

Designing an Autonomous Refueling Station for Rockets in Space

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Abstract

An alternative solution for the rocket to rocket refueling planed by SpaceX in Lower Earth Orbit, in their mission to bring humans both to the Moon and to Mars, is the addition of an autonomous station. This moves the equipment needed for transferring fuel from one rocket to another away from the rockets themselves and onto the station. This would save extra launches of fuel transport, multiples of ten million dollars per Starship mission, and would have paid for itself after only six runs. However, due to the late hour of this proposed solution, it could cause delay to the project now but it would always be useful to implement later and the gain would only increase with more activity. A complete outline of a possible design, with hardware and software structures, has been given, but a detailed risk analysis and an ethical discussion of the case should be carried out before further work is started.

Keywords: Starship, Autonomy, Refueling

1 Introduction

With the current explosion in the rocket industry, and SpaceX's mission of sending cargo and people to Mars [1] [2], there are many future problems on the horizon which will have to be addressed soon. One of these problems is how rockets will obtain the fuel needed to travel interplanetary.

1.1 Current System

From the beginning of space travel, and up until today, the problem of fueling rockets has been solved before launch. All rockets from the Apollo Saturn V to the Space Shuttle and SpaceX's current version of Starship have been exclusively fueled on Earth, before takeoff. The current Starship has a payload capacity of 100 to 150 ton of cargo, and a fuel tank of 1200 ton capacity [2], but uses almost all its fuel to reach Lower Earth Orbit(LEO), making the old way of having all fuel needed for the trip an ineffective or possibly impossible solution. This has prompted the idea of refueling the rocket in space, using about 10 other Starships to carry fuel up from the Earth. Right now, the plan is to do this via a direct connection, where the two rockets are directly connected, and fuel is moved from one rocket to another. This solution is simple to implement but

has the negative effect of forcing the refueling rockets to bring tools and actuators for performing this task automatically as part of their payload, which reduces the amount of fuel a rocket can carry. Assuming the tank capacity is always 150 tons, then refueling will be done by exactly eight ships, but with any weight loss from carrying tools an extra ship will be needed. If the weight loss is 20% of the payload, or 30 tons, then ten Starships are needed. All these extra ships will have to burn extra fuel and increase the time from LEO is reached until the mission can be continued.

In Figure 1, a nine window diagram of the system is shown, to help place the system into a context. The rows show the super system (the user dealing with the job of the system), the system itself, and sub systems (any important system parts currently worked on). The figure helps to highlight the needed steps to bring the current system into the future, and possibly beyond. It also highlights some of the possible stakeholders of the system today and in the past/future, which outlines where to acquire information about the current and past systems and whom to consider in the future.

	Past	Present	Future
Super System	NASA's rocket program.	SpaceX's Starship Mars Mission.	Privately owned rockets.
System	Ground based refueling towers.	The Autonomous Rocket Refueling Station.	Autonomous rocket "Gas station" for any rocket.
Sub System	Assembling space stations, containing liquid fuel, docking of rockets.	Pumping fuel in vacuum, recognizing rockets, orientation and movement of the station.	Station Security, Multi rocket docking system.

Figure 1. A „nine window diagram“ for the refueling of rockets. The diagram gives perspective on the situation of the problem, both in the past and possibly future works. The left to right columns are split into past, present and future, and the top to bottom rows are split into super system, system and sub system.

1.2 Goal of Project

The goal of this report is to outline an alternative solution to refueling by rocket to rocket docking in space, namely an autonomous refueling station in LEO. This could solve the weight problem by moving extra hardware from the rocket to the station.

The system must be capable of acquiring fuel from Starship transport rockets, navigating a risk-free path and transferring fuel over to the target Starship rocket. When not in active operation, the station must keep itself safe from outside threats and communicate with a control center to schedule tasks. All this should be performed without the directions of humans, outside of scheduled task parameters.

First, a brief description of the potential outside considerations and possible problems the system would face will be presented. Then a detailed description of the system is outlined, starting with the overall design and ending with a more detailed view of the hardware and software components. A rough comparison between the rocket to rocket and station to rocket solutions will be made, focusing on the cost-effectiveness of the solutions. Finally, the results will be discussed, some future work outlined and a summary with a conclusion will be drawn.

