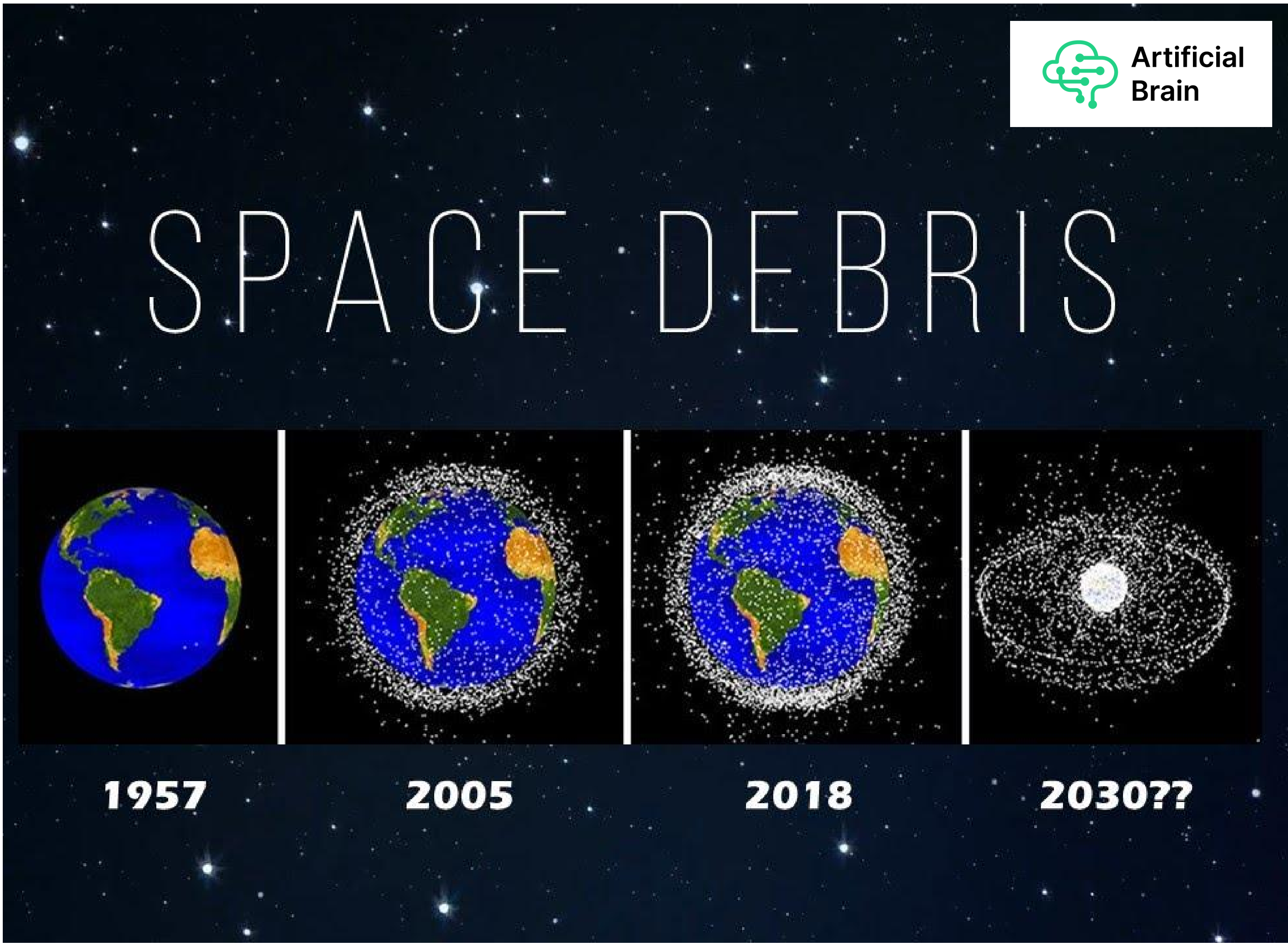
Space Sustainability Using Quantum Computing

White Paper, August 2022



Version 1.0, July 2022

Introduction

By 2040, the space industry is expected to generate $1 trillion in revenue, with launch costs dropping 95% to unlock more services like space travel, internet services, and weather monitoring, etc. Due to continuous development and the growing space industry, it also faces challenges and risks due to space debris, posing significant risks to existing satellites and those to be launched in the future. It has already alarmed major players and organizations in the space industry to develop solutions and technologies to reduce and remove the increasing amount of space debris in Low Earth Orbit (LEO).

