</u> while 3D obviously has more blank space on the page."

"Puts location of the satellite in <u>much perspective view.</u>"

"It is easy to get the information about region the satellite covers in its orbit and path."

*"Though the 2D map is distorted but it is easy to measure distance between two points. *(easy to understand)"*

"With the 2D it's <u>easier to understand the position</u> of the satellite. I like that both options are possible to see on the screen (the common 3D representation as well)."

"Because I know <u>which counties it covers."</u>

"if a purpose is mentioned would be great. therefore the 2d visualization looks less boring."

"easy to understand the trajectory of satellite. 3D map make it hard to imagine the trajectory behind the globe."

"3D can be too complicated. It doesn't work in the application."

"2D visualizations is much easier to learn than 3D."

"2D gives me a more practical spatial location"

"Better perspective"

"I think the 2d representation makes it easier to see the relative position of the satellite because the full area is visible while in the 3d form its only visible 60% of the time and at several angles its hard to tell above which location the satellite is . the 2D representation also has more familiarity as popularised by recent satellite launches in the media."

"<u>easier to see the coverage."</u>

The responses in favor of 2D are found mainly due to the easy understanding of the movement of satellites. For the 2D representation of the satellite, users had to click for an individual satellite as opposed to group satellites. Hence, it was easier to perceive the position or the trajectory of the individual satellite by the users. Some of the participants also found that this option was informative, and the position of the satellite is in a great perspective view. Additionally, they also thought that the 3D view was difficult to learn and is complicated.

Some respondents suggested having a combination of 2D and 3D representation together since they served different purposes. The 3D view has the indication of altitude, and the 2D view has the projected position of the satellite. As it was not possible to rotate the 3D globe in this prototype, the users chose 2D, but if given the option of the rotation, they would prefer 3D visualization. The following responses are the ones where participants chose both representations with conditions.

> *"Easier to understand. but I think they work great together."*

> *"I prefer the <u>combination of both</u>, actually. 3D representation indicates the 3D position of a satellite (especially its altitude), while 2D map shows clearly where the satellite is projected onto the earth and the period of the satellite's orbit."*

> *"The 2D representation has more details, so I feel that it should be in the highlight. However, a small 3D representation should also be there like in figure 6."*

> *"If the 3d globe could be panned with the control of some pointing device, such map is preferred. However, for the purpose of accuracy, specifically in the field of engineering, 2D is preferred more."*

> *"I think the 2D might give <u>a better representation</u> of the actual path. When examining both the 3D and 2D in comparison, are they supposed to match? They look like they show different trajectories. ooo or is this just because the rotation of the earth affects the trajectory when visualized in 3D. Yes, okay so in that case, I think the 2D is easier to understand unless the 3D is animated with earths rotation"*

> *"I don't have a preference but rather want to say that they both work really well complementary. So far both types are 2d visualizations from the prototype, to be fair also consiering no option with iteractivity.. makes it difficult to give a preference. I think that the transitioning effect works really well and that both visualizations in conjunction are really good. Not sure if a preferences matters here if used complementarily? Unfortunately, I have to pick an option though from the above to continue the survey..:/."*

One of the users also wrote that s/he would have chosen the combination if given a chance.

Like the previous section, main keywords from the user's description have been extracted that highlight the reason behind their preference for a 3D virtual globe over a 2D flat map.

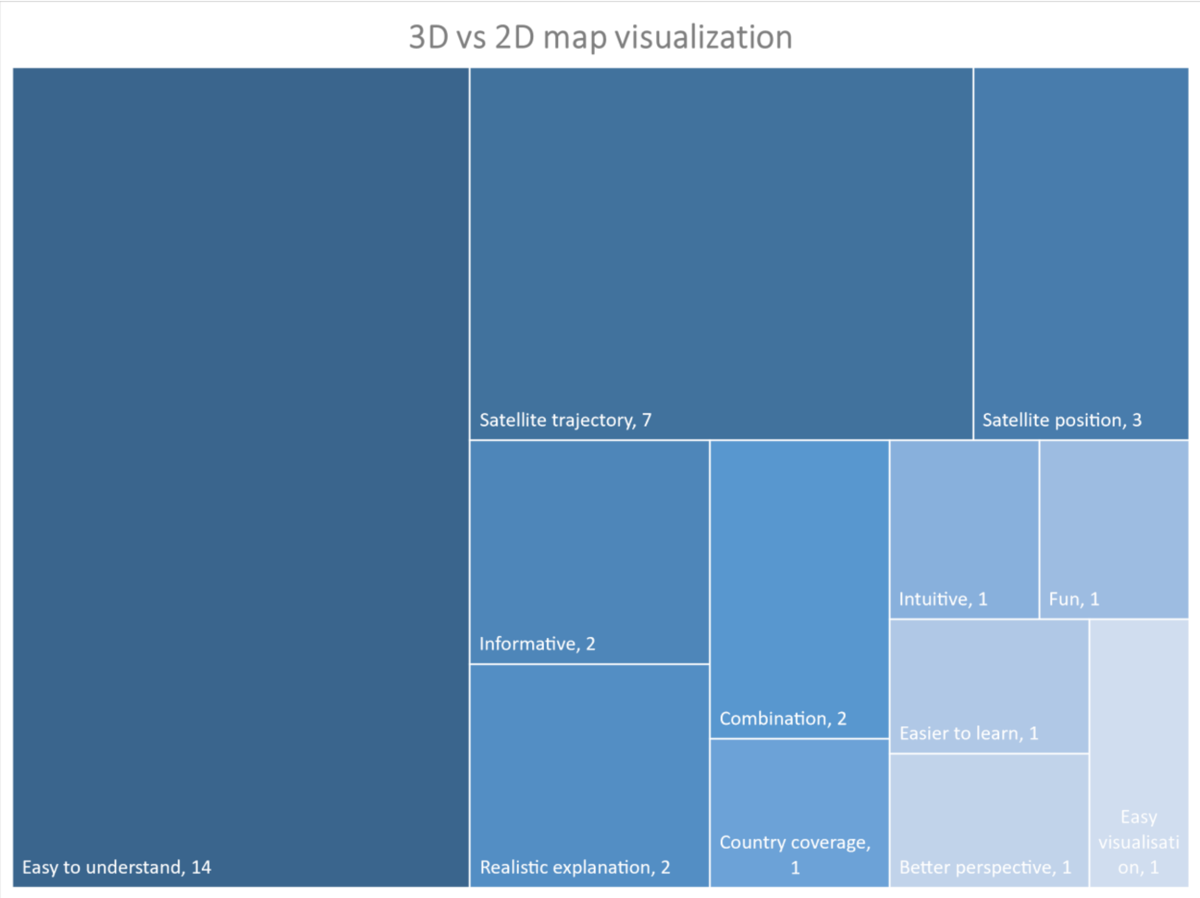


Figure 25 A treemap shows the keywords of preference of 3D globe over 2D map.

Figure 25 illustrates that users prefer the specific representation because of the easy understanding of the interface.

Most of the users chose the 3D virtual globe since they found it to be offering a realistic demonstration of the satellites. When the 3D virtual globe is used, the users find it easy to visualize and understand the provided information. When the interface is easy to grasp and more intuitive, the users can navigate efficiently. Nevertheless, there were enough users in favor of the 2D map. The 2D map representation allows the users to see the trajectory of the orbital path on a flat earth. This was the reason mentioned by the users for their preference for 2D maps.

From the user study, a 3D globe is preferable while visualizing many satellites, whereby the 2D map is preferred when one must visualize an individual satellite. The combination of both is more effective since it allows most users to track the movement of the satellite as well as visualize various satellites at once. Most of the applications at hand use the 3D globe in their interface to visualize many satellites, such as *ESRI satellite map*, *Low orbit Earth Visualization*, and *stuff in space*. *Satvis.space* gives an option of visualizing a group of satellites in both ways. However, in the case of 2D group satellite visualization, it seems confusing when multiple satellites are selected because the orbital paths of these objects overlap with each other, creating confusion. Hence, 2D is not suitable for visualizing multiple satellites.

4.2.3 Fixed vs customizable visualization

The distinct feature of this application is that it allows the users to customize the application. During the survey, participants were given an option to change some visualization – color, shape (for satellite), line type, and line color (for orbit). For the color representation, five color options were provided where the users could select the color of their choice. For the shape, the users could customize the satellites and classify them based on shapes and color and thereby visualize the satellite of their choice. In the case of line type, the users could customize it through solid or dashed lines. For the font option, serif and sans serif were provided to check the clarity of the text. When asked about the preference for fixed visualization of the interface or the customizable visualization, 25 participants were inclined towards having the visualization customizable. In the total of 40 participants, only 36 users answered the said question.

