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Space Debris Removal in Minimal Time

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Abstract: Millions of man-made objects are orbiting the globe, and they are multiplying, slowly covering Earth's orbit in a net of destruction. This problem is a variation of the traveling salesman problem or TSP for short. Thankfully Dario Izzo, Daniel Hennes, Ingmar Getzner, and Luís F. Simões researched possible ways to solve a TSP for minimizing fuel usage during space junk removal. This paper demonstrates the intricacies associated with finding efficiencies to cleaning up space debris as well as explores a potentially effective algorithmic solution when time considerations are introduced.

Keywords: Astronomy Travelling Salesman Problem Algorithm Space Debris

1. Introduction

Wernher Von Braun, a German scientist who surrendered to America after World War II, pioneered many advances in the field of space travel. The biography Von Braun: Dreamer of Space, Engineer of War by Micheal J. Neufeld about this famous scientist, reveals many interesting concepts about space travel. Not only did Von Braun and his team know that a four-stage rocket would be necessary to get people to the moon, he also went public with the information on a Disney program years before even Sputnik made it into orbit (Neufeld). Rocket staging utilizes sections of rockets and jettisons them off after that section's fuel runs out. This allows rockets to fly higher as excess weight can be shed as fuel is burned. However, many of these rocket stages are left behind as debris.

Quite ironically, many rocket stages are harming space travel when they are left behind as debris. Millions of man-made objects are orbiting the globe, and they are multiplying, slowly covering Earth's orbit in a net of destruction.g space travel when they are left behind as debris. Millions of man-made objects are orbiting the globe, and they are multiplying, slowly covering Earth's orbit in a net of destruction. There are also naturally occurring asteroids, space dust, etc. producing the same effect. There are four types of this debris: inactive payloads, operational debris, fragmentation debris, and microparticulate matter (Hollingsworth 241). Inactive payloads make up 20% of space junk and are satellites that humans have no control over any more (242). Operational debris accounts for 26% of space junk and is ejected intact components of spacecraft such as fuel tanks and insulation panels (242). Fragmentation debris makes up 49% of space junk and are small particulates formed by accidental explosions or collisions in space (242). Microparticulate matter is estimated to have at least ten billion individual pieces, however, is too small to be tracked (242). This small debris consists of propellant particles, paint flecks, space glow, and more (242). When the debris is added up the number of objects larger than a centimeter is in the one-hundred-thousands and that number is increasing (243). However, size does not matter so much because debris that is even as small as a paint chip can damage equipment or even kill an astronaut on a space walk (246). If the junk continues to accumulate, it could rip apart everything and anything that is put into orbit. The newly ripped into objects would then turn into more debris which in turn would rip apart more objects. This is what is called the cascade effect and if it is not prevented there will be a "cloud" of debris blocking everything from entering orbit (Hollingsworth 247). This space junk no matter how small could eradicate space exploration, satellite communication, global imaging, weather services, etc. It is for this reason that space junk must be cleaned.

To this end there have been many proposed ways to clean space junk. The European Space Agency proposed snagging debris with nets, harpoons, and even tentacles with its e.DeOrbit mission (Howell). The Japanese Aerospace Exploration Agency proposed to use an electrodynamic tether which uses an electric current to slow down satellites. Texas A&M University proposes to swing junk back towards earth with a catapult device (Howell). However, while the method of cleaning space junk is important, the path a craft would take to clean it is equally important. Without an optimal path millions of dollars of fuel could be wasted.

2. Optimal Pathfinding

Most research on this subject of optimal pathfinding focuses on minimizing fuel usage, such as the work done by Dario Izzo, Daniel Hennes, Ingmar Getzner, and Luís F. Simões. However, minimizing time is very important as well, especially when the cascade effect puts earth on an unknown time limit. The solution decided upon for cleaning space junk may also take up much time. This would make it very beneficial for the rocket to focus on speed rather than fuel consumption. There could also be rockets that have enough fuel to not only go the path of least fuel consumption, but also go the path of least time consumption. At the same time the algorithm should find this optimal timed path within reason. The rocket can not be expected to go on a straight shot to the target as this would set it on a collision course. Going on a collision course with a piece of debris at thousands of miles per hour would be of great concern. In fact it would only increase the magnitude of the space junk problem. It is for this reason that the path of least time should be modeled with rendezvous in mind.

Rendezvous is how spacecraft meet with another spacecraft or object ("Maneuvering In Space" 22). The trick with rendezvous is that the spacecraft must meet the object with the same speed in the same direction as the object's velocity. There are nearly infinite ways to rendezvous with an object due to the fact that multiple separate burns can be made and due to the fact that the object and the spacecraft would be moving as time progresses (22-27). Thanks to A. Miele, M.W. Weeks, and M. Ciarcià there are equations for minimizing both time and fuel for an orbital transfer and therefore, rendezvous. The data needed to solve these equations and to know the locations of the debris in general is given by the Science Applications International Corporation (SAIC) on space-track.org. This raw data is hard to visualize and read, thankfully the website stuffin. Space renders the debris and their trajectories for free using the SAIC data and updates itself daily. However when these orbital mechanics are combined this with the fact that multiple objects must be visited another problem arises.

3. TSP

This problem is a variation of the traveling salesman problem or TSP for short. The traditional traveling salesman problem is the problem of figuring out the shortest possible route that visits a number of locations(usually cities) once and then returns to the starting city (Diaby 1). The problem was formulated as a programming problem all the way back in the 1950s by Dantzig, Fulkerson, and Johnson where it gathered more and more attention over the years since it has a wide applicability (1).