What is Space Debris?

Space Debris includes rocket boosters, particles from satellite collisions, and non-functioning satellites. Currently, there are space debris objects of varying sizes as large as footballs and as small as sand grains. These objects pose a significant threat to the existing satellites. Space debris in space does not fall to the ground; instead, it revolves continuously around the earth due to its inherent speed. This speed is due to the fact that space debris was originally part of a satellite, a rocket, or other space objects. As long as space debris remains in orbit, its number does not decrease. In fact, it is expected that the number of space debris will only increase in the future. As a result, this can cause more chaos in terms of collisions for both existing satellites as well as the future satellites being planned.

In LEO, space debris orbits at speeds of about 15,700 miles per hour (25,265 kph), so collisions could damage satellites or spacecraft significantly. NASA tracks approximately 23,000 pieces of debris orbiting the Earth that are larger than a softball. There are half a million pieces of debris larger than 1 cm and 100 million pieces of space debris about 1 mm or larger. There is also a very high risk of collisions with the International Space Station due to space debris orbiting the Earth fifteen to sixteen times a day. According to the European Space Agency (ESA), all space objects orbiting the Earth weigh more than

9,600 tonnes. According to Holger Krag, Head of ESA's Space Safety Programme Office, some regions of space could become unusable in a few decades if space debris continues to build up.

Why is Space Debris so concerning?

Currently, satellites provide us with communication services, internet services, tracking services, disaster management services, and other essential services. If any of these essential satellites is damaged by space debris, it can cause a lot of recoveries both on the ground and in space, because collisions create more space debris, making the region less safe. Due to the fact that LEO is the current focus of all private players in space, it is also a region where a lot of space debris accumulates. Due to the presence of space debris in this region, satellites are 100% likely to make maneuvres to avoid collisions with the debris. There have been almost 6,000 maneuvres performed by SpaceX to avoid collisions with debris in space. These maneuvres are expensive, they sacrifice the satellite's functions (including collecting data or other services) for a limited period of time, fuel is lost as a result, and the agencies have to spend a lot of time and effort before and after the maneuvres. In addition, the number of maneuvres performed by space organizations has increased exponentially.