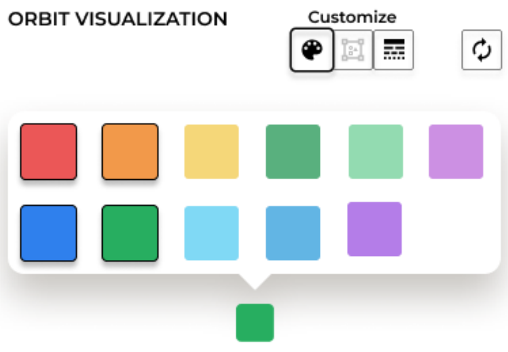


Figure 26 Color customizable option for the interface.

Figure 26 shows the option of color customizable in the interface.

The customizable feature was not found in any existing application of the satellites. This option is particularly useful in finding the preference of the users. In the survey, 25 out of 36 users favored the customizable option as opposed to a fixed design. It is inferred that the reason behind it could be that the customizable option allows the users to freely interact with the interface, is personalized, and contains multiple choices.

The application has provided a customizable option. Its features can be further revised for a better experience for users. Other visual variables such as transparency, saturation, texture, orientation, and arrangement can be included to provide additional options to users. Since the result shows the preference of users on having the customizable option, future research can be done to design a better version of user-friendly customizable option, which includes the explorative visual variables.

4.2.4 Comparison of satellites

The other option provided to the users was to compare the satellites based on their altitude and orbits, as shown in Figure 16 and Figure 17, respectively. Out of 32 participants, 25 chose the orbit comparison over altitude comparison. Since the concept of altitude comparison is not found in any of the existing applications, it is believed that the application could serve noble purposes in the domain of satellite visualization. Sven, in his thesis, developed a tool to compare the satellites based on the satellite selection of the users (Kardol, 2018). This *SatelliteViz* application was developed with the inspiration of his idea for orbit comparison, where the application is designed to compare the satellites based on their altitude and orbital path. The altitude comparison is divided into sections dedicated to LEO, MEO, and GEO along the Y-axis and allows easy identification of the altitude differences. Along the X-axis, the year when the satellite was launched is shown, as shown in Figure 27.

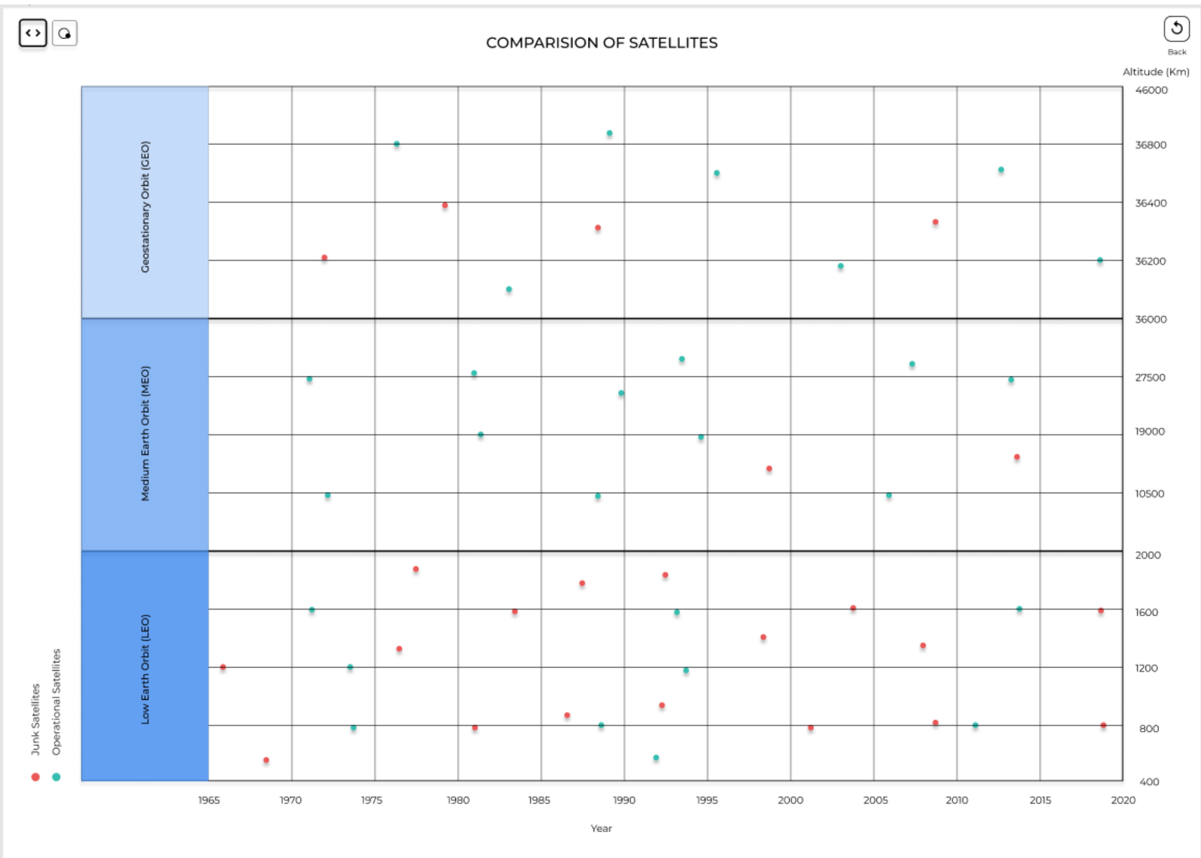


Figure 27 An altitude comparison window on expansion.

This comparison gives an idea of how the number of satellites has been increasing in recent years. Out of the total 40 surveyed, only 32 participants answered the question, “Which visualization (altitude comparison vs orbit comparison) do you prefer?”. Some of the users had left in the middle of the survey. This led to the platform recording only the partial data, where the majority of 25 participants chose the orbit comparison option. As the orbit comparison allows the users to visualize the satellite orbits in the past, present, and future, many users were in favor of that. Here, either an individual satellite or grouped satellites can be selected. When the orbit is compared, one can check if any objects are going to collide. As this is the prototype, it is assumed that the application design may be possible in the coding framework through the tool developed by Kardol (Kardol, 2018).

4.3 Evaluation

The evaluation of the interface is done based on how users felt while performing the tasks, and the utility and usability of the application were evaluated. The performance evaluation is done to check the effectiveness and satisfaction along with how mentally, physically, and temporally challenging the tasks were. Utility and usability were checked based on the ten questions provided.

4.3.1 Questionnaire

After the users answered the questions related to the interface, a different set of questions were asked regarding the difficulties felt by the users in the user test. The participants were asked to evaluate themselves in terms of mental, physical, satisfaction, temporal, and overall performance. The users were also asked to state how comfortable they felt while answering the interface questions. The reason behind this questionnaire was to examine the user's thoughts while solving the tasks. The answer to all the questions ranged from 1 to 7 with easy or difficult, less to more, low to high, relaxed to stressed, unsatisfied to satisfied, depending on the questions as mentioned later in this paper. Here, the questions were answered by 36 out of 40 participants.

The following Table 8 has briefly explained the individual breakdown of questionnaire evaluation:

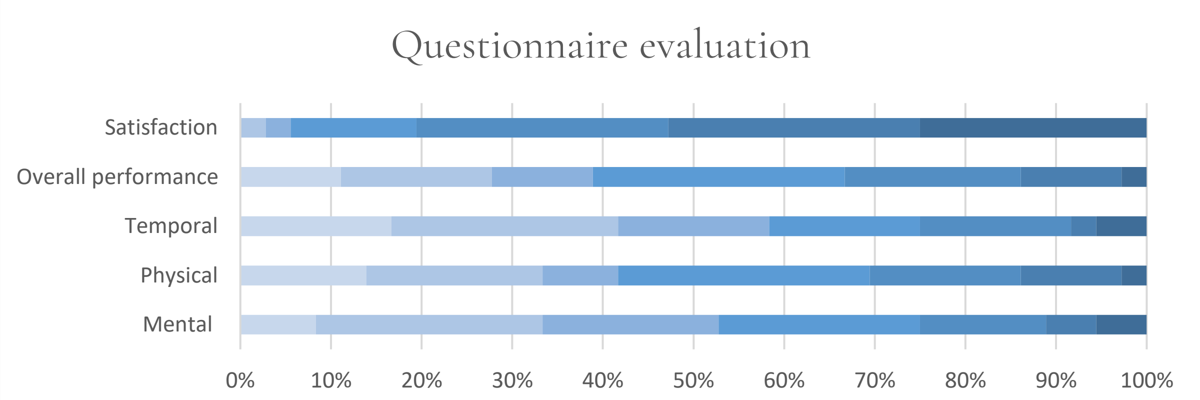
Table 8 Evaluation of questionnaires.