2 Methods

In this chapter, the problems and difficulties arising from environmental, technological and law constraints upon the system will be presented, along with a description of the system design first as an overall view and later looking more detailed into the hardware and software separately.

2.1 Environmental Problems and Law Constraints

Outlining the surrounding environment and context of operation for the system is important to identify possible problems which will arise during operation and ensure correct design.

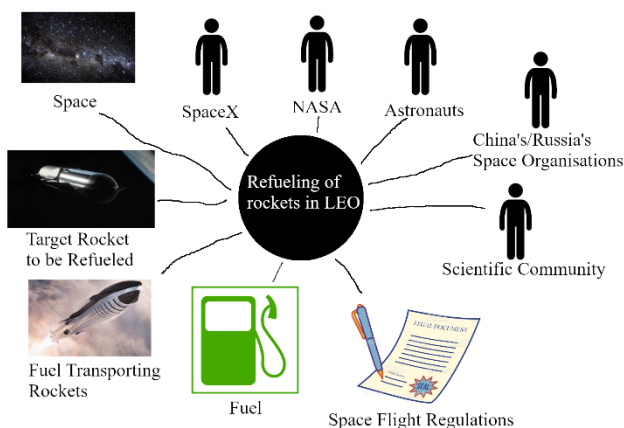


Figure 2. A context diagram for the solution to the problem of refueling rockets in LEO.

Figure 2 shows a context diagram for the problem solution, outlining the interactions it would have to deal with.

The physical environment is the near vacuum of space in the uppermost layer of the atmosphere. Here, the radiation is much higher than at the surface of the Earth, as the atmosphere normally would protect against harmful radiation. Extreme temperatures due to radiation from the Sun and little to no air cooling, are also problems. Furthermore, the potential pressure difference between the outside and inside of the rocket must also be considered. Finally, orbital decay, movement, and orientation in a near vacuum must also be considered. Space debris and other orbiting bodies on collision course could also pose a threat.

The stakeholders, SpaceX and NASA, will influence the design of the system by setting constraints upon the use case, frequency of use, security, safety, reliability and cost. For SpaceX, an efficient and as cheap as possible solution which can quickly be implemented while also being expandable to enable Moon and Mars missions and possibly travel to other planets is the most important. They also want a stylish design to uphold their reputation as a futuristic company. NASA has contracted a Starship mission to the Moon, and their culture is to put reliability, safety and security in front of everything else. There should be redundancy at all levels, and backup plans for every possible fault. In Figure 3, a diagram showing the key drivers, derived qualities, and the related system requirements are shown.

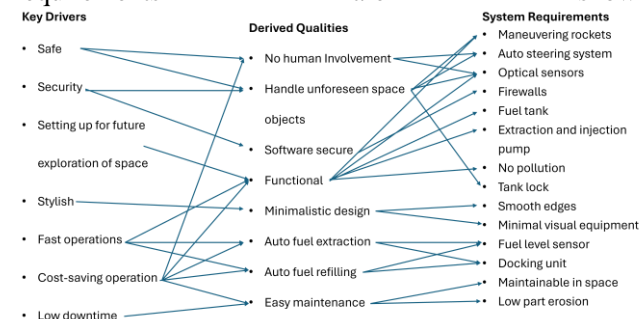


Figure 3. Key drivers, derived qualities and requirements diagram.

Astronauts working in space, either on the system or on other orbital objects in the future pose a safety concern as tanks of highly explosive liquids could send debris flying in all directions and pose a very life-threatening danger to people or destroy satellite or station hardware.

Unfriendly space organizations might pose a threat to the system, looking to sabotage operation, steal resources or copy and steal technology. For now, the only likely candidates for such operations in space are the Russian and Chinese space agencies, but in the future, other private contractors could be looking to damage such a system to enhance their own solutions

A small influence will be posed by the scientific community, either by influencing research upon fuel transfer options in weightlessness, or by limiting the

impact upon scientific tools in space or on Earth. As this is not a huge system or a too frequent use case yet, the impact on telescopes and the potential risk of hitting other satellites is not too high. However, with more frequent use in the future, the impact could grow and force regulations to be considered.