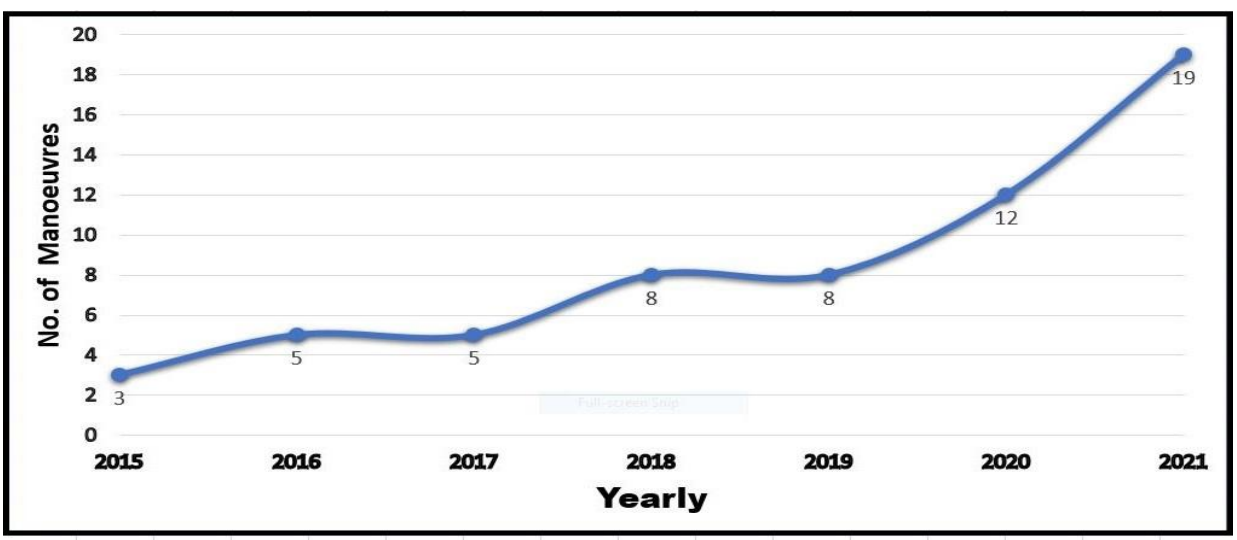


Fig 1: The chart represents the number of maneuvres ISRO has performed on a yearly basis from 2015 to 2021. (Image Source: [Data | How rising space debris will impact ISRO's budget - The Hindu]())

From Fig. 1, it can be easily interpreted that by 2015, the ISRO performed 3 maneuvres and by 2021 it has performed 19 maneuvres. The number of maneuvres performed by any space organization is increasing exponentially. While maneuvres are performed by spacecraft's propulsion systems, toxic gases are released which have a severe impact on the earth's atmosphere.

In 1978, NASA scientist Donald J. Kessler proposed a collision cascade theory which states that space debris in LEO, caused by space pollution, can cascade into more and more space debris, making LEO unsustainable and unsafe. In this way, a collision between a few objects can lead to an endless series of collisions between all other objects in the region.

Although Kessler's syndrome might not be true in the near term or in the future, it is clear that collisions between two space objects result in a large number of particles and objects ejecting into different directions resulting in an unsafe and unsustainable environment. Fig. 2 shows the consequences of Space Debris and also outlines the unsafe environment created on the Earth's Orbit.

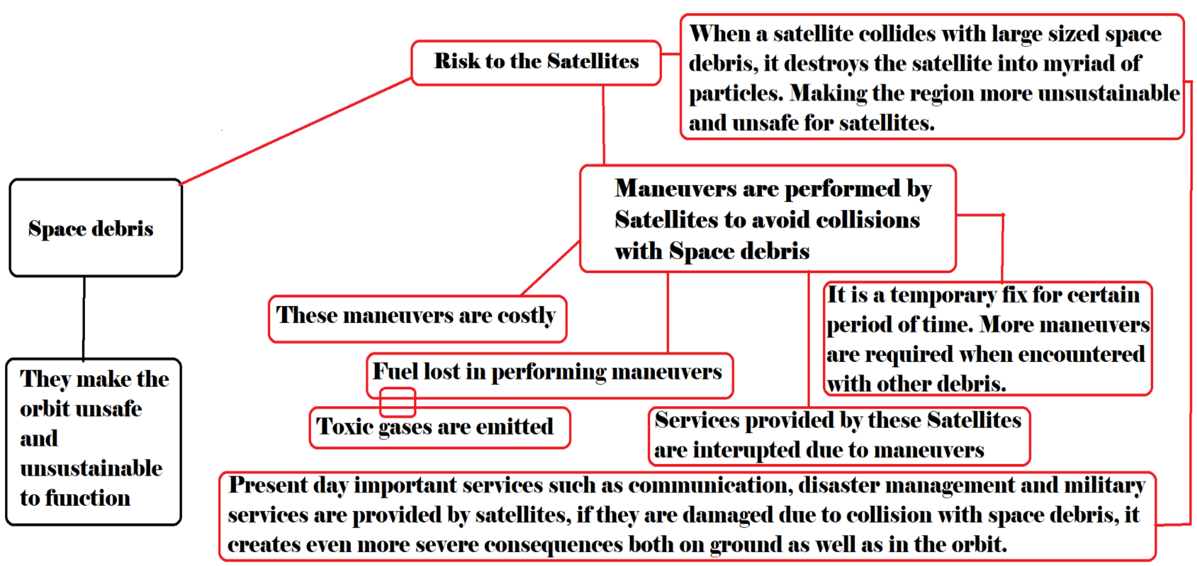


Fig 2: Unsafe environment created in earth's orbit due to Space Debris and its harmful effects