Mental Demand How do you evaluate the questions based on their complexity?	Users were asked this question to evaluate the interface-based question in terms of mental demand. The answer to the question ranged from 1 to 7, from easy to difficult, respectively. With 3.5 being the average, the question was ranged 3.47 in scale by the users, which seems they have found the questions to be slightly easier. However, it cannot be said that the questions were too easy or difficult in terms of their complexity.

Physical Demand How would you evaluate the number of clicks while completing the tasks?	Users were asked this question to evaluate the interface-based question in terms of physical demand. The answer to the question ranged from 1 to 7, being less to more respectively. The users stated that they had to click the cursor more than the average, as is shown by the answer reaching 3.58 on the scale. This might be the case because the application is designed in such a way that various visualization questions are answered, for which several windows have also been designed. This has led to the confusion of the users. Furthermore, this being a mock-up application with interaction limits, such as no rotate button, zoom-in-out option, or lack of effective back button, has also added up to the user's confusion creating more physical demand.
Temporal Demand How would you evaluate the time pressure you felt while performing the tasks and interacting with the interface?	Users were asked this question to evaluate the interface-based question in terms of temporal demand. The answer to the question ranged from 1 to 7, being low to high, respectively. The question was ranged 3.22 on the scale by the users, with 3.5 being the average. It appears that they had slightly less time pressure while solving the benchmark tasks. The reason for it is similar to that of physical demand, such as the existence of multiple windows, interaction limitation, and multiple sets of visualization questions.
Overall Performance How did you feel when completing the tasks?	Users were asked this question to evaluate their overall performance in completing the tasks. The answer to the question ranged from 1 to 7, being relaxed to stressed, respectively. With 3.5 being the average, the question was ranged 3.72 on the scale by the users, indicating they were slightly stressed in doing the tasks assigned.

Satisfaction Level How satisfied are you with your answers in the section where you performed the tasks?	Users were asked this question to evaluate their satisfaction level in performing the tasks. The answer to the question ranged from 1 to 7, being unsatisfied to satisfied, respectively. With 3.5 being the average, the question was ranged 5.5 in scale by the users, indicating they were satisfied in performing the tasks assigned. The fact that they have ranged the task performance to be satisfied reflects that the users are confident in their answers.

The above-given table depicts the individual breakdown of performance evaluation of the users. Figure 28 shows the stacked bar chart to put the evaluation all together and analyze the results effectively.



	Mental	Physical	Temporal	Overall performance	Satisfaction
1	3	5	6	4	0
2	9	7	9	6	1
3	7	3	6	4	1
4	8	10	6	10	5
5	5	6	6	7	10
6	2	4	1	4	10
7	2	1	2	1	9

Figure 28 A stacked chart shows the evaluation of the questionnaire.

In Figure 28, X-axis shows the percentage value depicting the users involved in the user test, whereas the Y-axis shows the various evaluating factors examined by the users through the questionnaires. The legend ranging from 1 to 7 shows the answers given by the users to the questions related to such factors. Here, the legend ranging from 1-7 is low to high, where 7 is the optimal value for the satisfaction level, and for the four succeeding factors such as overall performance, temporal demand, physical demand, mental demand, 1 is the optimal value. The lower flank of the bar is shown by the lighter color, and the higher flank is shown by, the darker one, which means that the users found the test to be relaxing, with slightly less time pressure, physical and mental demand, and more satisfying.

As shown in Figure 29 below, all the values except for the satisfaction level are slightly less or more than the average value. The standard deviation and mean of the evaluation parameter are shown in the radar chart below:

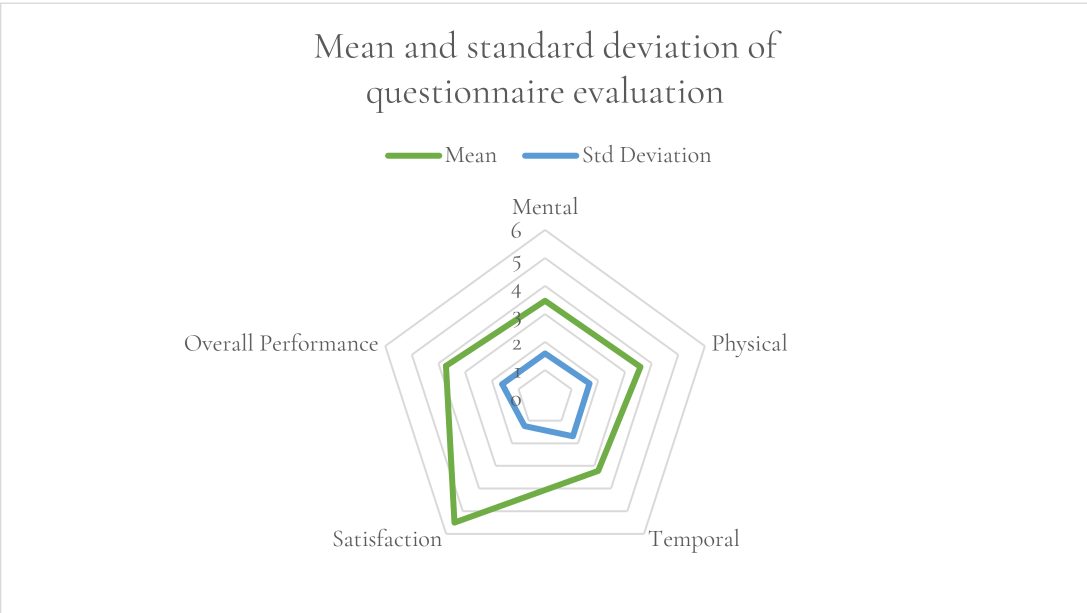


Figure 29 A radial chart to visualize the mean value of the questionnaire evaluation.

Figure 29 illustrates the mean and standard deviation of all the evaluation parameters. The mean value of the satisfaction level is different from others, as its optimal value is seven and that of others is one. The chart depicts that the mean value of all the evaluation parameters is close to the value of 3.5. This means that the feeling of users towards those parameters is neither strongly positive nor negative. However, the satisfaction value shows that most of the users were satisfied with their answers. The standard deviation shows the variation of the result from its average value.

4.3.2 Utility and usability

An online survey was made to collect feedback from target users to test the utility and usability of the interface. Users were more positive to utility than its usability; however, it cannot be said that the usability was unfavored. 36 participants out of 40 contributed to this part of the questionnaire.

Individual analysis of utility and usability is further explained in the following sub-sections.

Utility

In the survey questions concerned with the utility test, eight positive questions and two negative questions were asked. There was no similar pattern of answers, and the rating was mixed. Positively worded questions received an average of 4.83 out of 7 (7 being the optimal score), and negatively worded questions received an average of 3.5 out of 7 (optimal score of 1). With four being the average and 4.16 being the user's average result in terms of utility, it shows that they found the interface to be a bit more useful than average.

The utility rating table with the discrete scale ranging from 1 to 7, with the average values of all ten questions, are listed in Table 9 below:

Table 9 Utility evaluation table.