Space flight regulations, or for SpaceX's case, the Federal Aviation Administration's (FAA) legislations and policies for commercial space flight regulate vehicles operating in space and distribute licenses or permits needed for launching and reentering in US airspace or in any airspace where USA has jurisdiction. The FAA will also pause or delay any activity related to systems experiencing a deviation from planned operation [3]. As for rules of use and operation in space for all actors, the UN International Space Law specifies that all human astronauts must be helped to safety if they are in danger, and that all operators are responsible for the damage caused by their own endeavors. It also specifies that all objects launched into space must be registered by the UN [4].

The fuel used by the Raptor engines on Starship is a methane-oxygen mix created in the engines right before combustion [2]. This means the methane and oxygen must be kept separate from each other until used. Both reactants are kept in liquid form under high pressure.

Finally, the fuel transporting rockets bringing fuel into space, and the target rocket to fill with fuel must be identified, interacted with and communicated with.

2.2 Overall Design

The proposed autonomous fueling station will consist of a power source in the form of two solar panels at one end of the station, oriented to shield the liquid fuel engines from radiation to prevent heating. This power is used to run actuators inside the station and the control system responsible for processing information and deciding upon the actions to take. The control system also needs to communicate with both the rockets it should interact with, and a ground-based control center. Two tanks for containing the liquid fuel, with pumps for bringing the fuel in and out of the tanks, and surrounded by a steel shell. A docking station for a robot, capable of locking onto a rocket with clamps and sealing of a path between the tanks of Starship rockets and the stations tanks. Five raptor engines mounted in strategic places around the station to allow movement in all directions.

Finally, the main body is a steel construction to protect the insides from stray debris and radiation. This body contains the cables transferring electricity and signals between actuators and the control system. There are also pipes for creating paths between the fuel tanks and both the docking station and the raptor engines.

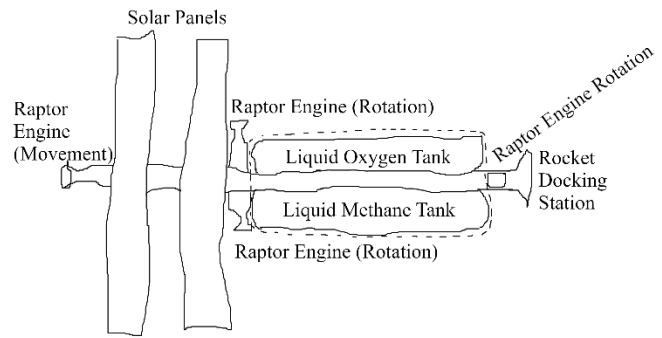


Figure 4. Sketch of refueling station for rockets in space. The most important features, a set of solar panels, the fuel tanks, and a docking station, are marked.

In Figure 4, a sketch of the design for the station is shown, with important hardware marked. The Raptor engine on the right is not easily visible, but it is possible to see the endpoint as a circle on the main body. This is because the engine here points directly out of the sketch. There is also a similar engine on the exact opposite side of the station body, which is not visible on this sketch. The dotted line around the fuel tanks is actually a solid cylinder of protective steel, which also helps round out the design of the station.

2.3 Sensors and Actuators

The two large solar panels supply electrical power for all sensors, actuators and the control system. To make sure the power is available when the station is not in direct sunlight, a battery is also connected to even out peaks and bumps in the power supply. As a general estimate of the capacity needed, the International Space Station (ISS) is used. The ISS has a power capacity of 105 kW under normal conditions [5]. The solar panels need to be attached to adjustable beams that can rotate to face the sun no matter the direction the station itself is facing.