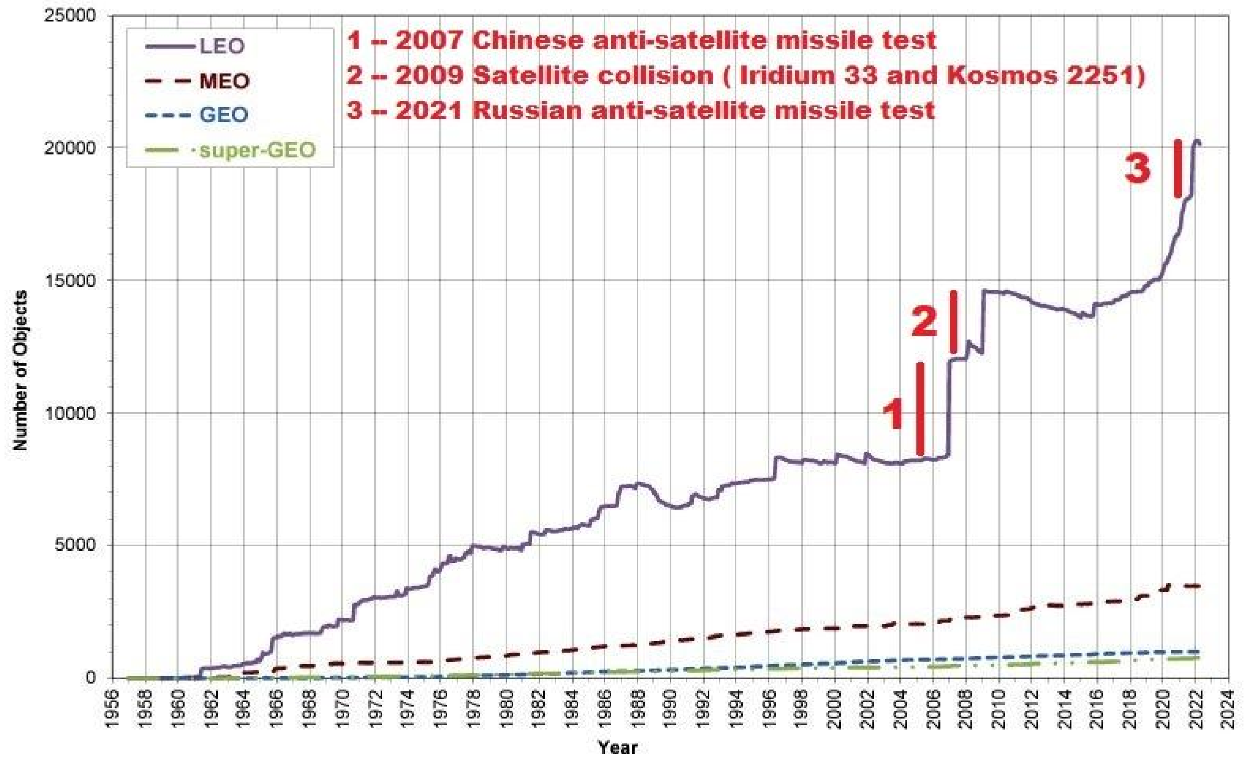


Fig 3: The above chart represents the rising amount of space debris from 1956 to 2022. The red lines indicate a sudden and steep increase in the amount of space debris due to collisions in space. (ImageSource: ARES | Orbital Debris Program Office | LEGEND)

Based on Fig. 3, it is evident that the number of space debris increased rapidly following multiple collisions in the years 2007, 2009, and 2021. As a result of collisions, satellites or spacecraft break into myriad pieces and eject in all directions. If collisions are not avoided, more space debris will be created, and satellite operations will become unsafe.