S.N	**Utility Rating**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Avg.**
		Disagree				Agree			
A	I would use SatelliteViz frequently.	6	5	4	11	7	0	3	3.56

B	It is not an application of my interest.	6	7	3	8	5	5	2	3.61
C	It would be useful for the visualization of satellites and their orbits.	1	1	0	1	7	10	16	5.94
D	It would be applicable for those users who want to understand the satellites and their orbits.	2	1	0	1	8	6	18	5.83
E	It would not be helpful for the users who are experts of the satellites.	10	4	6	5	4	3	4	3.39
F	It is a novel approach to provide information about satellites to general users.	2	2	4	5	6	8	9	4.97
G	It has all the required functions to explore the satellite data.	1	3	4	6	6	8	3	4.14
H	It has all the essential functions to analyze satellite data.	1	3	4	6	6	8	3	4.58
I	It has all the necessary visualizations to understand the mechanism of satellites.	4	1	6	10	4	6	5	4.31
J	It provides many ways to visualize the satellite data.	2	0	3	5	5	11	10	5.33
The average rating for positive questions (8)		**4.83**							

The average rating for negative questions (2)	**3.5**
Overall average with negative questions inversed	**4.16**

Particularly, the users strongly agreed more on #C and #D, which is the question related to the usefulness of the application on the visualization of the satellite and understanding the satellite and their orbits. Additionally, questions #F and #J got more support. These questions were related to the application being a novel approach and providing various ways to visualize the satellites. In terms of the questions related to the satellite data exploration and analysis, most of the answers were slightly inclined towards agreeing – an average of more than 4. #E – a question about the usefulness of the interface to the satellite expert, a negative question, has an average of 3.39. In general, most of the results do not show strong agreement or disagreement by the users. There is a contrasting answer in the question of #A and #B; that is, the higher average of #B and lower in #A shows that the users are interested in the interface although they may not use the application frequently. Upon the analysis, it can be said that the users being involved in the survey questions from various fields has affected this result. Some of the application features are interesting to the general users but require technical knowledge to understand. On the other hand, satellite-friendly users may not have found the interface as complicated to use since the application is designed for general users. The below-mentioned stacked chart gives an idea of the utility evaluation of the application.

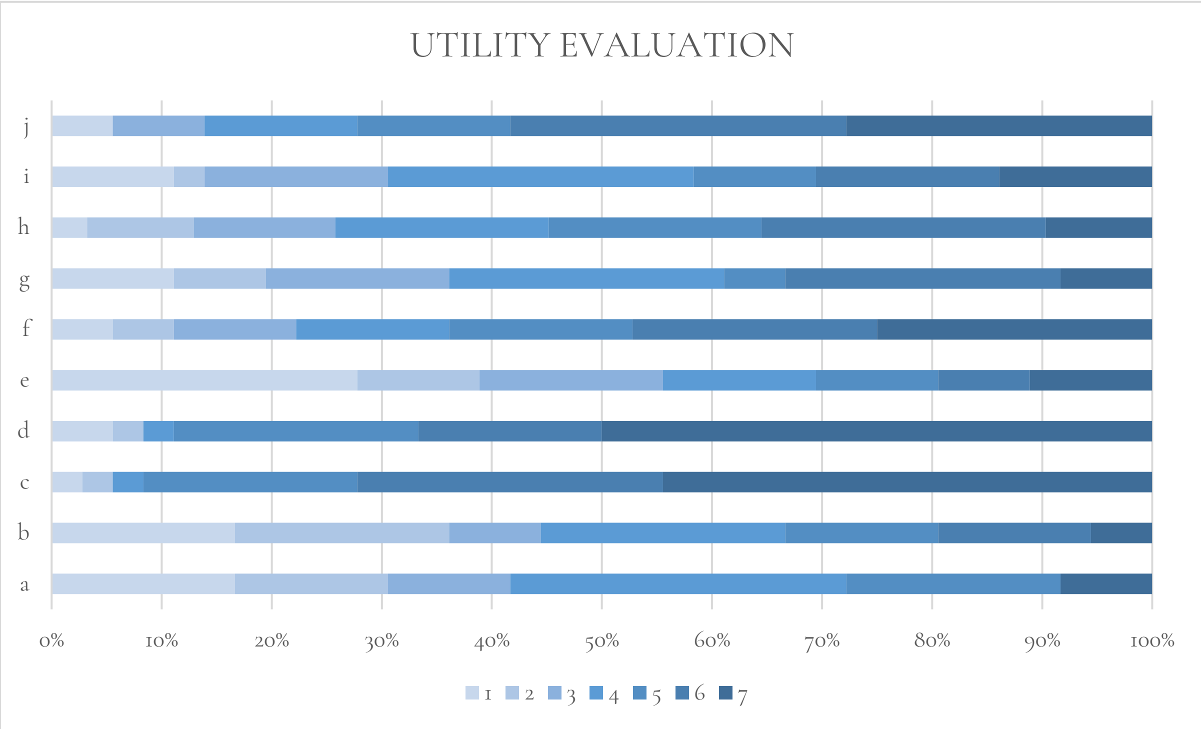


Figure 30 A stacked chart shows the utility evaluation.

In Figure 30, the X-axis shows the percentage value depicting the users involved in the user test, whereas the Y-axis shows the various evaluating questions here numbered from A-J. The legend ranging from 1 to 7 shows the answers given by the users to the questions related to the utility of the interface. Here, the legend ranging from 1-7 is low to high, where 7 is the optimal value for positively framed questions, and for the negatively framed questions (#A, #E), 1 is the optimal value. The lower flank of the bar is shown by the lighter color, and the higher flank is shown by the darker one. The balance of both colors means that the users have no strong agreement or disagreement in the usability of the interface. The result shows that the criterion of the interface is met. However, the interface can be revised based on these criteria, and the second phase of the user-test can be done for the improvement of the application utility.

Usability

In the survey questions concerned with the usability test, six positive questions and four negative questions were asked. There was no similar pattern of answers, and the rating was mixed. Positively worded questions received an average of 4.69 out of 7 (7 being the optimal score), and negatively worded questions received an average of 3.74 out of 7 (optimal score of 1). With 4 being the average – neither agree nor disagree, and 3.98 being the user's result in terms of usability, it shows that they found the interface to be a bit less practical than average.

The below-mentioned Table 10 gives an idea of the usability evaluation of the application.

Table 10 Usability evaluation table.

S.N	**Usability**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Avg.**
		Disagree				Agree			
A	SatelliteViz was easy to use.	4	3	2	6	10	8	3	4.42
B	It was troublesome to use.	8	6	4	8	5	2	3	3.39
C	A support of a technical person is needed to be able to use SatelliteViz.	10	6	2	7	7	1	3	3.28
D	Some detailed help and tutorial is required to be able to use SatelliteViz.	1	3	4	8	10	4	6	4.64
E	Many people will be able to learn to use SatelliteViz quickly.	2	0	2	13	8	7	4	4.72
F	Some previous knowledge of using an interactive map is necessary to be able to use SatelliteViz.	3	3	5	4	12	5	4	4.39
G	I felt confident while using SatelliteViz.	3	1	4	10	10	6	2	4.36

H	I was often confused about where to click or where to look when using SatelliteViz.	5	4	2	8	7	5	5	4.19
I	The visual design of the application is well done.	2	0	1	9	6	8	10	5.25
J	SatelliteViz violates basic cartographic principles.	11	10	4	8	1	2	0	2.56
The average rating for positive questions (4)		**4.69**							
The average rating for negative questions (6)		**3.74**							
Overall average with negative questions inversed		**3.98**							

The users did not strongly agree on the application being easy to use nor very troublesome to use, as shown by the result in #A and #B. This could be the case because the application is a mock-up, and it is trying to fit many interactions to get the answers to RQs. Question #F is a negatively worded question to which the users have mostly agreed, meaning that prior knowledge of using an interactive map is required to use the interface. There is a strong inclination of users in some questions, such as the majority of the participants strongly disagree on the violation of the cartographic principles and strongly agree that the visual design of the application is nicely done. It was an experiment to design the application with a white background in a minimalistic design as opposed to the existing applications (most of them have dark themes). The application was designed to emphasize the interaction rather than the busy background and catchy globe representation. The survey shows that the users agree on the minimalistic design to be more effective. Some participants slightly agree on providing a tutorial for using the application and the interactive map. There is enough room for revision in the interface to consider the suggestions of the users. So, the application can be revised, improved, and resent to the users for further evaluation.

The below-mentioned stacked chart gives an idea of the utility evaluation of the application.