The control system needs a set of antennas for transmitting messages from the refueling station to the rockets and to a ground-based center. The easiest way to do this is to use antennas capable of signaling to close objects and connect to either the Starlink satellite constellation or directly to a Starship rocket. As these satellites are open to commercial use, the signals and messages should be encrypted to ensure no information is given to outside parties. Since the same problems could arise during Starship operations, using the same information protocol Starship uses would be beneficial. The control system also needs access to optical cameras for object recognition and orientation purposes. These sensors should be optical since this is the most produced light by the sun, and will ensure best results. The cameras must be very high resolution to recognize help recognition of special markings on Starship rockets, ensuring the correct rocket is interacted with. They must also be equipped with light screening slid on walls for protection against direct sunlight when not in use. Three cameras for

taking pictures in three separate perpendicular directions will be used. A secure but available access port for servicing the control system manually if an unforeseen error occurs, is included in the side of the station closest to where the controller is placed. All information passing through this port must be heavily encrypted to ensure no unwanted changes are made, and the access must be securely locked to further prevent hacking attempts.

The two tanks and their piping system will use the same system implemented in starship to keep fuel in the rocket and transport it to the engines. However, as fuel needs to be both pumped into and out from the tank, an additional physical piston inside the tank, which can push the liquids toward the exit of the tank, is added. A set of sensors for measuring the pressure and the position of the piston is needed to control the system. Such sensors should be electrical or magnetic sensors with as few moving parts as possible, since these have a longer life time and require less maintenance. For this application a capacitive sensor for the pressure, and a laser distance meter for the pistons position is used. A temperature sensor for monitoring the liquid inside the tanks is also needed. Since the liquid is not ensured to be in contact with the sensor in weightless condition, a radiation temperature sensor is chosen.

The docking station needs to be shaped like a tract with a slightly curved form to fit snugly around an opening in the side of a Starship rocket. To ensure no fuel is spilled during pumping, the docking must create a pressurized, sealed path from one tank to the other, with the docking station rigidly connected to the outside of the rocket with four strong clamps. Thus, both the pressure and the clamps are holding the rocket and station together. To create this pressure, a small piston tank is connected to the end of the docking station and can be activated after the rocket is locked on.

The Raptor engines mounted to perform movement during operation are used to minimize the need for other fuel sources to be transported along with the fuel for Starship. This means having to burn part of the transported fuel to move, but since the station is already in orbit, and the fuel usage during operation will be small. The engine to the left in Figure 4 is mounted at one side pointing through the axis of the main body for easy control of thrust in a single direction. The two engines on the right are mounted perpendicular to the first engine at the end of the station to allow rotation. The finale two engines are mounted close to the center, but slightly offset, to allow rotation in the last direction. However, though it is not possible to see in the sketch, these last engines are also mounted at a slight angle directed back towards the leftmost engine, to allow for quick deacceleration without needing to rotate the whole station.

The main body itself, and the pipes inside, consist of welded stainless steel, just like the starship rocket, to withstand minor collisions from debris and pressure differences between the inside and out. This is a heavy material, but with a high strength, and protects well from

force, and outer penetration attempts. To add more radiation protection, a multilayer insulation material [6] lines the outer wall of body. The cables inside the body, used to transmit power and signals, are designed for 230 volt and up to 70 Amps. This is the same, or slightly greater than the ISS [5].

2.4 Control System Design

The control system is responsible for gathering and processing all information available to the system, and deciding how to act upon the information. Figure 5 shows a diagram of the control system, split into six parts, where the different tasks are spread among these six.

First, all sensors direct their results continuously to the sensor part, which is responsible for data cleaning and packaging.

Then, the information is sent to the perception block to be preprocessed and interpreted by an image recognition Convolved Neural Network, which has been trained to recognize threatening objects and fixed astronomic structures used as orientation markers. Distance and speed can also be estimated by taking multiple images at

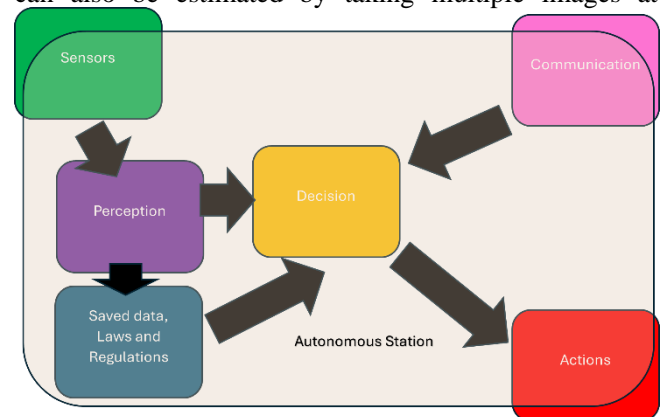


Figure 5. Design diagram for the control system. The control system is split into six parts, each with different responsibilities, to allow for high cohesion while maintaining low coupling.

slightly different angles and looking at the changes in sizes of the object. Another thing the perception block is trying to recognize is special markers on Starship rockets, to identify correct rockets to interact with.