An Overview of Recent Space Debris Events

Chinese Rocket Debris falls to the Earth: Chinese rocket debris re-entered the Earth's atmosphere over the Indian Ocean on 30th July 2022. The possibility that debris from the rocket might strike a populated area prompted people around the world to track its trajectory for days. NASA Administrator Bill Nelson released the statement that China did not share specific trajectory information as the Long March 5B rocket fell back to Earth. Nelson said that countries should "share this type of information in advance to allow reliable predictions of debris impacts, especially for heavy-lift vehicles, like the Long March 5B."

Space Debris slams into the International Space Station, leaving a hole in the robotic arm: Space Debris hurtling towards the station smashed into one of its robotic arms, leaving a hole. NASA and the Canadian Space Agency first noticed the damage on Canadarm2 on May 12, according to a recent statement. The debris left a gaping hole in a section of the arms boom and thermal blanket.

The International Space Station (ISS) maneuvers to dodge Space Debris: The International Space Station had been forced to move due to space debris from a U.S. launch vehicle sent into orbit in 1994. A close encounter was avoided by dropping by 310 meters (339 yards) as part of an unscheduled maneuver carried out by mission control.

Why do we need optimization techniques to clean Space Debris?

Removal of space debris is not an impossible task, but nevertheless, it is complex and hard. It requires the integration of various companies from satellite manufacturers, service providers, space agencies, and many other key players to complete the task smoothly.

Space debris orbits the earth constantly at high velocity, and it is dynamic (changing positions on a regular basis). Apart from the nature of the Space Debris, each satellite has its own limitations in the process of removing space debris in a particular region. The orbital mechanics, fuel capacity, weight limit, and many other factors of the satellite need to be considered to have a successful mission of getting space debris back to Earth.

What makes Space Debris Removal Optimization an NP-hard problem?

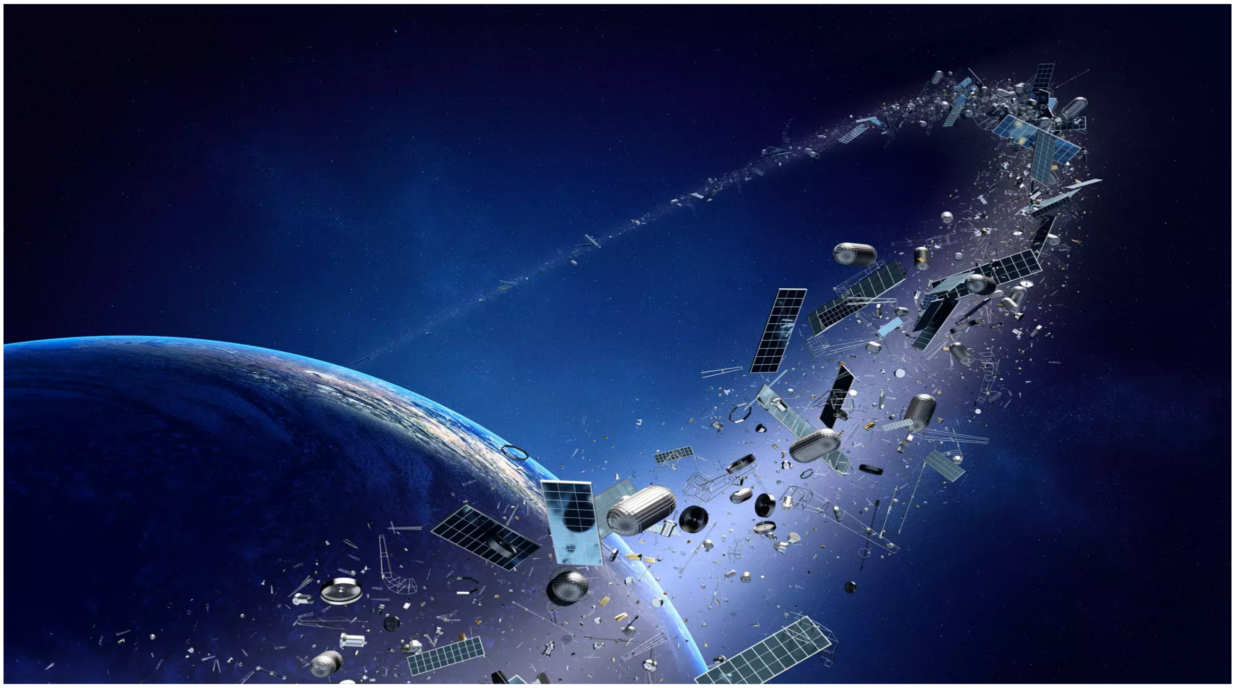


Fig 4: The above image represents the amount of space debris projected to be in the future. (Image source: Space debris from Russian anti-satellite test will be a safety threat for years)