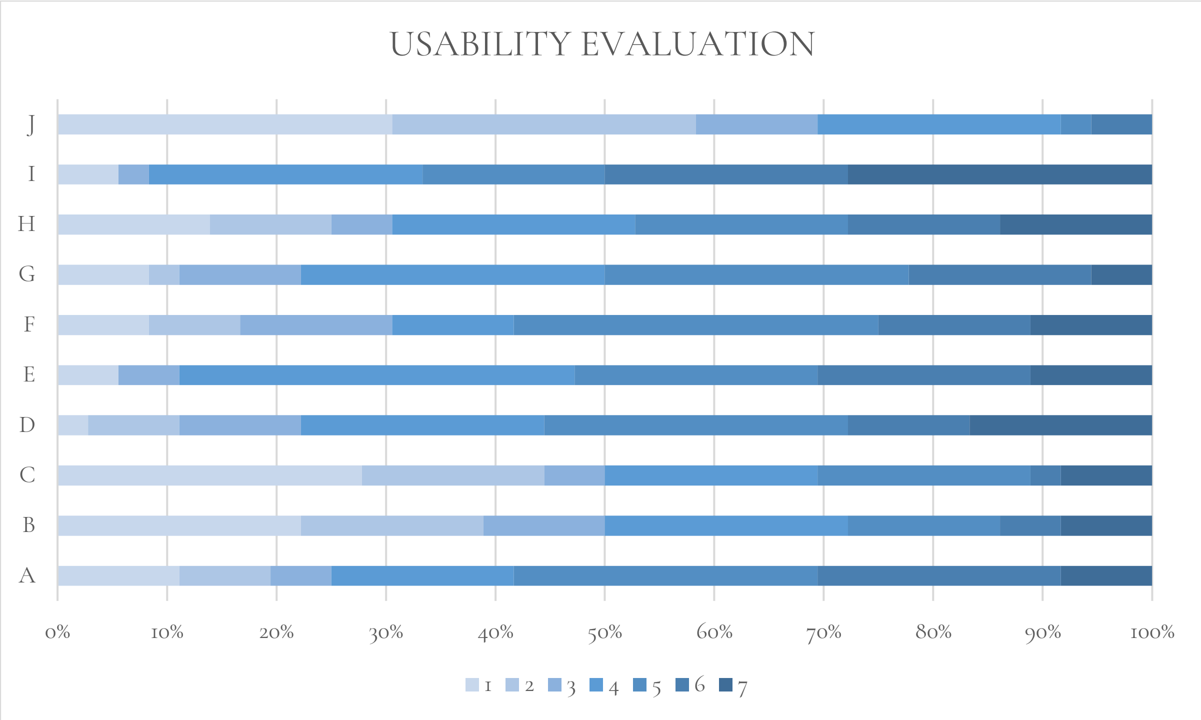


Figure 31 A stacked chart shows the usability evaluation.

In Figure 31, the X-axis shows the percentage value depicting the users involved in the user test, whereas the Y-axis shows the various evaluating questions here numbered from A-J. The legend ranging from 1 to 7 shows the answers given by the users to the questions related to the usability of the interface. Here, the legend ranging from 1-7 is low to high, where 7 is the optimal value for positively framed questions and for the negatively framed questions (#B, #C, #D, #F, #H, #J), 1 is the optimal value. The lower flank of the bar is shown by the lighter color, and the higher flank is shown by the darker one. The balance of both colors means that the users have no strong agreement or disagreement in the usability of the interface. It concludes that the interface can be revised based on these criteria, and the second phase of the user-test can be done for the improvement of the application usability.

4.3.3 Benchmark tasks

The efficiency of the application was evaluated based on the success rate of two benchmark tasks which are: (i) Finding the number of operational satellites and (ii) Finding the junk satellites in LEO, which are briefly explained below:

Number of operational satellites

The question asked to the participants was, "How many operational GPS satellites were launched in the year 2014?". A little hint was given to the participants to guide them in finding an answer and avoid the technical difficulty in using the interface. As shown in Figure 32 below, 27 participants answered correctly, 6 participants answered incorrectly, and 7 participants were unable to find the answer.

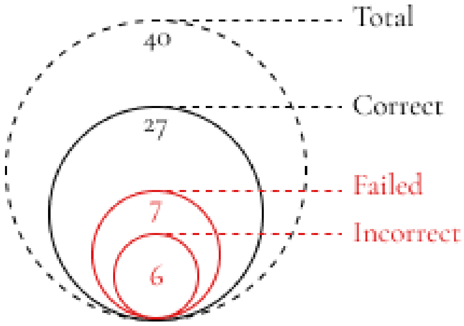


Figure 32 Evaluation of finding of the operational satellite task.

Number of junk satellites in LEO

Only 38 participants attempted the question "How many junk objects are present in Low Earth Orbit (LEO)?". The interface was designed in such a way that the users could not move on to the next page without answering the questions. However, out of the total surveyed, only 38 answered these questions since some of the users left in the middle of the survey. This led to the platform recording only the partial data. The result of this question is shown in Figure 33. Out of 38 participants, 24 were successful in finding the correct answer, 4 gave the incorrect answer, and ten were unable to find the answer.

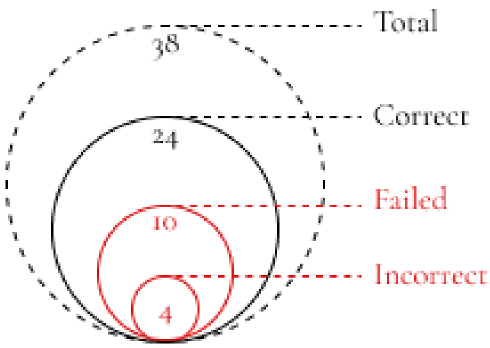


Figure 33 Evaluation of finding of the operational satellite task.

The analysis of these two tasks are shown in Table 11 below:

Table 11 Effectiveness evaluation of the interface.

Tasks	Total	Correct	Failed	Incorrect	Success percentage
T1	40	27	7	6	67%
T2	38	24	10	4	63%

The success percentage for T1 is 67%, and T2 is 63% which shows that most of the users were capable of finding the answers to the assigned tasks. It can be inferred from these success percentages that the interface was designed satisfactorily. Nevertheless, few users also found the interface to be difficult to navigate, which means that the application is not fully user-friendly. The future designers shall consider this result in redesigning the interface.

4.3.4 Informative interface

A question of whether the interface was innovative or not was asked to the user. A scale ranging from 1 to 7, where one is less innovative, and seven is highly innovative, was used. An average rating of 5.06 was obtained, which says that most of the users found the interface to be a novel application. Additionally, an open question was asked towards the end of the survey to check if the users learned something while interacting with the application. The idea behind this was to make the participants aware of the satellite data while they were interacting with the interface. It was mentioned in the question to write at least one piece of information that they took from this end-product.

Almost all the users mentioned learning something except two participants, who commented that they could not comprehend anything about the satellites. Based on the answers written, some keywords were extracted and analyzed to evaluate the informative nature of the application. The count of those words was made to make a treemap which is shown in the following Figure 34:

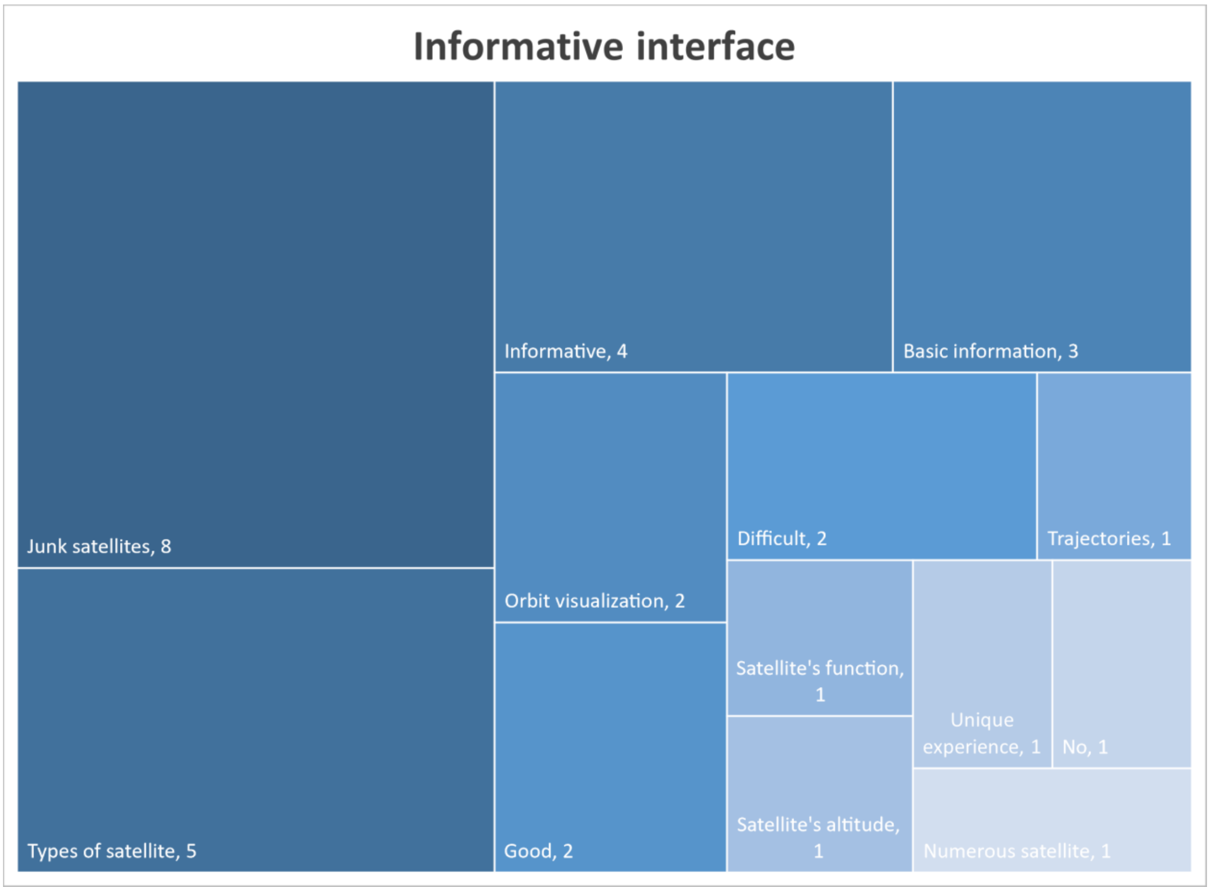


Figure 34 A treemap shows the keywords of the interface being informative.

Most of the participants wrote about being aware of the enormous amount of junk satellites present in space and the urgency to deal with this problem. Some participants mentioned that the interface is informative but did not give a specific answer. Additionally, the knowledge about the basic information of the satellites, their types, and orbit visualization gained the space in the answer. The information of the satellite's trajectory, function, and altitude was also indicated by the users. On the contrary, a few users said that it was difficult to take a lot of information in a limited time. Participants also stated that the interface is nicely designed. This

4.4 Summary

This section describes the outlook of the user interface and its various elements and their placement. Finally, the different use cases of the prototype are for educating the masses about satellites and their function, checking possible collision of satellites, and visualization of space debris. Most of the participants favoured different color representations because of aesthetic and clarity factors. Some suggestions were received to combine different colors and shapes, which was concluded to be the best way to represent the satellites. Similarly, a slight inclination of the users towards 3D-representation of the map was found due to aesthetics, while the users preferred 2D representation based on their disposition due to lucidity in understanding the trajectory of satellites. In extension, users also preferred being able to customize the elements like shape, line type, and font. Finally, most users selected orbital comparison instead of altitude comparison of satellites.

Most of the users found the test to be relaxing, satisfying and with low mental, physical, and temporal demand. Subsequently, the agreeing users were asked to rate the usability and utility of the interface and application. It was found that there was no strong agreement or disagreement in the utility and usability of the interface amongst the user, meaning the criterion of the interface was met. Additionally, it was found that the minimalistic design was to respondents' liking.

5
CONCLUSION & OUTLOOK

This thesis seeks to prepare the interactive web-based application to visualize the satellites and their orbits considering the concept of user-centered design for cartography. The theoretical analysis of the existing applications determined the requirement of the interface be designed. The research had two-fold objectives: (i) in-depth study of the existing literature to examine UCD for interactive maps; (ii) a design and evaluation of an interactive web-based application prototype.

In practice, there are a few satellite visualization applications. The TLE dataset can be extracted from two available sources to get the available information of satellites. The satellite.js library is used for the calculation of the position of satellites and their orbits. Different visualization platforms exist for the virtual 3D globe representation, which serves as a base map of these existing interfaces.

The various symbolic satellite representation can be found in these applications. Most of the visualization techniques use the 3D virtual globe for the base map. A customizable feature cannot be found in any of the existing interfaces. These applications also lack the feature to select two or more satellites to compare and analyze their features. In cartography, this research study is a novel step to find the effective visualization of the satellites in an interactive map with the UCD approach in the design process.

Most of the users chose the representation of the satellites visualized in a different color coding. The result indicates that the graphics of the satellite representation depends on the purpose of the application design. The use of multiple colors can be used when the application demands to visualize the satellites based on their classification. Nevertheless, if the goal is to visualize the total number of satellites, then a single color visualization can be used.

The 3D map was preferred over a 2D map by users for the visualization of multiple satellites. This study suggests that when the multiple satellites are to be displayed at once, then the virtual 3D globe is effective. However, the use of a 2D flat map is suggested when the individual satellite is visualized. Hence, the incorporation of the 3D and 2D maps in an interface is considered to be effective.

The inclination of the users towards having a customizable interface as compared to a fixed interface was found. An orbit comparison method was chosen over the altitude comparison visualization approach for the comparison of user-selected satellites.

The evaluation of the designed interface was done by considering the success rate of the benchmark tasks, utility, and usability. The success rate implies that the interface was satisfactorily designed. However, the interface lacks a few aspects of user-friendliness. The utility of the interface was convincing to the users as against the usability of the application. This depicts that the interface is useful for the visualization of satellites for the various target audience, but the interface should be further revised for the improvement of usability.

The limitation of this study is that the design of the application is merely a mock-up. The mock-up application, if implemented in the coding-based visualization platform, the feedback from the users may be more welcoming of the interface. In a coding-based visualization platform, one can allow various interactive features to the users for an easier transition from one window to other interface windows, thereby improving the usability of the application. For the evaluation, it is believed that an in-person interview with the users would have served as a better platform for collecting feedback regarding the interface.

For this study, only two loops of UCD are conducted. For future reference, it is concluded that this prototype can be reviewed, and another phase of user study may be done for the revised version of it. The refined mock-up prototype can be implemented into a coding based platform, and a few iterative processes of the evaluation of the application be done to get a successful interactive interface.

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APPENDIX 1

A link to the FIGMA prototype

SatelliteViz, (https://tinyurl.com/SatelliteVisualization)

APPENDIX 2

Questionnaire of the survey

WELCOME!!

Hello, you are invited to participate in the survey of the research study named "**Interactive cartographic visualization of real-time satellite data and their orbits"**. This survey is designed as a part of the master's thesis at the Technical University of Munich. It will take approximately 20-25 minutes to complete the questionnaire.

The data protection of the participants:
Your participation in this study is completely voluntary. There are no foreseeable risks associated with this project. However, if you feel uncomfortable answering any questions, you can withdraw from the survey at any point. The information collected from this survey will only be used for this survey and will not be passed to a third party. Your survey responses will be strictly confidential and stored anonymously.

If you have questions at any time about the survey or the procedures, you may contact me by email at ge46qiv@mytum.de. Thank you very much for your time and support.

DECLARATION:

I hereby confirm that I have been informed about data protection rights. I agree to the participation and wish to take part in this survey.

Yes, I agree to continue the survey.

No, I do not agree to continue the survey.

General Information

SECTION I: GENERAL INFORMATION

All the information are treated confidentially and stored anonymously.

What is your gender?

- ○ Male
- ○ Female

- Non-binary / third gender
- Do not want to answer

What is your age?

- Under 18
- 18 - 24
- 25 - 34
- 35 - 44
- 45 - 54
- 55 and above

What is your educational background (Major)?

How familiar are you with the interactive maps?

- Not familiar at all
- Slightly familiar
- Moderately familiar
- Very familiar
- Extremely familiar

Have you heard about the satellites, their types and purpose of their use?

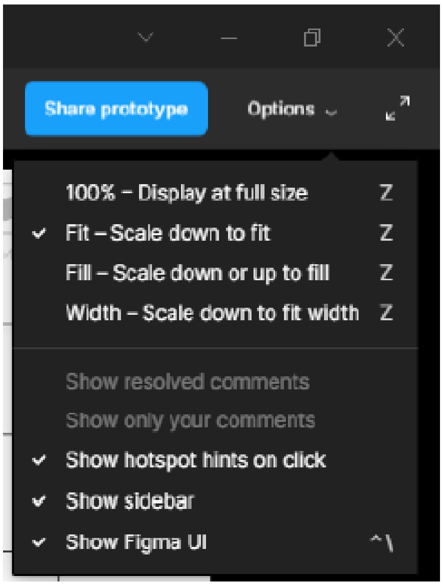
- Definitely not
- Probably not
- Might or might not
- Probably yes
- Definitely yes

INTERFACE INTERACTION

SECTION II: INTERFACE INTERACTION

In this section II, I would like to ask you to interact with the prototype of a web application to visualize the satellites [SatelliteViz](https://tinyurl.com/SatelliteVisualization) (https://tinyurl.com/SatelliteVisualization). Please open this link. If the entire screen is not visible, please use the **full-screen mode** (icon next to options menu) for better visualization or adjust the screen with the help of the **options** dropdown menu.