The Perception block sends recognized information on to both the data storage and the decision part. The data storage part evaluates the type of data and determines whether it should save it or not, while also sending information relevant to the decision part. This data storage is an SQL server, where maps of the stations surroundings, old path history, laws and regulations, current list of threatening objects with their parameters, data on who to contact when, how and what has been said, status of all parts of the system, missions under way or still relevant and lists of predetermined decisions to be made in specific cases, such as when errors occur and if the station is in significant danger.

The decision part uses a decision tree model, trained in a simulator beforehand, to arrive at a decision, and

constructs a plan of action. Supporting this decision model is a potential-field path planning algorithm. This algorithm has been chosen because the space is a mostly empty area, where a quick path planner is useful, and few local minima are possible, however the algorithm must make sure to consider not only a direct object as a hinder, but also the path that object is heading. The decision part also communicates with the communication block which again is responsible for the safe communication to other systems by implementing encryption, building messages and implementing a firewall to protect the rest of the system.

Finally, the plan is sent to the actions block which translates the plan into actable decisions and directly control the actuators by adjusting signals. This action block is a PLC program with direct control of the actuators and a predefined list of actions based upon what needs to be done.

From this description, it is also clear that the system is split into three larger categories. A data layer consisting of the data storage part. A business layer consisting of the sensor, perception, decision, and action part. And a Presentation layer where the communication block interacts with the outside users like rockets and humans.

3 Results

The result is a complete solution for the problem of refueling a Starship rocket in LEO, namely the autonomous refueling station for rockets in space. A comparison between this solution and the “old” solution of direct rocket to rocket refueling follows.

3.1 Comparison of New System to Old System

The main advantage of the new system compared to the old solution is the movement of needed tools weight away from the rocket and onto a separate unit. Assuming about the same weight as an unfueled starship, since most of the same hardware is present in both systems, the weight can be calculated by taking the estimated mass of a fully fueled Starship of about 1350 tons [7], and subtracting the mass of the propellant capacity of 1200 tons [2]. Then the mass is estimated to be 150 tons, which is the carrying capacity of a Starship rocket as well. This results in an initial cost of only one Starship launch to get the station into orbit, assuming the station can fit inside the Starship hold. If the building cost of the station is estimated at the same as the current 90 million dollar cost for a Starship rocket [8], the total initial cost of the station becomes 100 million dollars, assuming a 10 million dollar launch cost which is what SpaceX is planning [8]. Since the station saves about two rockets from needing to launch if the actual weight of what would have been included in the rockets is about thirty tons or 20 % of the station’s weight,

the station will have paid for itself after only six uses. Current plans and contracts for Starship use have already outlined three such uses, with the Moon mission using at least on rocket, and a human Mars mission sending one rocket with cargo and one with humans.

Another advantage is the saved time from the target rocket arrives in LEO until it has been refueled and is ready to continue its mission. By reducing the number of launches, the wait time is also reduced, but since the time from launch until a rocket typically reaches LEO is not very long, the main source of reduced time is not in the flight duration but in the possible wait time if weather conditions are unstable, or if there are errors with the rockets needing to be fixed.

A downside of the new system is the reliance of a permanent structure in space which is much harder to perform maintenance on if damaged. This could cause major delays on missions, while waiting for a manned rocket to be launched with a repair crew. However, if maintenance is planned and scheduled at times where the station is not in use, there is no delay.

A finale disadvantage of the new compared to the old system is the initial cost of time, and the added possibility of delays to the project. The Starship rocket must already be developed, but a whole separate station is a new project and could take extra time to develop. Especially this late in Starships development, it could produce problems.