Considering the weight of the satellite, the amount of fuel consumed, and the risk that the satellite will be exposed during and after the collection of space debris, determining the best orbital path is key to collecting more space debris. In order to find the best orbital path, there are a large number of variables that are varying with time and trillions of combinations. Due to the large number of variables involved in the optimization problem, it is an NP-hard problem.

Space Debris Removal Optimization using Quantum Computing

Space Debris Removal Optimization can be formulated into an NP-hard combinatorial optimization problem. Combinatorial optimization is the process of searching for maxima (or minima) of an objective function ***'F'*** whose domain is discrete but in large configuration space.

With the advancement of classical computing systems, complex, unsolvable, and NP-hard combinatorial optimization problems may be solved and simulated within a fraction of a second. However, classical computations have their own limitations, and hence it cannot efficiently solve combinatorial optimization problems when the number of variables is too large. As the number of variables increases, the number of possible combinations also increases exponentially. Hence, space debris removal being an NP-hard combinatorial optimization problem with large variables, classical computers may not be able to solve it efficiently within a limited time frame.

Space Debris Removal Optimization problem can be formulated as a combination of two optimization problems (the Knapsack Problem and the Travelling Salesman Problem) that are described below:

(a) **Knapsack Problem**: The Knapsack problem can be better illustrated by taking an example. Suppose there is a bag that comprises a set of items, each with a particular weight and a particular price value (Fig. 5). The problem can be as follows: **Determine the number/counts of each item in the bag such that the total weight of the bag is less than or equal to a certain limit and the total price value is as large as possible?**

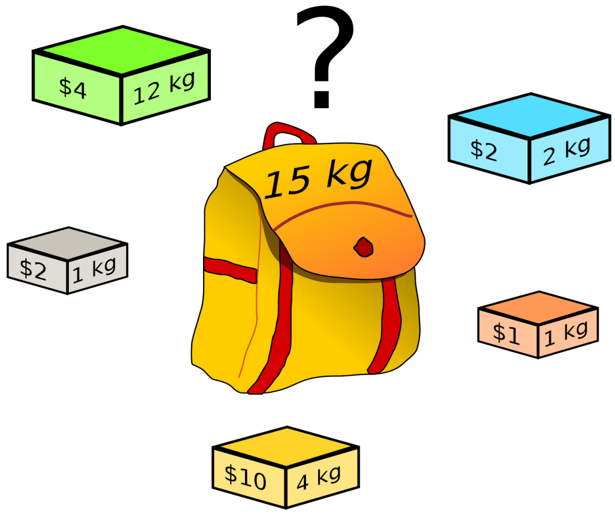


Fig 5: The above image represents the generic layout of the Knapsack problem. (Image source: Knapsack problem - Wikipedia)

(b) **Travelling Salesman Problem**: This optimization problem can also be explained by a question: **Suppose a set of cities and the distances between each pair of cities are known (Fig. 6), what is the shortest possible route that visits each city exactly once and returns to the origin city?**