Disclaimer: *As this is a prototype, not all icons are functional. In case of any doubt in the interface please click the home button. It will take you to the main page. You can then try new interactions.*



Please take few minutes to explore the interface, then you can get back to the questionnaire.

SUB-SECTION 1: Classification of satellites

Please interact with the interface (open the above-mentioned link) to find the answer to the below-mentioned question:

How many operational GPS satellites were lanched in the year 2014? *Hint: Click the search function to choose the specific type of satellite.*
Please mention if you can not find the answer!

SUB-SECTION 2: VISUALIZATION OF SATELLITES

The dots/shapes here represent the satellites in the space.

Figure 1: With single color

Figure 2: With single color and effect

Figure 3: With different colors

Figure 4: With different shapes

Which satellite visualization do you prefer? If the picture is not clear, you can also view it in detail in the interface.

- ○ Figure 1: With single colour
- ○ Figure 2: With single colour and effect
- ○ Figure 3: With different colour
- ○ Figure 4: With different shapes

Please briefly explain why do you prefer the above representation.
(Example: the visual aesthetics? the satellite classification? etc.)

SUB-SECTION 2: VISUALIZATION OF SATELLITES

This application allows the user to visualize the satellites in 3D and 2D maps as you can see in the following figures.

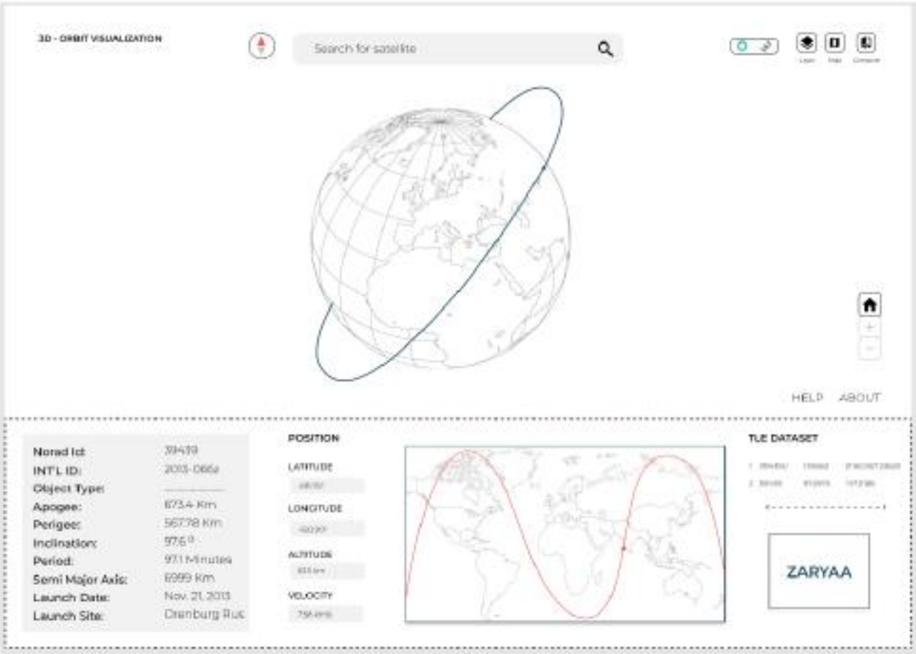


Figure 5: 3D orbit visualization of a satellite.

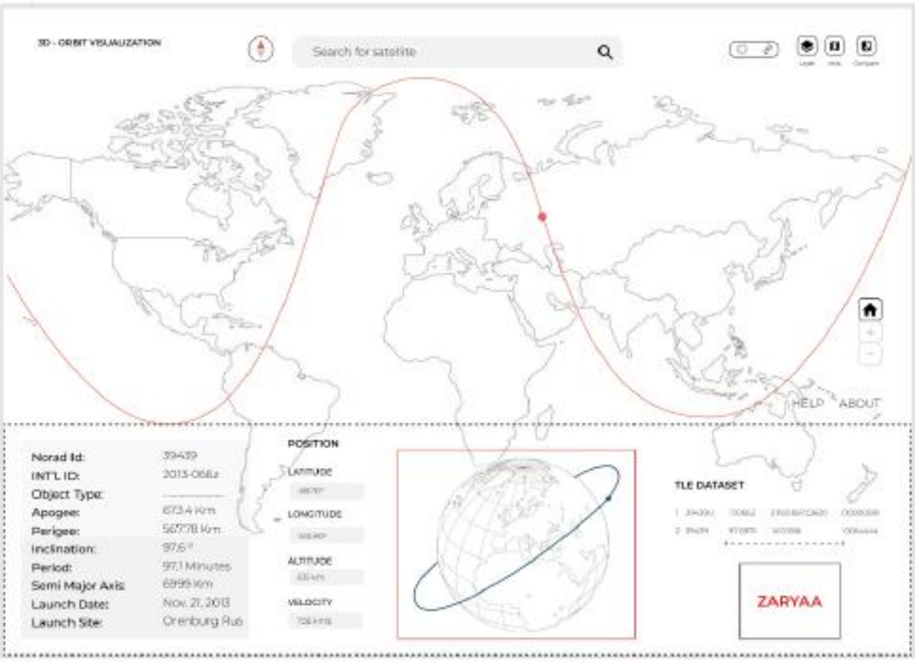


Figure 6: 2D orbit visualization of a satellite.

Do you prefer a 2D map or 3D map/globe representation to visualize satellites?

○ 3D representation

○ 2D representation

Please briefly explain why did you choose the above representation.
(Example: the visual aesthetics, easy to understand, etc.)

This application also allows the user to customize the visualization of the satellite's orbital path. You can customize the interface by changing the line type and colour of the orbital path in 2D and 3D visualization.

Hint: Click orbit from layer icon in home screen.

What do you prefer? (Select one answer)

- ○ • To have a fixed design visualization
- ○ • To have a customizable interface

SUB-SECTION 3: TYPES OF SATELLITE

How many junk objects are present in Low Earth Orbit (LEO)? *Hint: Click the filter dropdown icon to select the type of the satellite.*
Please mention if you can not find the answer!

SUB-SECTION 4: COMPARISON OF SATELLITES
The designed application allows comparing the selected satellites based on their altitude and orbits.