There are multiple ways to solve the traditional TSP. The first and simplest solution is the Naïve or brute-force approach which looks over each and every possible path for the greatest solution (Mathew et al.). This solution is very inefficient with a possible runtime of $O(|N!|)$ but produces the actual true solution to the problem. A second solution to the TSP is the Nearest Neighbor (NN) approximation algorithm which gives a decent solution but does not necessarily give the true solution (Mathew et al.). The Nearest Neighbor approximation algorithm chooses the closest city to the starting one, goes to that city and then repeats. A famous solution to the TSP is Christofides' Algorithm which was made by Nicos Christofides in the late 70's. This solution is more complex than many others, but it guarantees a solution within three halves of the true one and in a significantly better time than the Naïve approach's $O(|N|!)$ with a max runtime of $O(|N|^4)$ (Mathew et al.).

Christofides' Algorithm works in multiple steps. The first step is to create a minimum spanning tree. This tree is made with the shortest possible lines needed to connect all nodes. This means all that is needed is to edit the connections in order to make sure no node is visited twice. The next step is to find every node with an odd number of connections, or odd degrees. The algorithm then looks for the connections between the odd degrees that result in minimum distances (Mathew et al.). The step after that is called the Eulerian Circuit and it overlays the connections from the odd degrees onto the original tree connections. The program then creates a Hamiltonian Path by removing excess connections to cities, resulting in a good solution (Mathew et al.).

4. Fuel Efficiency

Dario Izzo, Daniel Hennes, Ingmar Getzner, and Luís F. Simões researched possible ways to solve a TSP for minimizing fuel usage during space junk removal (1209-1210). They found a solution that takes a note from evolution to arrive at a good answer. Their solution when applied to a general TSP with cities starts with finding the Hamiltonian path (the solution to Christofides' Algorithm) which will serve as a sort of control. The algorithm then picks 3 random paths that have distances less than that of the Hamiltonian path and "breeds" the two best ones (1209-1210). This is where the evolutionary and biological influence comes into play. Snippets of paths(the transfer from one city to one city) from the two best ones are combined such that a new coherent path is formed (1209-1210). This process is repeated multiple times until a very good solution is formed almost out of thin air. The process is called the Inver-over algorithm. However, as the team points out, the problem changes when applied to orbiting debris.

5. Dynamic Problem

To change the problem to suit the removal of space debris minimizing fuel usage, the weights of the paths change from distances, to the amount of fuel expended (Izzo et al. 1210-1211). This weight does not simply take into account the fuel expended in traveling to an object, but also the amount of energy expended in destroying the object. This is a relatively simple change that does not change the effectiveness of the algorithm. There is another change that must also be taken into account: limited fuel. Unlike a traditional TSP where the traveler can travel an unlimited distance, a rocket can only expend so much fuel. This turns the problem into a city selection traveling salesman problem(TSP-CS) where the cities, or in this case space junk, must be assigned priority values (1211). The algorithm then no longer looks for the minimum fuel usage in order to destroy all space junk, it looks at how large the cumulated priority values of the space junk it managed to clean are (1211). This also means that the Hamiltonian path used in the Inver-over algorithm must be calculated with respect to these priority values. This is unfortunately not the last change from a simple TSP.

The TSP is made even more complicated when the dimension of time is added. The problem becomes a dynamic problem which essentially means the "cities" or equivalent objects are in motion. This turns the aforementioned TSP-CS into a dynamic city selection traveling salesman problem(TSP-DCS) (Izzo et al. 1210-1211). However, not much has fundamentally changed from a TSP-CS, only the fuel expenditure weights. These weights change with time, meaning that if a ship waits at one piece of debris any length of time, the weights could differ significantly. To this end Izzo et al. decided to sample the weights at certain intervals and choose the best priority weighting (1213).

6. Solutions

A solution in regards to minimizing time would be very similar to the TSP-DCS solution for minimizing fuel usage. In this case any combination of time or fuel could be restricted. The weightings for traveling to a piece of debris would change from fuel based to time based and the weightings for priority debris would remain the same. The only other things the algorithm might have to take into account is that it might take more time to destroy some pieces of debris and that if the ship waits at a piece of debris before moving to the next one, it takes time. To this end, the algorithm would most likely need a better way of calculating the optimal time to leave a piece of debris.

There are many benefits to finding a good algorithm for minimizing time for cleaning space junk. Companies that want to put things into space will be able to do so at high rates with a cleanup service that can clean the junk up as fast as the company's launch rate. If some sort of attack from small outside celestial bodies infects the earth with debris, cleaning satellites could quickly respond, clearing low earth orbit for further launches. The whole world benefits from this by extension, since the satellites that the companies would put up provide GPS, weather data, etc.

There are multiple other future and current applications for this proposed algorithm. In the future, this algorithm could be used not just for the sake of timeliness in regards to cleaning, but also for the future of travel. It is conceivable that eventually humans will live on other planets and moons, making shuttles to and from them paramount. These shuttles will want to be on the fastest path to not only generate more money for themselves, but also to ship more people to the planets. In an interesting twist, this would make the TSP come full circle. The algorithm could also lead to quick delivery of supplies which would be paramount if there were to be natural disasters or other tragedies on other worlds. If there is ever an attack from another country in space, this algorithm would help our own weapons intercept the attacker's faster than they can hit us.

7. Conclusion

An algorithm for calculating the path of a spaceship to visit all of its target destinations in the quickest time possible is complex. Orbital mechanics and the fact that the targets move causes the algorithm's formulation to be a difficult one, but it is possible. This algorithm could very likely be made to a decent level of success with a variant of Izzo et al.'s solution to a TSP-DCS. More research should be done on ways to help efficiency when cleaning space debris.

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