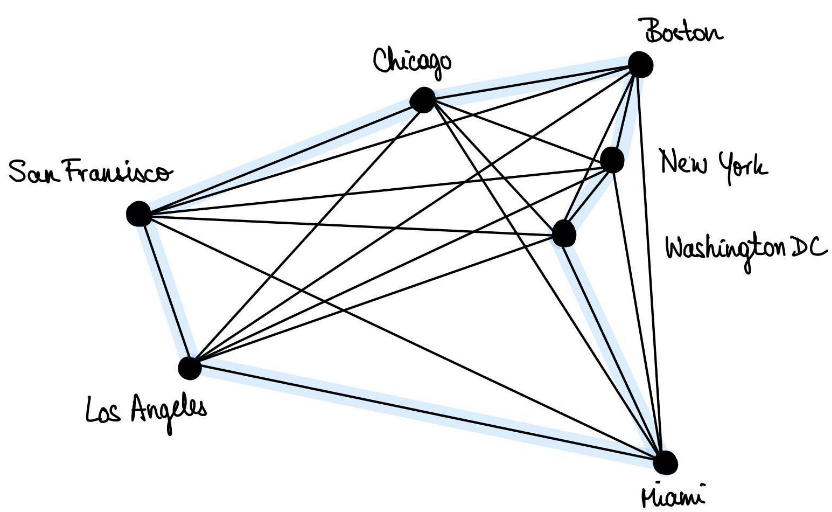


Fig 6: The above image represents the generic layout of the Travelling Salesman problem. (Image source: https://github.com/ab-jiteshlalwani/Hackathon2022/blob/main/team%208/Business_Application.md)

Similar to the Knapsack problem, the spacecraft must choose the debris that will fit in the spacecraft to collect the most space debris in one pass. In addition to selecting which debris to collect, choosing the optimal collection path is crucial, similar to the Travelling Salesman problem. By finding the optimal route, time and money can be saved throughout the entire mission of removing space debris, making the mission more commercially viable.

Utilizing quantum properties of qubit (quantum bit) such as superposition, entanglement and interference can help us to achieve solutions in real-time even to the most complex problems. Using the inherent nature and properties of quantum computers, we can compute the objective function in a short span of time. The characteristics of the Space Debris Removal Combinatorial Optimization problem make it naturally well-suited to be solved by quantum computing.

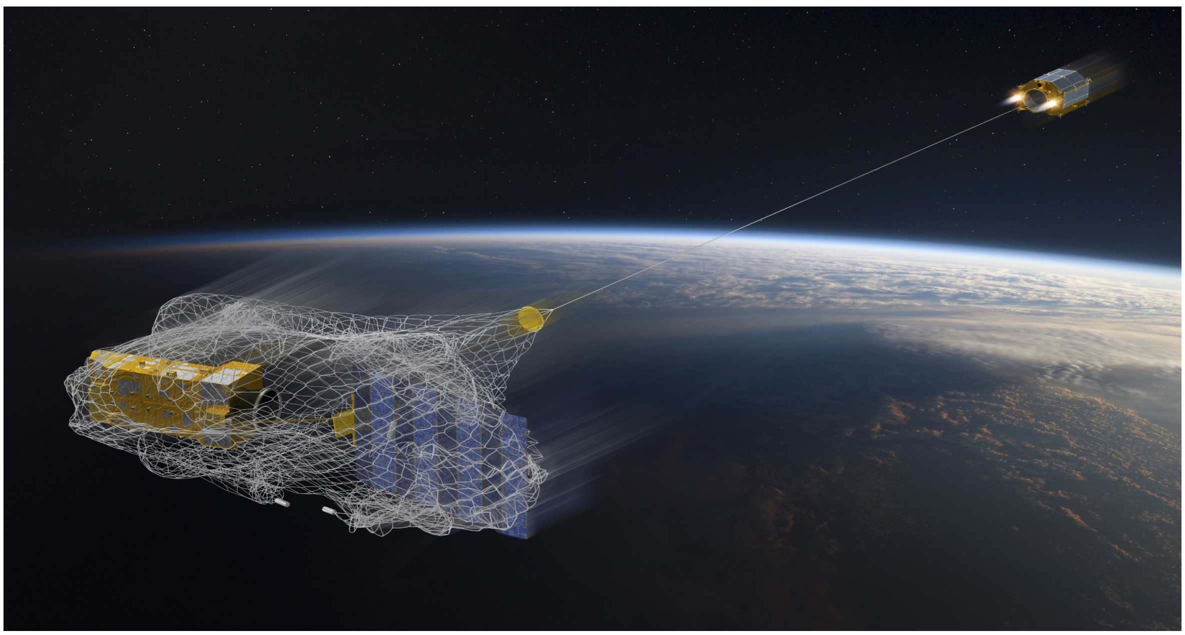


Fig 7: The above image represents the visualization of ESA's Clearspace-1 spacecraft to clean space debris. (ImageSource: [Europe is sending a robot to clean up space. Why is the junk there in the first place?])