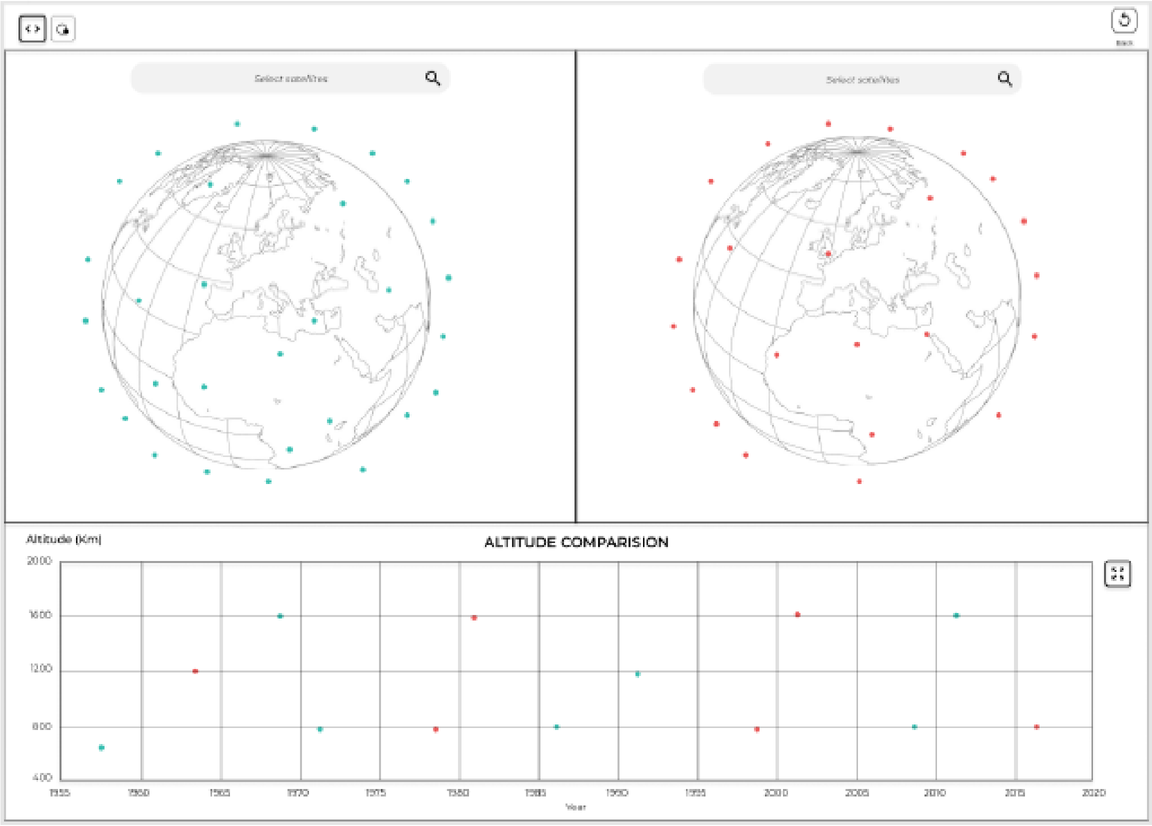


Figure 7: Comparison of satellites based on their altitude and launch year.

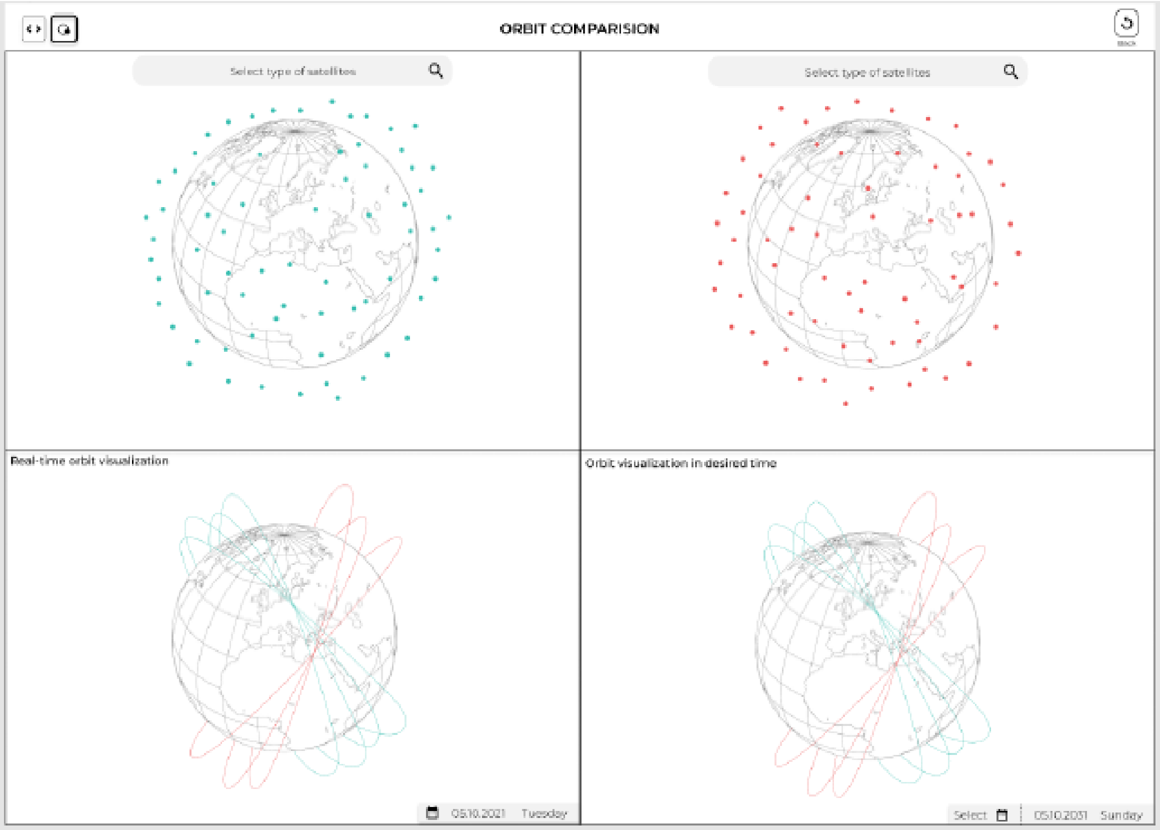


Figure 8: Comparison of satellites based on their orbits. The upper two squares allow the selection of individual or grouped satellites. The bottom two windows visualize the orbits of selected satellites in real-time and the user-selected time (future or past) respectively.

Which visualization do you prefer? Please select one answer!

- ○ with the comparison of altitude of satellites
- ○ with the comparison of orbits of satellites

UTILITY AND USABILITY

SECTION IV: UTILITY AND USABILITY TEST OF THE INTERFACE

SatelliteViz = Name of the designed interface

Please answer the following questions:

UTILITY RATING

	Disagree 1	2	3	4	5	6	Agree 7
1. I would use *SatelliteViz* frequently	○	○	○	○	○	○	○
2. *SatelliteViz* is not an application of my interest	○	○	○	○	○	○	○
3. *SatelliteViz* would be useful for the visualization of satellites and their orbits	○	○	○	○	○	○	○
4. *SatelliteViz* would be applicable for those users who want to understand the satellites and their orbits	○	○	○	○	○	○	○
5. *SatelliteViz* would not be helpful for the users who are experts of the satellites	○	○	○	○	○	○	○
6. *SatelliteViz* is a novel approach to provide information about satellites to general users	○	○	○	○	○	○	○
7. *SatelliteViz* has all the required functions to explore the satellite data	○	○	○	○	○	○	○
8. *SatelliteViz* has all the essential functions to analyze satellite data	○	○	○	○	○	○	○
9. *SatelliteViz* has all the necessary visualizations to understand the mechanism of satellites	○	○	○	○	○	○	○
10. *SatelliteViz* provides many ways to visualize the satellite data	○	○	○	○	○	○	○
	1	2	3	4	5	6	7

USABILITY TEST

	Disagree 1	2	3	4	5	6	Agree 7
1. *SatelliteViz* was easy to use.	○	○	○	○	○	○	○
2. *SatelliteViz* was troublesome to use	○	○	○	○	○	○	○
3. A support of a technical person is needed to be able to use *SatelliteViz*	○	○	○	○	○	○	○
4. Some detailed help and tutorial is required to be able to use SatelliteViz	○	○	○	○	○	○	○
5. Many people will be able to learn to use *SatelliteViz* quickly	○	○	○	○	○	○	○
6. Some previous knowledge of using an interactive map is necessary to be able to use *SatelliteViz*	○	○	○	○	○	○	○
7. I felt confident while using *SatelliteViz*	○	○	○	○	○	○	○
8. I was often confused about where to click or where to look when using *SatelliteViz*	○	○	○	○	○	○	○
9. The visual design of the *SatellizeViz* interface is well done	○	○	○	○	○	○	○
10. *SatelliteViz* violates basic cartographic principles	○	○	○	○	○	○	○
	1	2	3	4	5	6	7

EVALUATION

SECTION III: EVALUATION OF THE PERFORMANCE

Mental Demand:

		Easy		Neutral		Difficult	
	1	2	3	4	5	6	7
How would you evaluate questions based on their complexity?							

Physical Demand:

		Less		Neutral		More	
	1	2	3	4	5	6	7
How would you evaluate the number of clicks while completing the tasks?							

Temporal Demand:

		Low		Neutral		High	
	1	2	3	4	5	6	7
How would you evaluate the time pressure you felt while performing the tasks while interacting with the interface?							

Overall Performance:

		Unsatisfied		Neutral		Satisfied	
	1	2	3	4	5	6	7
How satisfied are you with your answers in the section where you performed the tasks?							

Satisfaction Level:

	Relaxed		Neutral		Stressed	
1	2	3	4	5	6	7

How did you feel when completing the tasks?

Innovation:

	Basic		Neutral		Innovative	
1	2	3	4	5	6	7

How innovative did you find the interface?

SUGGESTION

SECTION IV: SUBJECTIVE QUESTIONS

How informative was the interface? Did you get some knowledge about the satellites today? Please give at least one example!

Do you have any suggestion to improve the interface? Please give at least one suggestion or comment about the interface.