4 Discussion

4.1 Discussion of Analysis

As a result of the comparison and cost analysis of the new system compared to the old, a station based solution is to be recommended because of its money and time saving properties. However, because of the Starship projects late stage, starting a new project would be unwise at the moment. However, the need for interplanetary travel is only going to increase, and as a result of the rapid saving profile of the project, the solution would be good to implement at any time.

When it comes to the analysis performed in this report, the numbers are only a very rough estimate. The actual results of the analysis is however not as influenced by changes in the numbers, since the estimate is based on a bad case scenario for the autonomous station. Assuming the cost of the station and the mass to be equal to a starship rocket is only marginally realistic. Starship must be a much larger and more protected construct, as it has to fly both in and out of the Earth’s atmosphere. Also, assuming the launch cost of 10 million dollars any time soon is optimistic, so the potential for saving money is higher.

4.2 Future Works and Design

Security and risk reduction has not been looked closely into here. Performing a Preliminary Hazard Analysis to identify and mitigate possible hazardous events is needed before further planning and testing can be performed.

A proper ethical analysis of the implementation, with a more complete analysis of the laws applicable and ethical problems the system could face, should also be constructed before stepping into simulation and planning. Expandability of the system, with the possibility of adding multiple docking stations for faster refueling, should also be considered when the use for refueling in orbit increases. When this becomes the case, moving the station further out from the Earth to not risk flooding LEO with more debris should also be discussed. To reduce the waste of fuel during operation even further, a photon propulsion [9] engine should replace the Raptor engines. This is however not an available technology, and only a theoretical proposition.

Finally, simulations of the systems performance and the feasibility of the solution with a piston inside the tank should be simulated with a realistic physical model.

5 Conclusion

The recent explosion in rocket science has led to the problem of refueling rockets in LEO, and SpaceX has proposed a solution of a direct docking between two rockets to transfer fuel from one Starship to the next. In this report, an alternative solution of an autonomous refueling station for rockets in space has been outlined, with a presentation of its environment and stakeholder which will influence its design. A complete description of its design, including both hardware design and components as well as software structure and components. Finally, a comparison between the rocket to rocket and station to rocket cost-efficiency was performed, outlining that the station is cheaper in the long term, but might pose a problem with time early on. And a future for the project was proposed.

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References

- [1] SpaceX, "Starship Mission to Mars," 11 April 2023. [Online]. Available: <https://youtu.be/921VbEMAwY?si=j6FpjIgSKmM50G13>. [Accessed 18 December 2024].
- [2] SpaceX, "Starship," 2024. [Online]. Available: <https://www.spacex.com/vehicles/starship/>. [Accessed 18 December 2024].
- [3] Federal Aviation Administration, "51 USC Ch. 509: COMMERCIAL SPACE LAUNCH ACTIVITIES," 20 October 1984. [Online]. Available: <https://uscode.house.gov/view.xhtml?path=/prelim@title51/subtitle5/chapter509&edition=prelim>. [Accessed 19 Desember 2024].
- [4] United Nations Office For Outer Space Affairs, "Part one United Nations treaties," *International Space Law: United Nations Instruments*, pp. 1-29, May 2017.
- [5] E. B. Gietl, E. W. Gholdston, B. A. Manners and R. A. Delventhal, "The Electric Power System of the International Space Station - A Platform for Power Technology Development," NASA Center for Aerospace Information, Hanover, 2000.
- [6] M. M. Finckenor and D. Dooling, "Multilayer Insulation Material Guidelines," NASA Center for AeroSpace Information, Linthicum Heights, 1999.
- [7] E. Ralph, "Teslarati," 17 March 2020. [Online]. Available: <https://www.teslarati.com/spacex-starship-super-heavy-booster-design-tweaks/>. [Accessed 20 December 2024].
- [8] S. Clark, "Rocket Report: A new estimate of Starship costs; Japan launches spy satellite," *Ars Technica Rocket Report*, vol. 6, no. 27, 2024.
- [9] K. B. Young, "Prospective of Photon Propulsion for Interstellar Flight," *Physics Procedia Volume 38*, pp. 253-279, 7 November 2012.