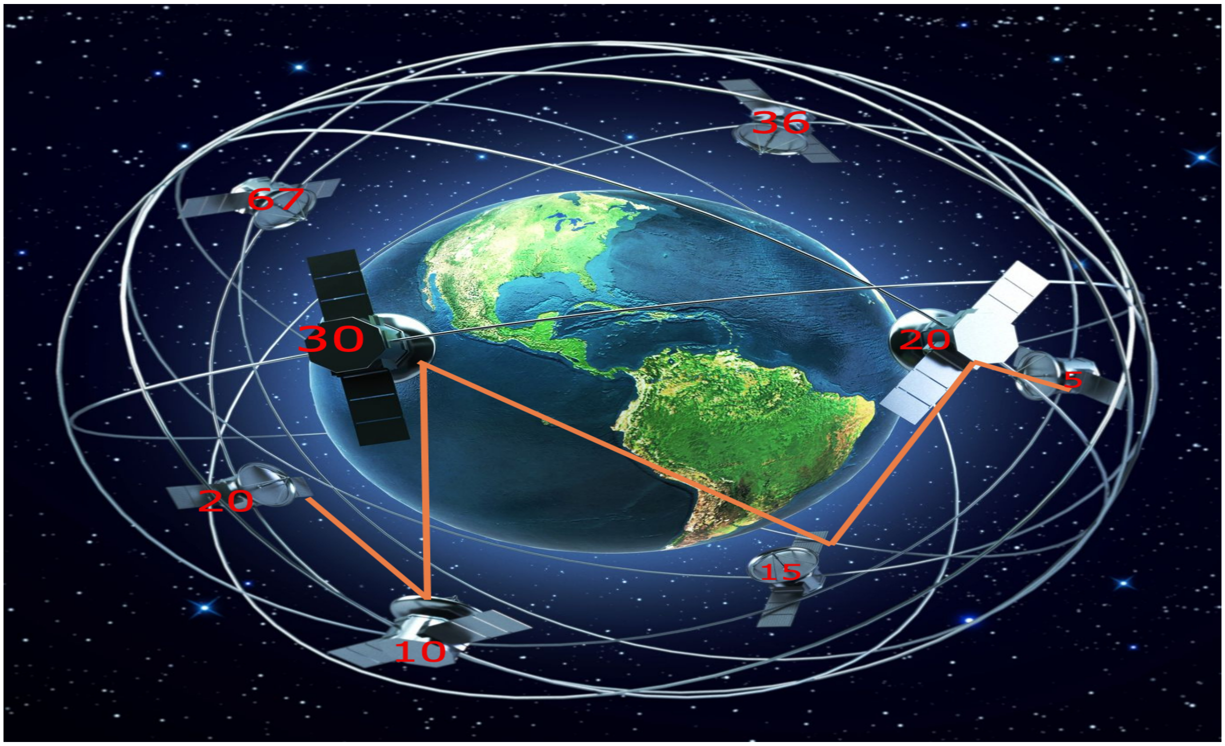


Fig 8: The above image represents the visualization of the optimal route computed using the QAOA algorithm or Quantum Annealer.

Quantum solutions based on variational Quantum algorithms such as Quantum Approximate Optimization Algorithm (QAOA) and Quantum Annealers can provide the optimal solution by solving the Knapsack and Travelling Salesman problems in real-time for successful removal of space debris.

Using quantum-based solutions, the spacecraft (Fig. 7) will be able to determine the best route (Fig. 8) to collect and remove significant space debris. Considering that the system would evolve as a result of collisions with satellites or space debris objects, the solution might change over time. Real-time solutions are very crucial in the space industry, classical algorithms would not be able to compute the combinations required to achieve the solution. Quantum-based solutions would be able to compute the solution with the evolving system, making it much more efficient.

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